

Puerto Rico's State of the Climate 2010-2013

Assessing Puerto Rico's Social-Ecological
Vulnerabilities in a Changing Climate



Temperature



Precipitation



Sea Level



Storms



Ocean Acidification

Suggested Citation for the entire document:

Puerto Rico Climate Change Council (PRCCC). 2013. Puerto Rico's State of the Climate 2010-2013: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate. Puerto Rico Coastal Zone Management Program, Department of Natural and Environmental Resources, NOAA Office of Ocean and Coastal Resource Management. San Juan, PR.

Suggested citation for individual chapters:

Puerto Rico Climate Change Council (PRCCC) Working Group 1. 2013. Geophysical and Chemical Scientific Knowledge. WG1, 21 – 84. In Puerto Rico's State of the Climate 2010-2013: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate. Eds. Jacobs, K.R., A. Terando, E. Diaz. Puerto Rico Coastal Zone Management Program, Department of Natural and Environmental Resources, NOAA Office of Ocean and Coastal Resource Management. San Juan, PR.

Puerto Rico Climate Change Council (PRCCC) Working Group 2. 2013. Ecology and Biodiversity WG2, 85 – 250. In Puerto Rico's State of the Climate 2010-2013: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate. Eds. Jacobs, K.R., L. Carrubba, E. Diaz. Puerto Rico Coastal Zone Management Program, Department of Natural and Environmental Resources, NOAA Office of Ocean and Coastal Resource Management. San Juan, PR.

Puerto Rico Climate Change Council (PRCCC) Working Group 3. 2013. Society and Economy. WG3, 251 – 306. In Puerto Rico's State of the Climate 2010-2013: Assessing Puerto Rico's Social-Ecological Vulnerabilities in a Changing Climate. Eds. Jacobs, K.R., L. Carrubba, E. Diaz. Puerto Rico Coastal Zone Management Program, Department of Natural and Environmental Resources, NOAA Office of Ocean and Coastal Resource Management. San Juan, PR.

Cover photo credits:

Puerto Rico Coastal Zone Management Program

This publication was funded in part through NOAA Grant NA11N054190162



Puerto Rico's State of the Climate 2010-2013

Assessing Puerto Rico's Social-Ecological
Vulnerabilities in a Changing Climate



PRCCC COLLABORATORS AND AFFILIATIONS

Cándido Adorno

Puerto Rico Emergency Management Agency

Dr. José Alameda Lozada

University of Puerto Rico – Mayagüez

Prof. Félix Aponte

University of Puerto Rico – Rio Piedras
Graduate School of Planning

Dr. Richard S. Appeldoorn

University of Puerto Rico – Mayagüez

Dr. Roy Armstrong

University of Puerto Rico – Mayagüez

Katia R. Avilés-Vázquez, MS, Ph.D.c

Proyecto Enlace Caño Martin Peña

Dr. Maritza Barreto Orta

University of Puerto Rico – Rio Piedras

Dr. Jorge F. Bauzá-Ortega

San Juan Bay Estuary Program

Dr. Conrado M. Calzada Cordero

Pontificia Universidad Católica de Puerto Rico
Departamento de Biología-Programa de Ciencias Ambientales

Miguel Canals

Department of Natural and Environmental Resources

Dr. Miguel Canals Silander

University of Puerto Rico – Mayagüez
CariCOOS

Dr. Jorge Capella

University of Puerto Rico – Mayagüez
CariCOOS

Dr. Carlos Carrero Morales

Puerto Rico Sea Grant College Program

Dr. Lisamarie Carrubba

NOAA Fisheries
Caribbean Field Office

Juan A. Castañer, MA

Estudios Técnicos, Inc.

Graham A. Castillo -Pagán, Esq.

Estudios Técnicos, Inc.

Sindulfo Castillo, P.E.

U.S. Army Corps of Engineers

Ruperto Chaparro

Puerto Rico Sea Grant College Program

Isatis Cintrón

Enlace Latino de Acción Climática

Dr. Jaime Collazo

North Carolina State University

Dr. Ricardo J. Colón-Rivera

Texas A&M University
Spatial Sciences Laboratory
Department of Ecosystem Science & Management

Dr. Jorge Corredor

University of Puerto Rico – Mayagüez
CariCOOS

Dr. Jennifer Costanza

North Carolina State University

Wanda I. Crespo-Acevedo, PPL

Estudios Técnicos, Inc.

Dr. Angel David Cruz Báez

University of Puerto Rico – Rio Piedras

Dr. José A. Cruz-Burgos

U.S. Fish and Wildlife Service

Dr. David Cuevas

U.S. EPA
Caribbean Environmental Protection Division

Dr. Elvira Cuevas Viera

University of Puerto Rico – Rio Piedras
Department of Biology
Center for Applied Tropical Ecology and Conservation

Carmelo Dávila

Department of Natural and Environmental Resources
Jobos Bay National Estuarine Research Reserve

Damaris Delgado López
Department of Natural and Environmental Resources

Anselmo De Portu
Department of Natural and Environmental Resources
Society of Puerto Rico Planners

Dr. Walter Díaz
University of Texas

Dr. Yasmin Detrés
CariCOOS
University of Puerto Rico – Mayagüez

Ernesto L. Díaz, MS, MEM
Puerto Rico Coastal Zone Management Program
Department of Natural and Environmental Resources

Dr. Pedro L. Díaz
U.S. Geological Survey – Puerto Rico

Angel Dieppa
Department of Natural and Environmental Resources
Jobos Bay National Estuarine Research Reserve

Carlos Diez
Department of Natural and Environmental Resources

Raimundo Espinoza
The Natural Conservancy – Puerto Rico

María Falcón
GeoAmbiente del Caribe

Dr. Rusty Feagin
Texas A&M University

Dr. Denny S. Fernandez del Viso
University of Puerto Rico – Humacao

Carlos Fuller
Caribbean Community Climate Change Center

Dr. Miguel García
Department of Natural and Environmental Resources

Luis Garden Acosta
El Puente

Dr. Graciela García Moliner
NOAA
Caribbean Fisheries Management Council

Dr. Jorge García Sais
University of Puerto Rico – Mayagüez

Soledad Gaztambide Arandes
Environmental Policy and Government Relations
Coordinator
Conservation Trust of Puerto Rico

Pedro A. Gelabert
Professional Geologist

Jorge Gelpí Pagán
Wapa Television

Dr. Fernando Gilbes Santaella
University of Puerto Rico– Mayagüez
Center for Hemispherical Cooperation in Research
and Education in Engineering and Applied Science
(CoHemis)

Carmen González
Department of Natural and Environmental Resources
Jobos Bay National Estuarine Research Reserve

Dr. William Gould
International Institute of Tropical Forestry
U.S. Forest Service
Caribbean Landscape Conservation Cooperative

Dr. Yogani Govender
Manager
Science, Education and Public Policy Division
Conservation Trust of Puerto Rico

Dr. Rosana Grafals-Soto
University of Puerto Rico – Rio Piedras

Astrid Green
Department of Natural and Environmental Resources

Carmen Guerrero, PPL
Secretary of Puerto Rico Department of Natural and
Environmental Resources

Dr. Katharine Hayhoe
Texas Tech University
AtmosResearch

Dr. Edwin A. Hernández Delgado
University of Puerto Rico – Rio Piedras
Center for Applied Tropical Ecology and
Conservation

Dr. Victor Huérfano Moreno
Puerto Rico Seismic Network

Karla Hevia, PPL
Puerto Rico Coastal Zone Management Program
Department of Natural and Environmental Resources

Kasey R. Jacobs, MESc
Puerto Rico Coastal Zone Management Program
Department of Natural and Environmental Resources

Dr. Rafael L. Joglar
University of Puerto Rico – Rio Piedras
Department of Biology

Dr. Michael Johansson
Center for Disease Control and Prevention
Dengue Branch – San Juan

Dr. Nilda M. Jimenez
Department of Natural and Environmental Resources

María Juncos Gautier
UMET Centro de Estudios para el Desarrollo
Sustentable
The Climate Reality Project

Dr. Mark R. Jury
University of Puerto Rico – Mayagüez
Department of Physics

Dr. Eddie Laboy Nieves
(CIEMAD es)
Puerto Rico Center for Environmental Studies and
Sustainable Development

Glenn Landers, P.E.
U.S. Army Corps of Engineers

Dr. Javier Laureano
San Juan Bay Estuary Program

Ivan Llerandi-Roman
U.S. Fish and Wildlife Service

Dr. Craig Lilyestrom
Department of Natural and Environmental Resources

Carla Loubriel, Esq.
Independent Lawyer

Dr. Ariel Lugo
International Institute of Tropical Forestry
U.S. Forest Service

Nilda Luhring González, PhD
Sustainable Tourism Division
Puerto Rico Tourism Company

Odalys Martínez-Sánchez
NOAA National Weather Service

Israel Matos
Former Director of the NOAA National Weather
Service in San Juan

Melissa Meléndez Oyola
University of Puerto Rico – Mayagüez
CariCOOS

Dr. Rafael Méndez Tejeda
University of Puerto Rico – Carolina

Prof. Aurelio Mercado Irizarry
University of Puerto Rico – Mayagüez

Dr. Pablo A. Méndez Lázaro
University of Puerto Rico – Medical Sciences Campus
Graduate School of Public Health
Department of Environmental Health

Rafael Mojica
NOAA National Weather Service

Carolina Morales Gonzalez
Sustainable Tourism Division
Puerto Rico Tourism Company

Alexis Molinares
Independent

Prof. Julio M. Morell
University of Puerto Rico – Mayagüez
CariCOOS

Edwin Muñiz
U.S. Fish and Wildlife Service

Rafael Mojica
NOAA National Weather Service

Dr. José Molinelli
University of Puerto Rico – Rio Piedras

Ada Monzón
Univision

Roberto Moyano, MS
Estudios Técnicos, Inc.

Arq. Victor Nieto
University of Puerto Rico – Rio Piedras
School of Architecture

Chris Nytch
Luquillo Forest Dynamics Plot
Institute for Tropical Ecosystem Studies
University of Puerto Rico – Rio Piedras

Coralys Ortiz Maldonado
Puerto Rico Coastal Zone Management Program
Department of Natural and Environmental Resources

Maria Ortiz Rivera
Universidad Metropolitana

Dr. Jorge R. Ortíz-Zayas
University of Puerto Rico – Rio Piedras Campus
College of Natural Sciences
Institute for Tropical Ecosystem Studies

Dr. Ernesto Otero-Morales
University of Puerto Rico – Mayagüez

Dr. Susan Pacheco
University of Texas Health Science Center
University of Puerto Rico School of Medicine
Climate Reality Project - District of Puerto Rico

Dr. Carlos M. Padín
Universidad Metropolitana

Dr. Luis R. Pérez Alegría
University of Puerto Rico

Benito Pinto Rodríguez
La Regata Newspaper

Dr. Alberto R. Puente-Rolón
Department of Natural and Environmental Resources

Francisco Javier Quintana Alamo
Department of Natural and Environmental Resources

Lillian Ramírez Durand
Puerto Rico Sea Grant College Program

Dr. Antares Ramos
National Oceanic and Atmospheric Administration

Pedro Ríos
U.S. Forest Service
El Yunque National Forest

Marelisa Rivera
U.S. Fish and Wildlife Service

Maricelis Rivera Santos
Periodista

Dr. Neftalí Ríos López
Department of Biology
University of Puerto Rico-Humacao

Dr. Loretta Roberson
University of Puerto Rico – Rio Piedras

Lyvia Rodríguez
Corporación del Proyecto Enlace del Caño Martín
Peña

Lyzaida Rodríguez
Corporación del Proyecto Enlace del Caño Martín
Peña

Miguel A. Rolón
Caribbean Fishery Management Council

David W. Román
University of Puerto Rico – Rio Piedras
Independent Lawyer

Aida Rosario Jiménez
Department of Natural and Environmental Resources

Jean A. Ruiz Cortés
Enlace Latino de Acción Climática
Climate Reality Project – District of Puerto Rico

Dr. Jorge E. Saliva
U.S. Fish and Wildlife Service

Mayra Sánchez
University of Puerto Rico – Rio Piedras

Colibrí Sanfioorenzo Barnhard
Grupos Ambientales Interdisciplinarios Aliados-
GAIA

Arq. Pedro Santa
Ae.i.ou Research & Design Collective

Raúl Santiago Bartolomei, P.E., MS, MP
Estudios Técnicos, Inc.

Dr. Luis E. Santiago

University of Puerto Rico – Rio Piedras

Raúl Santini-Rivera

Puerto Rico Coastal Zone Management Council
Department of Natural and Environmental Resources

Dr. Jenniffer M. Santos-Hernandez

University of Puerto Rico – Rio Piedras Social
Sciences

Heriberto N. Sauri

Puerto Rico Emergency Management Agency

Dr. José Seguinot Barbosa

University of Puerto Rico – Medical Sciences Campus
Department of Environmental Health

Lilibeth Serrano

U.S. Fish and Wildlife Service

Dr. Clark Sherman

University of Puerto Rico – Mayagüez

Susan Silander

U.S. Fish and Wildlife Service

Brenda M. Soler-Figueroa

University of Puerto Rico – Mayagüez

Susan Soltero

Univision

Paul Sturm

Ridge to Reefs

Dr. Adam Terando

North Carolina State University
Department of Interior Climate Science Center
Southeast and Caribbean

Arq. José Juan Terrasa-Soler

Former Planning and Development Director
Puerto Rico Tourism Company

Dr. Ernesto Torres

Inter American University

Brenda Torres-Barreto

Caribbean Sustainable Response

Dr. Jesús Vega

Independent Archaeologist

Aileen T. Velazco Domínguez

Department of Natural and Environmental Resources

Dr. Manuel Valdes Pizzini

University of Puerto Rico – Mayagüez

Evelio Valeiras, PPL

Department of Natural and Environmental Resources

Hector L. Vélez Cruz, Esq.

U.S. EPA
Caribbean Environmental Protection Division

Eduardo A. Ventosa-Febles

Department of Natural and Environmental Resources

Dr. Vance P. Vicente

Vicente & Associates, Inc.

Dr. Joseph Henry Vogel

University of Puerto Rico- Rio Piedras

Dr. Ernesto Weil

University of Puerto Rico – Mayagüez

Dr. Amos Winter

University of Puerto Rico – Mayagüez



T A B L E O F C O N T E N T S

Foreward in English	1
Prólogo en español	3
Introduction	5
Working Group 1 Report: Geophysical and Chemical Scientific Knowledge	21
Working Group 2 Report: Ecology and Biodiversity	85
Working Group 3 Report: Society and Economy	251

PUERTO RICO CLIMATE CHANGE COUNCIL

FOREWARD

In 2007, the Intergovernmental Panel on Climate Change (IPCC) of the United Nations Framework Convention on Climate Change released its Fourth Scientific Report. This report recognized the need for the mitigation of Global Greenhouse gases emissions to offset or to reduce emissions below current and projected levels. This Convention defines climate change as:

...a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

That year, over one hundred scientists signed the “Puerto Rico Declaration on Climate Change” and the Sea Grant program convened a round table discussion “Facing the Consequences of Climate Change in Puerto Rico” where researchers and experts of various disciplines evaluated potential effects and impacts, as well as mitigation and adaptation alternatives to global changes. As a result of these initiatives, the Executive Order 2008-09 of February 29th, 2008 was issued establishing the Strategic Affairs Commission to Mitigate Global Warming and Adaptation to Climate Change. These efforts captured the citizenry’s attention through intermittent press releases.

In 2009, the Academies of the Group Eight + Five (G8+5) integrated by the largest economies of the World: Canada, France, Germany, Italy, Japan, Russia, the United Kingdom, and the United States plus the emerging economies Brazil, China, India, Mexico, and South Africa, unanimously recognized the need to combat the climate changes associated to human activities. That year, the Department of Natural and Environmental Resources (DNER) through the Puerto Rico Coastal Zone Management Program (PRCZMP) developed the Puerto Rico Climate Adaptation proposal. This proposal was approved by the National Oceanic and Atmospheric Administration (NOAA) as the Puerto Rico Coastal Adaptation project. The NOAA also approved a 2-year fellowship to support PRCZMP’s project coordination.

In 2010, over 50 researchers, planners, economists, architects, sociologists, health professionals, and hydrologists, as well as several other professionals and experts of other fields relevant to the study of climate variability and change met and agreed to contribute to assess potential effects and impacts associated to climate variability and change in Puerto Rico. The main objective of the initial group was to assess the vulnerability of coastal communities, critical infrastructure, and biodiversity and to initiate the development of adaptation strategies. However, it was necessary to broaden the scope of work as new members from other sectors and disciplines joined the group. This group of volunteers adopted the name Puerto Rico Climate Change Council. The Council’s work was conducted under four sub-groups: (1) Geophysical and Chemical Scientific Knowledge; (2) Ecology and Biodiversity; (3) Economy and Society; and (4) Communicating Climate Change and Coastal Hazards. The Puerto Rico Coastal Zone Management Program coordinates and serves as Executive Secretariat of the Puerto Rico Climate Change Council. At the time of publishing this report the Council has 157 members and collaborating partners.

The world’s societies need to increase their knowledge and understanding of climate change, as well as its effects and impacts in order to effectively adapt. Adaptation demands fundamental changes

in the ways we produce goods and services, and in our individual lifestyles. These changes can and should provide opportunities for job creation and stimulus to emergent markets. In Puerto Rico, the general public is primarily concerned about the potential impacts of climate change to life and property, and the potential increase in the frequency and magnitude of storms and hurricanes, storm surges, floods, and coastal erosion. General public is less aware of climate change impacts on human health, food production, water supply, and biodiversity.

The DNER through the Puerto Rico Coastal Zone Management program continues the analysis of current and potential impacts of climate change and sea level rise on coastal communities, infrastructure, ecosystems, habitats, and populations of coastal and marine species. Other partner organizations, as well as researchers from Federal and Commonwealth agencies, universities, non-governmental and community-based organizations represented in the PRCCC also continue investigating, evaluating, assessing, and contributing to develop and catalog the best scientific, technical, and communications' knowledge to support decision making in the public and private sectors and by each individual member of our population.

This first Climate Change Vulnerability Assessment report will be followed by the Adaptation Strategies document. Both documents will be periodically updated by the Climate Change Council with the support of the Puerto Rico Coastal Zone Management Program. It is our aspiration that these documents contribute to guide public policy formulation and implementation, coastal areas planning and development, as well as to strengthen public education and awareness about the risks and alternatives to adapt to future climate scenarios.

We are witnessing multiple changes in global processes, not only those that are climate related. We must address these changes in an informed manner, with creativity, innovation, and solidarity.

Ernesto L. Díaz
Director
Coastal Zone Management Program

CONSEJO DE CAMBIOS CLIMÁTICOS DE PUERTO RICO

PRÓLOGO

En el 2007, el Panel Intergubernamental sobre el Cambio Climático constituido en el marco de la Convención de las Naciones Unidas sobre los Cambios Climáticos emitió su cuarto informe científico. En este Informe se enfatizó que resultaba imperativo lograr mitigar o reducir significativamente las emisiones de gases de invernadero, principalmente del dióxido de carbono CO₂ a nivel mundial, para desacelerar el incremento de las concentraciones de estos gases a nivel global y así reducir los impactos asociados a estos. Esta Convención define al cambio climático como:

...cambio de clima atribuido directa o indirectamente a la actividad humana que altera la composición de la atmósfera mundial y que se suma a la variabilidad natural del clima observada durante períodos de tiempo comparables.

Ese mismo año, sobre un centenar de científicos firman la “Declaración sobre el Cambio Climático en Puerto Rico” y el Programa *Sea Grant* convoca a mesa redonda “Enfrentando las consecuencias de los cambios climáticos en Puerto Rico” en la cual investigadores y expertos de diferentes disciplinas evaluaron los posibles efectos e impactos, así como las posibles alternativas de mitigación y adaptación a estos cambios globales. Como resultado de estas iniciativas, el 29 de febrero de 2008, se crea la Comisión de Asuntos Estratégicos para la Mitigación del Calentamiento Global y Adaptación al Cambio Climático en Puerto Rico mediante la Orden Ejecutiva 2008-09. Estos esfuerzos lograron capturar la atención de la ciudadanía de manera intermitente a través de reseñas de los medios de comunicación.

En el 2009, las Academias de los países del Grupo de los Ocho mas Cinco (G8+5) que integra a las economías más importantes del planeta: Alemania, África del Sur, Brasil, Canadá, China, Estados Unidos, Francia, India, Italia, Japón, México, Reino Unido y Rusia, reconocieron de manera unánime la necesidad de combatir las consecuencias de los cambios climáticos asociados a la actividades humanas. Al mismo tiempo, en el Departamento de Recursos Naturales y Ambientales de Puerto Rico desarrollábamos la propuesta para la evaluación integral de la vulnerabilidad y el desarrollo de estrategias de adaptación a los cambios climáticos y el incremento del nivel del mar en el marco del Programa de Manejo de la Zona Costanera (PMZC). Nuestra propuesta fue aprobada por la Agencia Nacional Oceánica y Atmosférica (NOAA, por sus siglas en inglés), logrando además que se aprobara el financiamiento por dos años de una beca para que un estudiante graduado apoyara los esfuerzos del PMZC.

En el 2010, iniciamos los trabajos convocando a 50 científicos, planificadores, economistas, arquitectos, sociólogos, profesionales de la salud e hidrólogos, entre otros profesionales y expertos de diferentes disciplinas relevantes para el estudio de la variabilidad y los cambios climáticos. Este grupo inicial de expertos acordó contribuir a la evaluación de los posibles efectos e impactos de estos cambios en Puerto Rico. El objetivo central planteado era evaluar la vulnerabilidad de las comunidades, la infraestructura y la biodiversidad en nuestras costas e iniciar el desarrollo de estrategias de adaptación. Sin embargo, se hizo necesario ampliar el ámbito de los trabajos al sumarse al grupo un nutrido grupo de expertos de otros sectores y disciplinas. El grupo de voluntarios adoptó el nombre de Consejo de Cambios Climáticos de Puerto Rico y los trabajos fueron organizados bajo cuatro sub-grupos: (1) Conocimiento Científico Geofísico y Químico, (2) Ecología y Biodiversidad, (3) Economía y Sociedad, y (4) Comunicación de Riesgos Costeros y los Cambios Climáticos. Los trabajos han sido coordinados a través del Programa de Manejo de la Zona Costanera que funge como Secretaría Ejecutiva y Técnica del Consejo. Al momento de presentar este primer informe, el Consejo cuenta con 157 miembros y colaboradores.

La necesidad de incrementar nuestro conocimiento y la capacidad de las sociedades para adaptarse a los impactos de los cambios climáticos exige cambios fundamentales en la forma de producir bienes y servicios, así como en nuestros estilos de vida. Estos cambios también pueden y deben generar oportunidades para la creación de empleos y el estímulo a mercados emergentes.

En Puerto Rico, las principales preocupaciones de la población con respecto a los impactos de los cambios climáticos globales se relacionan a los riesgos para la vida y propiedad asociados a los incrementos potenciales en la frecuencia y magnitud de los fenómenos atmosféricos como tormentas y huracanes, marejadas ciclónicas, inundaciones y la erosión de las costas. Los impactos a la salud humana, la producción de alimentos, los abastos de agua y a la biodiversidad, por ejemplo, son menos conocidos por la población.

El Departamento de Recursos Naturales y Ambientales, a través del Programa de Manejo de la Zona Costanera, continúa el análisis de los impactos presentes y potenciales de los cambios climáticos y el incremento del nivel del mar sobre las comunidades costeras, la infraestructura y los ecosistemas, hábitats y poblaciones de especies marinas y costeras, mientras que múltiples organizaciones e investigadores de agencias federales, estatales, universidades, organizaciones no gubernamentales y de base comunitaria que forman parte del Consejo de Cambios Climático de Puerto Rico, continúan investigando, evaluando y contribuyendo a desarrollar y catalogar el mejor conocimiento científico, técnico y comunitario para que este sea integrado a los diferentes procesos de toma de decisiones de los sectores público y privado y de nuestra población.

Este primer informe sobre la vulnerabilidad a los cambios climáticos será acompañado por el documento de las estrategias de adaptación. Ambos documentos serán actualizados periódicamente por el Consejo de Cambios Climático mediante apoyo del Programa de Manejo de la Zona Costanera. Aspiramos que estos documentos contribuyan a orientar la formulación e implantación de políticas públicas, la planificación y el desarrollo de las áreas costeras, así como fortalecer los procesos de educación y concienciación ciudadana sobre los riesgos y las alternativas de adaptación a escenarios climáticos futuros.

Nos encontramos ante procesos globales de cambios en múltiples dimensiones, no sólo aquellos relacionados al clima. Debemos encarar estos cambios de manera informada, con creatividad, innovación y solidaridad.

Ernesto L. Díaz
Director
Programa de Manejo de la Zona Costanera de Puerto Rico

INTRODUCTION

The world is changing and will continue to change at rates unprecedented in recent human history. Both rapid-onset and slow-onset hazards pose substantial risks to many coastal communities of Puerto Rico. Storm surges, winter swells, tsunamis, coral bleaching are examples of rapid-onset events, while sea level rise and ocean acidification are examples of slow-onset events. Risks from these phenomena are projected to increase due to continued development in hazardous locations, changes in the frequency and intensity of inundation events, and acceleration in the rate of change along vulnerable shorelines. Adequate attention must be given to respond to the impacts of coastal hazards that are already occurring and at the same time prepare for future impacts. Strengthening the ability of Puerto Rico to reduce risks will safeguard economic progress and increase the resilience of our ecosystems and our people.

In Puerto Rico, approximately 419,000 people live within the coastal zone, and 2.3 million live within the 44 coastal municipalities of the Commonwealth (Diaz and Hevia 2011). Although all of Puerto Rico (including Culebra and Vieques) are coastal areas, the coastal zone is defined as 1 kilometer inland with additional distance for key natural systems. These populations are exposed to specific hazards such as coastal and riverine flooding, tsunamis, hurricanes, landslides, earthquakes and droughts. Hazard events and related social consequences are described in historical documents dating back before and after the Spanish-American War (Bush 1995; Fassig 1928; Jibson 1987; McCann 1984; Palm and Hodgson 1993; Reid and Taber 1919; Rouse 1992; Wilson 2007), specifically hurricanes (Schwartz 1992), and some have been described and passed on through oral history, pottery, and petroglyphs since the Tainos (Culture 2012; Ewald 1987; Maclachan 1990). Vulnerabilities to these recurring hazards are widespread in Puerto Rico and a result of multiple factors, such as continuing development in high hazards areas, poor maintenance of existing shoreline stabilization structures and stormwater management systems, poor maintenance and dredging of rivers, canals and reservoirs, lack of soil management practices on land and in watersheds, and from the elimination of dunes, reefs, mangroves, and other naturally protective features that reduce the negative effects of hazard events. While these problems persist, some corrective measures have been implemented since the 1970s, such as water quality and flood control initiatives, habitat restoration and other enhancement projects.

A new threat has the potential to exacerbate these already existing vulnerabilities and may even create new ones – climate change. There is consensus among the scientific community that anthropogenic activities are driving changes in the global climate and increasing global average temperature (IPCC 2007). Even if all greenhouse gas-emitting activities were halted immediately, the planet would still experience decades of climate effects due to the inertia change is often thought of as a global systemic problem; systemic as its causes are initiated anywhere on earth, and the effects felt worldwide (Frederick & Gleick, 1999; Wigley, 1999). While climate change is a global problem, it already has and is predicted to continue manifesting locally in Puerto Rico.

Many decisions made on a daily, weekly, annual, and decadal basis in Puerto Rico come with a long-term commitment and can be very sensitive to climate conditions. Examples of these types of decisions include land-use plans, risk management strategies, infrastructure development for water management or transportation, coastline and flood defenses (e.g., dikes, shoreline stabilization structures, flood control and stormwater management infrastructure design), urbanism (e.g., urban density, parks),

energy production, and building design and norms. These decisions have consequences over periods of 50-200 years and perhaps longer. Decisions, as well as investments, are potentially vulnerable to changes in climate conditions such as changes in precipitation and temperature patterns, sea level rise, greater intensity of storms, etc. In the past, these climate-driven parameters could be observed and measured. Today, engineers and public works officers use statistical analyses and optimization algorithms to determine the “best” designs as a function of known climate conditions (e.g., dike or revetment heights as a function of the return time of storm surges, building characteristics as a function of typical temperature levels) and planners often lay out coastal communities with a historical view of the shoreline. In the future, there will be substantial climate uncertainty making these methods more difficult to apply. Additionally, decisions and actions on how to adapt to changes in climate by people and institutions within or managing the coastal zone are shaped and constrained by a range of factors, including the resources available to decision-makers and the social, economic, and political context in which decisions are made.

This report puts the discussions that are happening about this global problem and decision-making in a changing climate into the Puerto Rico context. Certain sectors should already start taking climate change into account because they involve long-term planning, long-lived investments and some irreversibility in choices and are exposed to changes in climate conditions (Hallegatte, 2009:241). To guide decision making processes in Puerto Rico around coastal development and natural resource management the Puerto Rico Coastal Zone Management Program (PRCZMP) has partnered with over 140 researchers, planners, architects, practitioners, agency representatives and communications experts to develop a comprehensive climate change vulnerability assessment for Puerto Rico. Employing multiple collaboration and facilitation tools, scientific knowledge management, spatial analysis, and communication methods, the PRCZMP has been working through the newly created Puerto Rico Climate Change Council (PRCCC) to accurately assess vulnerability to life and property.

The PRCCC has found that climate change will impact the social, economic, and ecological fabric of life in Puerto Rico, affecting key sectors such as economic development, tourism, services, natural resources and biodiversity, cultural and historic resources, security, and critical infrastructure. The size, history, and relative isolation of the islands of Puerto Rico will make them feel the effects of climate change differently than other U.S. coastal zones. For years this picture has been incomplete due to lack of a coordinated effort to compile the best available scientific and local knowledge. This section discusses the history of climate change efforts in Puerto Rico and the process and techniques used from 2010 to 2013 to create and coordinate the work of the PRCCC. The section concludes with information about the next steps of the PRCCC and a brief discussion about the need for climate change adaptation efforts in island states like Puerto Rico that currently make decisions based on a static environment.

History of climate change efforts in Puerto Rico

While recent years have brought more attention to the issue of climate change in the islands of Puerto Rico, efforts have been made since the 1990’s to inform climate-sensitive decision making and natural resource management. Scientific studies have been carried out in Puerto Rico in the fields of physical oceanography, forestry, wildlife biology marine biology, and epidemiology recognizing the importance of climate stressors and the potential affects they could have on Puerto Rico and the Caribbean’s social-

ecological systems, such as on root function (Van Noordwijk et al. 1998), amphibian decline (Burrowes et al. 2004), coral disease and bleaching (Hernández-Pacheco et al. 2011; Weil et al. 2009; Winter et al. 1998), forest disturbances (Thompson et al. 2007), fisheries management (Nurse 2011), flood prevention (López-Marrero and Yarnal 2010; Staes et al. 1994), and vector borne diseases (Johansson et al. 2009), just to name a few.

The information coming from global and local studies prompted the University of Puerto Rico and NOAA's Sea Grant College Program to conduct two roundtables, one in 2007 and the second in 2009. These roundtables brought together the most prominent scientists working in Puerto Rico to share the current state of knowledge on climate science as well as the potential impacts to natural resources and society. After the first roundtable in 2007 a local advocacy organization Citizens of the Karst published a *Climate Change Declaration to the Government and Citizens of Puerto Rico* by 174 members of the scientific and academic community. The declaration highlighted the findings of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007) as well as brought attention to Puerto Rico being an island located in the Caribbean region subject to hurricanes with one of the highest population densities in the world (in 2007 it was at 1,140 people per square mile) and a history of human impacts on Puerto Rico from the loss of agricultural soils, degradation of catchment areas and water supply replenishment, increased number of threatened or endangered species of flora and fauna, growing threat to life and property from construction in areas susceptible to coastal and riverine flooding and landslides, and unsustainable land use. The declaration called for all agencies of the Commonwealth of Puerto Rico to use the best scientific information and a precautionary framework for decisions on land development and the use of natural resources. In addition to other requests like the reduction of greenhouse gas emissions and dependence on fossil fuels, they demanded an immediate halt to the endorsement and approval of projects in coastal areas vulnerable to the effects of sea level rise.

In 2008 the Commonwealth Governor produced an executive order (Boletín Administrativo Número 0E-2008-09) to create the Strategic Affairs Commission for Mitigation of Global Warming and Adaptation to Climate Change in Puerto Rico and to Develop a Comprehensive Plan of Action about Global Warming. The Commission meet a few times to develop a plan outline and to assign tasks, but has not meet since 2008 (Matos, I. 2010, pers. comm., 15 September) and may even have been formerly repealed.

The creation of the Puerto Rico Climate Change Council

Recognizing the limited success of previous efforts combined with the numerous challenges to implementing climate adaptation policies, the Puerto Rico Coastal Zone Management Program began strategizing with its numerous partners in other agencies and university programs. In 2009 the Puerto Rico Coastal Zone Management Program submitted a proposal to the National Oceanic and Atmospheric Administration (NOAA)'s Coastal Services Center to gain assistance in climate and coastal hazards efforts. In 2010 a NOAA Coastal Management Fellow through the PRCZMP and NOAA Coastal Services Center was placed in the Coastal Zone Management division office to coordinate the Puerto Rico Coastal Adaptation Project for a period of two years. The 1972 Coastal Zone Management Act (CZMA) of the U.S.A. is in large part the vehicle for the ability of the PRCZMP to work on coastal hazard and climate change. Under Section 309 of the CZMA each program office is eligible for Coastal Zone Enhancement Grants and one of the objectives of these enhancement grants is "preventing or significantly reducing threats to life and

destruction of property by eliminating development and redevelopment in high-hazard areas, managing development in other hazard areas, and anticipating and managing the effects of potential sea level rise and Great Lakes level rise” (CZMA 1972: 16 U.S.C. § 1456b).

Through collaboration with numerous stakeholders the goal is to develop a coastal zone vulnerability assessment and appropriate adaptation strategies to help Puerto Rico cope with existing coastal hazards and future climate changes. Employing multi-stakeholder collaboration techniques, spatial analysis tools, geophysical and chemical scientific knowledge, and utilization of the best available data from Puerto Rico’s experts the Project is operating with a vision for a safe, healthy, productive, sustainable and resilient Puerto Rico. The project is being conducted with the intention that outputs will be adopted by government, civil society, and the private sector.

In November 2010, the PRCZMP initiated Puerto Rico’s third roundtable on climate change. As was done in the 2007 and 2009 roundtable events, experts from the scientific and academic community came together to share the current state of climate science. In addition to this sharing of knowledge, representatives from the media also presented their views on climate change and a dialogue was facilitated between scientists and the media. The goal was to find gaps in communications between the two groups and begin devising a strategy to work together in the future. The afternoon of the roundtable was devoted to pitching the idea of the Puerto Rico Coastal Adaptation Project and discussing as a large group the creation of a panel of experts to assess the effects of climate change on Puerto Rico’s society and ecosystems. The idea met with excitement and encouragement and together the participants of the roundtable discussed process and sectors to be assessed.

Between November 2010 and April 2011 critical partners were recruited and the panel decided on a name, The Puerto Rico Climate Change Council (PRCCC), and a collaboration process. By researching previous efforts from around the world and especially other island communities, the PRCCC together decided on objectives, a vision, guiding principles, and the sectors to be assessed.

The PRCCC began collaboration to ensure a coordinated effort in assessing risks and impacts from coastal hazards and climate changes and in recommending adaptation strategies. Operating with a vision for a Safe, Healthy, Sustainable, Productive, and Resilient Puerto Rico, the collaboration is working towards the following objectives: (1) To use the best available scientific knowledge to identify the communities and ecosystems most at-risk from coastal hazards and climate change; (2) To identify, assess, prioritize, and develop effective adaptation strategies and policies that could be implemented in Puerto Rico; (3) To communicate findings, consensus, and recommendations to government, civil society, the media, and the private sector; and (4) To cultivate a well-informed Puerto Rican society about coastal hazards, climate change adaptation and mitigation.

Membership selection in the PRCCC has been ongoing and as such the PRCCC is constantly growing. At the time of writing, the PRCCC is comprised of over 140 partners representing researchers, planners, architects, practitioners, agency representatives and communications experts. Participants are selected based on expertise and recommendations from current participants. The PRCCC is collaborating using a set of 14 guiding principles to ensure a coordinated effort in assessing risks and impacts from coastal hazards and climate changes and recommending adaptation strategies to government, civil society, and the private sector.

PRCCC guiding principles

Understand that global climate variability and change is occurring (as asserted by the Intergovernmental Panel on Climate Change and the United States Global Change Research Program).

Ensure assessment of climate impacts on the time scale of present day, 2020, 2050, and 2100.

Ensure that recommended adaptation strategies range from efforts that can be implemented in 1-5 years as well as by 2020, 2050, 2100.

Understand that data (both historical, current, and prospective) continues to be collected and that knowledge about climate change is still evolving. As such, an effective adaptation strategy is “living” and will itself be adapted to account for new science.

Identify and involve relevant and willing stakeholders in identifying, reviewing, and refining the recommended adaptation strategies.

Give priority to adaptation strategies and policies that initiate, foster, and enhance existing efforts that improve economic and social well-being, public safety and security, public health, environmental justice, species and habitat protection, and ecological function.

When possible, give priority to adaptation strategies that modify and enhance existing policies rather than solutions that require new funding and new staffing.

Include community-based and participatory approaches to adaptation when developing recommendations.

Understand the need for adaptation policies that are effective and flexible enough for circumstances that may not yet be fully predictable.

Ensure that climate change adaptation strategies take into consideration the need to reduce greenhouse gas emissions and therefore do not further contribute to global issues.

Ensure that our natural systems are resilient to likely change. Maintaining healthy ecosystems is essential to our long-term success in meeting the vision for a safe, healthy, sustainable, productive and resilient Puerto Rico. Efforts to build resilience for Puerto Rico’s communities and people must go hand-in-hand with strategies that minimize both impacts to the natural and environment and losses of ecosystem services upon which we and Puerto Rico’s natural resources depend.

Recognize that these issues go beyond the coastal zone and where possible include watersheds and other non-coastal zone areas into assessments and strategies.

Adaptation includes reducing existing stresses on natural and human systems. Recommendations should specify which current stressors are likely to be exacerbated by climate change impacts.

Ensure that we prepare for both incremental and acute impacts. Although most climate change effects are taking place over time, some will be episodic and unpredictable, such as insect outbreaks or greater impacts to coastal areas from combined sea level rise and increased storm intensity. Puerto Rico’s adaptation efforts must work simultaneously to address slower-arriving impacts and

those that are more immediate or acute.

To carry out the objectives of the PRCCC four working groups were formed: (1) Geophysical and Chemical Scientific Knowledge; (2) Ecology and Biodiversity; (3) Society and Economy; (4) Communicating Climate Change and Coastal Hazards. The sectors being assessed by the first three working groups can be found in figure 1. Working Group 4 is different than the first three working groups in that they do not make assessments, but rather they review the outputs or products of the other three working groups and in addition create an outreach and communications strategy for the entire effort to ensure results will be widely and effectively disseminated.

Working Group 1: Geophysical and Chem Scientific Knowledge	Assessing historic trends and possible future climate conditions for: • Air and sea surface temperatures • Precipitation • Extreme events (downpours, droughts) • Sea level rise • Tropical Storms and Hurricanes • Ocean Acidification
Working Group 2: Ecology and Biodiversity	Assessing effects of climate change on: • Beach ecosystems • Wetlands • Forests • Coral Reefs • Submerged Aquatic Vegetation • Lagoons/Bioluminescent Bays • Cays and Islets • Amphibians and Reptiles • Sea Turtles • Marine Mammals • Sea Birds and Shore Birds • Coastal and Pelagic Fishes
Working Group 3: Society and Economy	Assessing effects of climate change on: • Economic development (i.e., livelihoods, tourism and recreation, industry, fisheries) • Critical infrastructure • Coastal communities • Historical and cultural preservation • Disaster management
Working Group 4: Communicating Climate Change and Coastal Hazards	• Reviewing content of Working Groups 1, 2, and 3 to unify messages and make understandable to general audiences and policymakers. • Developing outreach and media strategies.

Figure 1: PRCCC Working Groups, their responsibilities, and sectors assessed

Listserv and research library

Large partnership requires a very systematic approach to coordinating communications between members as well as to collect and organize the best available knowledge in order to be successful. A system of communication within the PRCCC and a system of organizing scientific information and knowledge was created early on. These systems and their processes were frequently modified throughout the process based on lessons learned and input from PRCCC partners.

Due to a limited budget and time constraints the coordinators created a listserv using a free service called Google Groups that creates a webpage and an email list. It is fully supported by the most popular browsers and available in most languages. The PRCCC's Google Group was named the Puerto Rico Cambio Climático/Climate Change Council Listserv (PR-CC-L). The objective of the PR-CC-L is to provide a free, moderated community communications tool, allowing subscribers to post announcements regarding research, meetings, policy developments, publications and new initiatives that address issues related to Puerto Rico's vulnerability and adaptation to coastal hazards and climate changes. This is a peer-to-peer announcement list. Any member can post to this list, read the archives, and view the members list. At the time of writing the PR-CC-L has posted 173 messages and includes 204 members.

In February 2011, the coordinators created the Puerto Rico Climate Change Research Library using another free, online tool called Dropbox. Dropbox is a service that lets you bring all your photos, documents, and other files anywhere and share them easily. Any file you save to your Dropbox will automatically save to all your computers and mobile devices, and the Dropbox website. PRCCC members were invited to join and install the Dropbox software. At the time of writing the Puerto Rico Climate Change Research Library has 45 active users, 136 folders, and 591 files (a size of 2.05 GB). The research library has 10 main folders. An *add new documents here* folder where PRCCC members drop new files for the library manager to document and place in the appropriate folder. Each of the four working groups have their own folders that contain subfolders of sectors being assessed and current drafts of the working groups reports. Another main folder is *other vulnerability assessments* which is where all the vulnerability assessments the PRCCC has found from around the world are located. These reports are from many of the 50 coastal states of the United States as well as national communications to the United Nations from developing countries and island states. The other main folders are *notes from climate events* where members can share notes they have taken at relevant meetings, *PRCCC documents*, where members can view documents that were discussed and modified at PRCCC meetings, and *vulnerability assessment methods*, where guides from government agencies on vulnerability assessments are located as well as information on spatial analysis for vulnerability assessments. Lastly, *Phase II_Adaptation Strategies* is a folder where members drop any documents, articles, or reports that are relevant to the collection or development of adaptation strategies. These documents will be used now that the vulnerability assessment is complete for Puerto Rico. The PRCCC will now begins developing recommendations for adaptation to government, civil society, the media, and the private sector.

Working Group meetings and VCAPS as a writing tool

Starting in January 2011 working groups began meeting to discuss Puerto Rico's vulnerabilities to climate change. Early on it became clear that with so many people working on a volunteer basis on such a complex issue a process would be needed that allows for working group members to connect key concepts and find areas of agreement and disagreement quickly and efficiently. At the Coastal Zone 2011 conference in Chicago, Illinois the PRCCC coordinators were introduced to a tool that could be useful for this purpose. The Vulnerability-Consequence Adaptation Planning Scenarios (VCAPS) process was developed by the Social Environmental Research Institute, the University of South Carolina, the Carolinas Integrated Sciences and Assessments, and the South Carolina Sea Grant Consortium to help community decision-makers, staff, and planners clarify their understanding and assumptions about climate change adaptation challenges their communities will face in the future ((SERI) 2011). A key part of the VCAPS process is the development of diagrams that visually document a group's discussions in real time. The diagrams illustrate the links between climate hazards or *stressors*, outcomes, consequences, vulnerabilities, and potential adaptation or mitigation strategies. The diagrams also serve as a library of what a community knows about the unique and special ways that it is vulnerable and resilient to different kinds of climate stressors. Proceeding through the VCAPS process allows the participants to include expertise and knowledge from many aspects of community management, to review the adequacy of knowledge, and to easily spot gaps in knowledge or planning.

Based on the mediated modeling technique, participants in a VCAPS session direct someone from the facilitation team (known as the *scribe*) through the process of documenting the outcomes and consequences of climate stressors, such as increased temperature, sea level rise, drought, etc. It is somewhat like concept mapping or influence diagramming, although the VCAPS map shows clear chains of cause and effect. See figure 2 for the Building Blocks of VCAPS Diagrams and figures 3 and 4 for examples chains created by the PRCCC's Society and Economy working group.

The PRCCC Coordinator was trained by the VCAPS process developers and then along with the Working Groups the VCAPS process was modified to the needs of the PRCCC. Each working group member submitted a preliminary, descriptive vulnerability assessment for their topic of expertise and the PRCCC Coordinator placed the information provided in the VCAPS diagrams prior to the start of the meeting. During working group meetings the members would modify the diagrams through facilitated dialogue and the use of the scribes. The working groups connected important concepts and identified areas where more information was needed and where agreements or disagreements existed. One important outcome of the process was a better ability for the working group members to identify reasons why Puerto Rico's citizens should care about certain chains. These reasons for caring are called *consequences* in the VCAPS process. Ultimately the VCAPS process allowed for the descriptive vulnerability assessments to be made more complete and understandable.

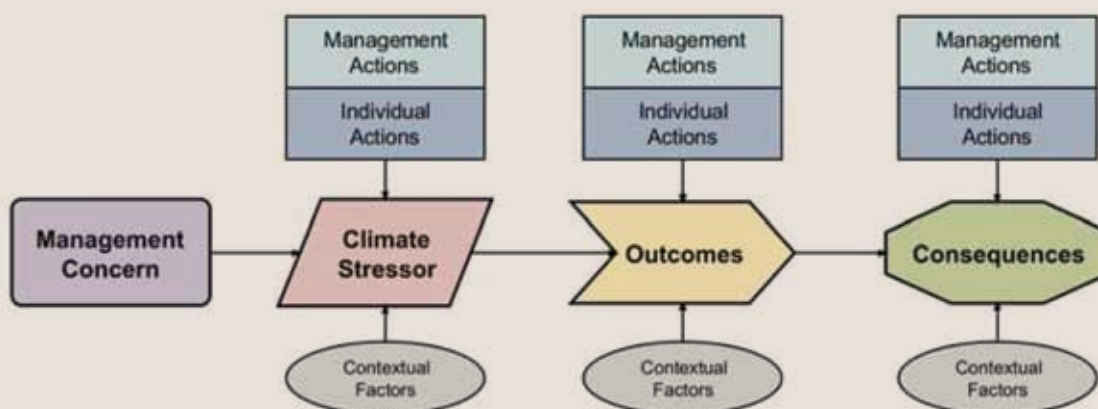


Figure 2 Building Blocks of VCAPS Diagrams (source: SERI 2011)

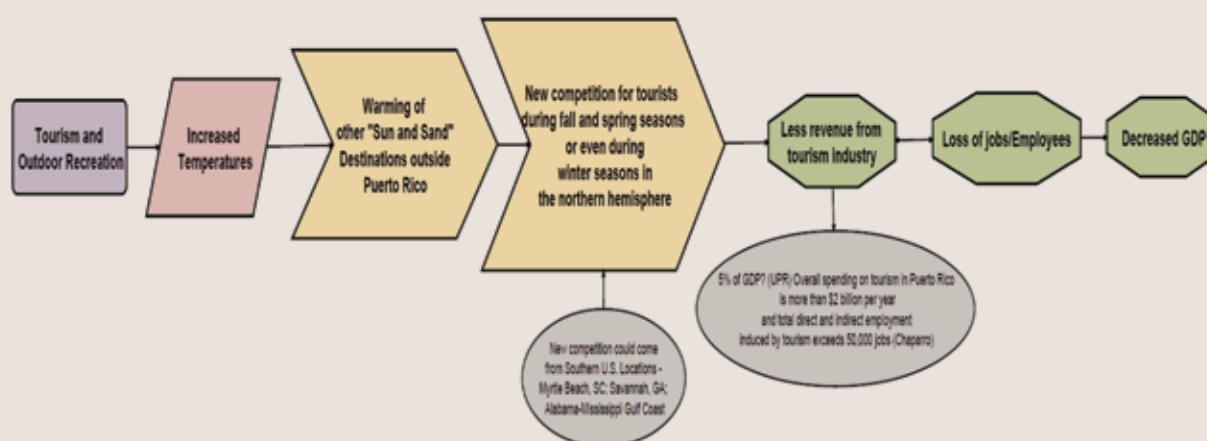


Figure 3 One chain of the PRCC's Working Group 3 Society and Economy's diagram for tourism and outdoor recreation. All VCAPS building blocks are included except *Management* and *Individual Actions*

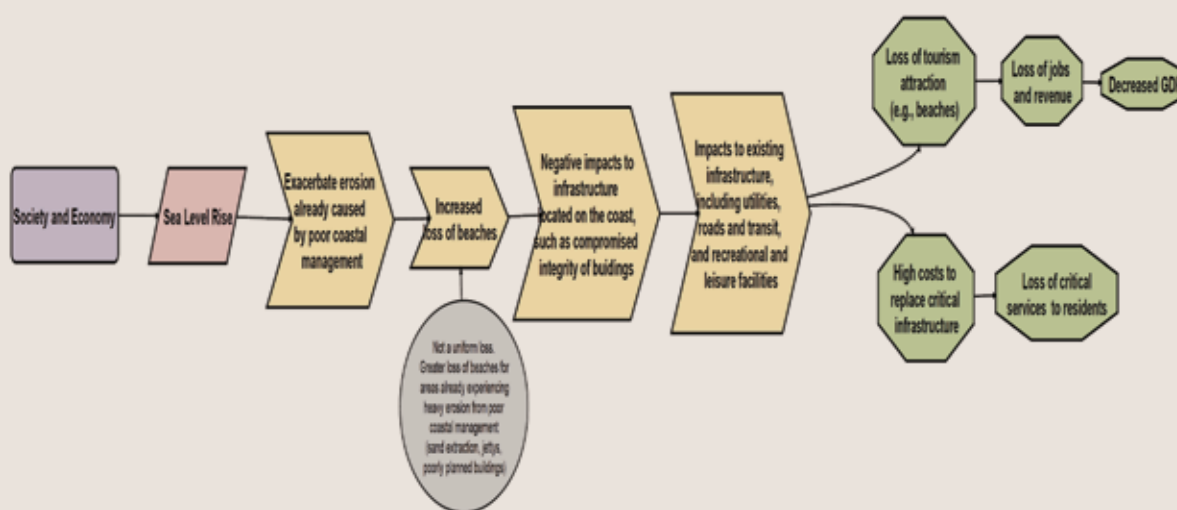


Figure 4 One chain of the PRCC's Working Group 3 Society and Economy's diagram for the affects of sea level rise on coastal infrastructure. All VCAPS building blocks are included except *Management* and *Individual Actions*

Opportunities to Build the Network

As was previously mentioned, membership selection in the PRCCC has been ongoing and as such the partnership is constantly growing. The PRCCC coordinators use different avenues to recruit new partners and find relevant information. *Chain referral* allowed recruitment based on recommendations by current members. In addition, the PRCCC Coordinators also attended and presented at events in Puerto Rico and the United States to connect with those outside the PRCCC informal network and to have a presence in specific communities. These communities include the Puerto Rico Planners Society, the Puerto Rico Association of Architects, the Association of Engineers and Professional Land Surveyors, the University of Puerto Rico (Mayaguez, Rio Piedras, and Medical Sciences campuses), InterAmerican University, Metropolitan University, the Catholic University of Ponce, and the Coastal Areas Climate Change Education Partnership.

The third method to expand the network of the PRCCC was by co-organizing a conference with five federal agencies (U.S. EPA Region 2, NOAA, and the Department of Interior's U.S. Geological Service, U.S. Fish and Wildlife Service, and the U.S. Forest Service). The conference, *Climate Change in the Caribbean 2011: Puerto Rico and the U.S. Virgin Islands*, took place November 15-16, 2011 at the Inter-American School of Law in San Juan and had close to 350 people in attendance. The two-day conference covered the science behind climate change and solutions to reduce greenhouse gas emissions and cope with changes. By organizing the conference with so many partners the PRCCC was able to gain new PRCCC members and observers as well as uncover new information that would be useful for the vulnerability assessment and adaptation strategy development.

Validation and Peer Review of Working Group Findings

Prior to formal, external review the preliminary findings were validated through the use of two risk assessment workshops with coastal municipalities: *Workshops for the Evaluation of Current and Future Risks in the Coastal Zone*. 30 of the 44 coastal municipalities of Puerto Rico attended with representatives from planning offices, emergency managers, and public works officers (figure 4). The PRCCC coordinators presented the preliminary findings and through a series of facilitated small group discussions the participants confirmed the main climate stressors impacting important sectors of their municipalities (e.g., infrastructure assets, economic development areas, and natural resources); further quantified the magnitude and likelihood of impacts occurring for the features assessed; and discussed the linkages between island-wide concepts and municipal realities. Additionally, the last session of each workshop was devoted to the brainstorming of adaptation strategies by sectors identified as the most important by the workshop participants. Multiple organizations assisted with these workshops. Namely, the Puerto Rico Department of Natural and Environmental Resources, the Puerto Rico Conservation Trust, the Caribbean Coastal Ocean Observing System, the Sierra Club, University of Puerto Rico, the National Oceanic and Atmospheric Administration, and the Nature Conservancy.



Figure 4 The PRCCC conducted two *Workshops for the Evaluation of Current and Future Risks in the Coastal Zone*. These 30 municipalities attended on either March 6th or March 8th, 2012.

After the municipal review and subsequent revisions the PRCCC extended invitations through a number of different channels to international, national and local scientists and practitioners to review the working group reports in different rounds. The call for reviews went out on a monthly basis from April 2012 to July 2012. After receiving multiple external reviews the PRCCC members received updated review drafts of the individual working group chapters and from June to July 2012 PRCCC members had another opportunity to revise their reports. An in-person meeting of the PRCCC was conducted on June 29th, 2012 in Carolina, Puerto Rico to revise the report further. Dozens of reviews were received for each working group report in which the report co-authors and editors made the appropriate corrections. The last part of the review process was a solicitation of comments and recommendations from the Secretary of the Department of Natural and Environmental Resources to Puerto Rico's universities and professional associations. Formal letters were sent April 30th, 2013 requesting report reviews by June 3, 2013. The universities and professional associations solicited were the University of Turabo, the Catholic University of Ponce including the Architecture School, the University of Puerto Rico (UPR), including the Department of Marine Sciences, School of Engineering, and School of Architecture, the Metropolitan University (UMET), the Puerto Rico Planning Society, Puerto Rico Association of Chemists, the Polytechnic University of Puerto Rico, the Institute of Architects and Landscape Architects of Puerto Rico, the Association of Architects and Landscape Architects of Puerto Rico, the Puerto Rico Institute of Surveyors, and the Association of Engineers and Surveyors of Puerto Rico. Three letters with comments were received from the UPR School of Engineering, the UPR Mayagüez Campus, and the Ponce Catholic University of Puerto Rico.

Collection of Adaptation Strategies

Communicating effectively with specific stakeholders and the public at large is key and in addition to creating a robust understanding of why climate is changing and the social-ecological consequences of these changes, solutions need to be communicated too. While the vulnerability assessment was being finalized, the PRCCC began identifying, developing and prioritizing adaptation strategies at each of the events organized or attended to be recommended to government, civil society, the media, and the private sector. Using categories like these the PRCCC's next steps will be to identify, develop, assess and prioritize adaptation strategies using the results of the island-wide vulnerability assessment.

Discussion: Climate-related decision support systems

The vulnerability of island populations is not only influenced by geophysical parameters such as sea level rise, erosion and extreme events, but is also influenced by decisions and actions by people and institutions living within or managing the coastal zone. Since many decision makers are experiencing or anticipating a new climate regime and are asking questions about potential responses, in 2008 the U.S. Environmental Protection Agency and the National Oceanic and Atmospheric Administration asked the National Academies to undertake a study to provide a framework and a set of strategies and methods for organizing and evaluating decision support activities related to climate change. In response to this request, the Panel on Strategies and Methods for Climate-Related Decision Support examined basic knowledge of decision making; past experiences in other fields, such as hazard response, public health, and natural resource management; experience with early efforts in the climate arena; and input from a range of decision makers (National Research Council 2009). A number of their findings are relevant to informing decisions in island states such as Puerto Rico.

The Panel found that *Climate-Related* or *Climate-Sensitive Decisions* are choices by individuals or organizations, the results of which can be expected to affect climate change or to be affected by climate change and its interactions with ecological, economic and social systems. Notably, the Panel stressed that decisions are climate sensitive regardless of whether or not decision makers recognize them as such at the time of decision making. In other words, decision makers make climate-related or climate-sensitive decisions all the time and may not realize it. Decision support can potentially help all climate-affected decision makers get better results, but a decision maker who does not yet realize that their decisions are sensitive to climate will not perceive a need for such support.

Conclusion

The decision support system of the Puerto Rico Climate Change Council is working to protect the social, economic, and ecological fabric of life in Puerto Rico from changes in increasing temperatures and sea levels, changes in precipitation and extreme events. The vulnerability of key sectors is being assessed such as economic development, tourism, services, natural resources and biodiversity, cultural and historic resources, security, and critical infrastructure. As Puerto Rico begins to adapt to climate change with the help of this decision support system certain challenges will present itself. One major challenge will be the desire for perfect information. More and more cities, states, and countries are relying on climate modelers to provide possible future climate scenarios to be used for decision making, both more climate adaptation as well as climate mitigation (the reduction of greenhouse emissions). In fact, Puerto Rico will within the next year or two have access to such climate projections (Hayhoe, K. 2011, pers. comm., 15 Nov). However, decision-makers or users of this information should not expect climate scientists to solve this problem by providing certain and accurate climate forecasts. Therefore, public entities and private developers, have to change the way they make decisions, to introduce climate uncertainty caused by anthropogenic climate change in their everyday operations. If climate change is taken into account in all long-term decisions, many public and private projects will be better adapted for the future, and both taxpayer and private investments will be better protected and both taxpayer and private investments will be better protected. It is with this goal in mind that Puerto Rico's first island-wide vulnerability assessments was completed.

References

- (IPCC), Intergovernmental Panel on Climate Change. 2007. "Summary for Policymakers." In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY: Cambridge University Press.
- (NRC), National Research Council. 2009. *Informing Decisions in a Changing Climate. Panel on Strategies and Methods for Climate-Related Decision Support, Committee on the Human Dimensions of Global Change. Division of Behavioral and Social Sciences and Education.* . Washington, DC: The National Academies Press.
- (SERI), Social and Environmental Research Institute, University of South Carolina and South Carolina Sea Grant Consortium. 2011. "Diagramming Climate Change-Related Vulnerability-Consequence Adaptation Planning Scenarios (VCAPS): A facilitation guide and tutorial.." Social and Environmental Research Institute.
- Burrowes, P., R.L. Joglar and D.E. Green. 2004. "Potential causes for amphibian declines in Puerto Rico." *Herpetologica* 60(2):141-154.
- Bush, D.M. 1995. *Living with the Puerto Rico Shore*. Durham, NC: Duke University Press.
- Culture, Powhatan Museum of Indigenous Arts and. 2012. "The Caribbean Hurricane."
- Diaz, E. and K. Hevia. 2011. "El Estado de la Costa de Puerto Rico." eds. Programa de Manejo de la Zona Costanera y El Departamento de Recursos Naturales y Ambientales (DRNA): Programa de Manejo de la Zona Costanera.
- Ewald, P. 1987. "The Evolution of Chiefdoms: A Reconstruction of Taino Kinships Politics." *American Anthropologists* 91(1987):627-628.
- Fassig, Oliver L. 1928. "San Felipe-The Hurricane of September 13, 1928, at San Juan, PR." ed. U.S. Weather Bureau: U.S. Weather Bureau.
- Feifel, K. 2010. "Proactive Incorporation of Sea Level Rise into the Design of the Deer Island Wastewater Treatment Plant. Case Study on a project of the Massachusetts Water Resources Authority." In *Product of EcoAdapt's State of Adaptation Program*, ed. EcoAdapt.
- Frederick, K. and P. Gleick. 1999. "Water and Global climate change: Potential impacts on U.S. Water Resources." Pew Center Global Climate Change.
- Granovetter, M. 1973. "Strength of weak ties." *American Journal of Sociology* 78:1360-1380.
- Groves, D.G., D. Knopman, R. Lempert, S. Berrg and L. Wainfan. 2007. In: *Presenting Uncertainty about Climate Change to Water Resource Managers - Summary of Workshops with the Inland Empire Utilities Agency*. Santa Monica, CA: RAND.
- Groves, D.G. and R. Lempert. 2007. "A new analytic method for finding policy-relevant scenarios." *Global Environmental Change* 17:73-85.
- Hallegatte, S. 2006. "Panel on Strategies and Methods for Climate-Related Decision Support, Committee on the Human Dimensions of Global Change. Division of Behavioral and Social Sciences and

Education." AEI-Brookings Joint Center.

- Hallegatte, S. 2009. "Strategies to adapt to an uncertain climate change." *Global Environmental Change* 19:240-247.
- Hernández-Pacheco, R, E.A Hernández-Delgado and A.M. Sabat. 2011. "Demographics of bleaching in a major Caribbean reef-building coral: *Montastraea annularis*." *Ecosphere* 2(1):Article 9.
- Jibson, R.W. . 1987. "Landslide hazards in Puerto Rico. A workshop on "assessment of geologic hazards and risks in Puerto Rico,"" In Open-file report 87-008, eds. W. Hays and P. Gori. Reston, VA: U.S. Geological Survey.
- Johansson, MA, F Dominici and GE Glass. 2009. "Local and global effects of climate on dengue transmission in Puerto Rico." *PloS Negl Trop Dis* 3(2):e382.
- López-Marrero, T and B. Yarnal. 2010. "Putting adaptive capacity into the context of people's lives: a case study of two flood-prone communities in Puerto Rico." *Natural Hazards* 52:277-297.
- MacLachan, Morgan. D. 1990. "Archaeology of the Ethno-Tyrannies." *American Anthropologists* 92(4 (1990)):1011-1023.
- McCann, W. 1984. "Effective communication of information about chemical hazards." *Science of the Total Environment* 51:149-183.
- Meehl, Gerald A., Warren M. Washington, William D. Collins, Julie M. Arblaster, Aixue Hu, Lawrence E. Buja, Warren G. Strand and Haiyan Teng. 2005. "How Much More Global Warming and Sea Level Rise?" *Science* 307(5716):1769-1772.
- Nicholls, R.J. 2007. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. M.L. Parry. Cambridge, UK: Cambridge University Press.
- Nicholls, R.J. and S. Leatherman. 1996. "Adapting to sea-level rise: relative sea-level trends to 2100 for the United States." *Coastal Management* 24(4):301-324.
- Nurse, Leonard. 2011. "The implications of global climate change for fisheries management in the Caribbean." *Climate and Development* 3:228-241.
- Palm, R. and M.E. Hodgson. 1993. "Natural Hazards in Puerto Rico." *Geographical Review* 83(3):280-289.
- Reid, H.F. and S. Taber. 1919. "The Porto Rico earthquake of 1918." ed. 66th Congres House of Representatives, 1st Session. November 19, 1919.
- Rouse, I. 1992. *The Tainos: Rise and Decline of the People Who Greeted Columbus*. New Haven, CT: Yale University Press.
- Schwartz, Stuart B. 1992. "The Hurricane of San Ciriaco: Disaster, Politics, and Society in Puerto Rico, 1899-1901." *The Hispanic American Historical Review* 72(3):303-334.
- Staes, C., C. Orengo, J. Malilay, J. Rullán and E. Noji. 1994. "Deaths due to flash floods in Puerto Rico, January 1992: Implications for Prevention." *International Journal of Epidemiology* 23(5):968-975.
- Thompson, J., A.E. Lugo and J. Thomlinson. 2007. "Land use history, hurricane disturbance, and the fate of introduced species in a subtropical wet forest in Puerto Rico." *Plant Ecology* 192:289-301.
- Tompkins, E.L., E. Boyd, S.A. Nicholson-Cole, K. Weatherhead, N.W. Arnell and W.N. Adger. 2009. "An inventory of adaptation to climate change in the UK: challenges and findings." Tyndall Centre for

Climate Change Research.

- Van Noordwijk, M, P. Martikainen, P Bottner, E Cuevas, C Rouland and S.S. Dhillon. 1998. "Global change and root function." *Global Change Biology* 4(7):759-772.
- Wasserman, S. and J. Galaskiewicz. 1994. *Advances in Social Network Analysis*. Thousand Oaks, CA: Sage Publications.
- Weil, E., A. Croquer and I. Urreiztieta. 2009. "Temporal variability and impact of coral diseases and bleaching in La Parguera, Puerto Rico from 2003-2007." *Caribbean Journal of Science* 45(2-3):221-246.
- Wigley, T. 1999. "The science of climate change Global and U.S. perspectives." Pew Center on Global Climate Change.
- Wilson, S.M. 2007. *The archaeology of the Caribbean*. Cambridge, UK: Caribbean University Press.
- Winter, A., R.S. Appeldoorn, A. Bruckner, E.H. Williams and C. Goenaga. 1998. "Sea surface temperatures and coral reef bleaching off La Parguera, Puerto Rico (northeastern Caribbean Sea)." *Coral Reefs* 17(4):377-382.





Working Group 1: Geophysical and Chemical Scientific Knowledge

Observed Trends and Future Projections

Editors:

Kasey R. Jacobs¹, Adam Terando², and Ernesto L. Diaz¹

Contributing Authors (In Alphabetical Order):

Miguel Canals^{3,4}, Jorge Capella⁴, Jorge Corredor^{3,4}, David Cuevas¹⁰, Pedro Diaz⁵, Mark Jury^{3,4}, Glenn Landers⁶, Katharine Hayhoe⁷, Odalys Martinez⁸, Melissa Melendez^{3,4}, Pablo Mendez⁹, Aurelio Mercado^{3,4}, Julio Morell^{3,4}, Adam Terando²

¹ Department of Natural and Environmental Resources – Coastal Zone Management Program

²U.S. Department of Interior Southeast and Caribbean Climate Science Center at North Carolina State University

³University of Puerto Rico - Mayagüez

⁴Caribbean Coastal Ocean Observing System

⁵U.S. Geological Survey

⁶U.S. Army Corps of Engineers

⁷Texas Tech University

⁸National Oceanographic and Atmospheric Administration

⁹University of Puerto Rico – Medical Sciences Campus, Department of Environmental Health

¹⁰U.S. Environmental Protection Agency – Caribbean Environmental Protection Division

TABLE OF CONTENTS

INTRODUCTION.....	24
ABOUT PUERTO RICO	24
REPORT ORGANIZATION.....	26
CHANGES IN GLOBAL CLIMATE	27
CLIMATE IS ALWAYS CHANGING	27
THE WORLD IS WARMING.....	27
CHANGES IN CARIBBEAN CLIMATE.....	29
CARIBBEAN CLIMATOLOGY	29
PRECIPITATION VARIABILITY IN THE CARIBBEAN.....	29
RECENT CLIMATIC TRENDS IN THE CARIBBEAN.....	30
FUTURE CARIBBEAN CLIMATE	33
PREVIOUS MODELING EFFORTS FOR THE CARIBBEAN.....	34
UNIVERSITY OF THE WEST INDIES – MONA CLIMATE STUDIES GROUP AND THE CUBAN METEOROLOGICAL INSTITUTE (2003)	34
UNIVERSITY OF PUERTO RICO, SANTA CLARA UNIVERSITY AND OAK RIDGE NATIONAL LABORATORY STUDY (2007).....	35
UNIVERSITY OF OXFORD AND UNITED NATIONS DEVELOPMENT PROGRAM (2009)	35
THE UNITED NATIONS DEVELOPMENT PROGRAMME (UNDP) CLIMATE CHANGE COUNTRY PROFILES PROJECT (2010)	36
CARIBBEAN COMMUNITY CLIMATE CHANGE CENTER (2010).....	36
PUERTO RICO CLIMATE CHANGE COUNCIL (2011).....	36
KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS FOR CARIBBEAN CLIMATE CHANGE STUDIES.....	38
PUERTO RICO'S CLIMATE	39
HISTORIC TRENDS AND CLIMATE PROJECTIONS BY PARAMETER.....	44
AIR TEMPERATURE.....	44
OBSERVED AIR TEMPERATURE TRENDS IN PUERTO RICO	44
PROJECTED CHANGES IN TEMPERATURES.....	46
KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS.....	47
SUMMARY OF OBSERVED AND PROJECTED TEMPERATURES FOR PUERTO RICO	47
PRECIPITATION	47

OBSERVED PRECIPITATION TRENDS IN PUERTO RICO	47
PROJECTED PRECIPITATION CHANGES IN PUERTO RICO	49
KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS	50
SUMMARY OF OBSERVED AND PROJECTED PRECIPITATION CHANGES.....	50
EXTREME WEATHER EVENTS	53
EXTREME TEMPERATURES IN PUERTO RICO	53
EXTREME PRECIPITATION IN PUERTO RICO	54
PROJECTIONS FOR EXTREME PRECIPITATION EVENTS.....	54
KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS	55
SUMMARY OF HISTORIC TRENDS AND PROJECTIONS FOR EXTREME EVENTS.....	55
SEA SURFACE TEMPERATURES (SST)	58
OBSERVED SEA SURFACE TEMPERATURE TRENDS IN THE NORTHEASTERN CARIBBEAN.....	58
FUTURE SEA SURFACE TEMPERATURE PROJECTIONS FOR PUERTO RICO	60
SUMMARY OF HISTORIC TRENDS AND PROJECTIONS FOR SEA SURFACE TEMPERATURES.....	60
SEA LEVEL RISE.....	60
OBSERVED SEA LEVEL RISE TRENDS IN PUERTO RICO.....	60
FUTURE SEA LEVEL RISE PROJECTIONS FOR PUERTO RICO.....	64
KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS	67
SUMMARY OF OBSERVED AND PROJECTED TRENDS FOR SEA LEVEL RISE	67
TROPICAL STORMS AND HURRICANES.....	68
OBSERVED TRENDS IN TROPICAL STORMS AND HURRICANES IN PUERTO RICO	68
FUTURE OF HURRICANES IN PUERTO RICO	70
KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS	72
SUMMARY OF OBSERVED AND PROJECTED TRENDS FOR TROPICAL STORMS AND HURRICANES.....	72
OCEAN ACIDIFICATION	74
TRENDS IN OCEAN ACIDIFICATION	74
STATUS OF OCEAN ACIDIFICATION IN THE CARIBBEAN	75
FUTURE SATURATION STATE SCENARIOS FOR THE CARIBBEAN.....	76
KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS.....	76
SUMMARY OF OBSERVED AND PROJECTED TRENDS FOR OCEAN ACIDIFICATION	77
WORKING GROUP 1 REPORT REFERENCES.....	78

INTRODUCTION

About Puerto Rico

Puerto Rico's main island is the eastern-most and the smallest of the Greater Antilles. The Puerto Rico archipelago is located in the northeastern portion of the Caribbean plate between the North Atlantic and the Caribbean Sea (figure 1).



Figure 1 Location of Puerto Rico (red box), between the North Atlantic Ocean and the Caribbean Sea.

Climate has played a key role in shaping Puerto Rico, a small and varied island with 3,435 square miles. The main island accounts for 99 percent of Puerto Rico's area; the interior of the main island is mountainous with a peak elevation at Cerro Punta of 1,338 meters (4,390 feet) above mean sea level. Vieques and Culebra islands to the east are populated year-round, while Mona, Monito and Desecheo to the west, and Caja de Muertos to the South are natural reserves. The tropical climate ensures year-round warm temperatures, with an island-wide mean annual temperature near 25°C (77°F). Temperatures do vary however, between the warmer coast and inland mountains, with average annual temperatures between 26 and 27°C (78°F and 80.6°F) in San Juan and the other lowland areas as opposed to the mean annual temperatures in the mountainous interior that are below 20°C (68°F). Precipitation also varies across the island based on interactions between the island's topography, urban population, and vegetation

cover, and the dominant easterly trade winds. These interactions lead to high spatial variability in annual precipitation across the island. Total annual precipitation ranges from over 4000 mm in the rainforest of El Yunque to 800 mm in the dry forests of Guánica.

The elevation map (figure 2a) shows the range of mountains lying east-west across the center of the island, exceeding 600 m in most places. The vegetation map (figure 2b) indicates that dense forest canopies occupy much of the central and western interior. These feed moisture into the air, which contributes to afternoon thundershowers over the western half of the island.

The precipitation on land generates enough runoff that results in permanent or intermittent rivers and creeks depending on the geology and relief of the various regions of the islands. The south side has fewer perennial rivers, has a broader insular shelf and a low energy Caribbean coast. These conditions offer greater stability to marine ecosystems such as coral reefs, mangrove swamps, and submerged seagrass beds. The northern coast has more and larger perennial rivers which empty their waters on the narrower shelf and higher energy Atlantic coast. Marine biodiversity is lower on northern Puerto Rico, but it has the largest mangrove and fresh water wetland extent (this is further described in Working Group 2's report).

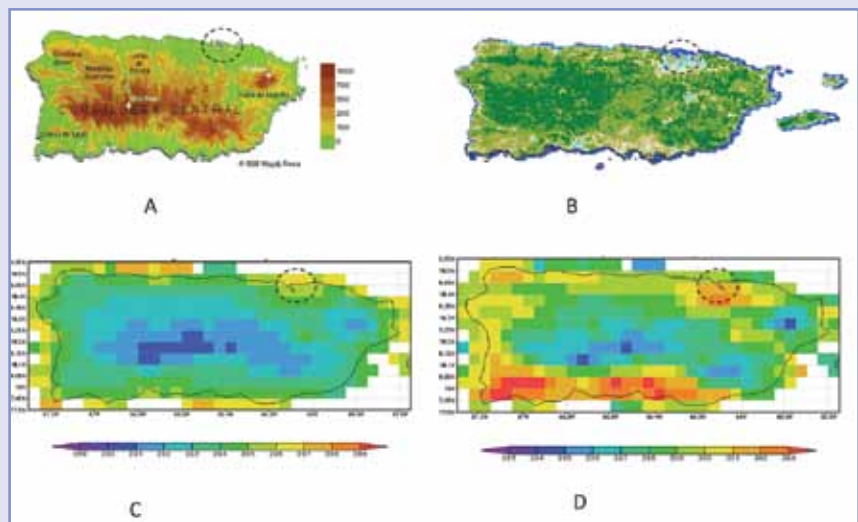


Figure 2 (A) Elevation map of Puerto Rico, and (B) Satellite vegetation land cover with areas of substantial urbanization in light blue; (C) Mean night (left) and (D) day-time (right) surface temperature at 5km resolution from infrared satellite over past decade. San Juan area is circled. Scales in degrees Kelvin (K) vary.

Prior to the arrival of humans to Puerto Rico the area of the main island expanded and contracted in response to global sea levels, which in turn would rise and fall in conjunction with glacial and interglacial periods. This expansion and contraction of land area sometimes led to connections between the main island and the surrounding islands of Culebra and Vieques. Additionally, Puerto Rico is an area of the Caribbean with high species endemism and thus a hotspot of biodiversity for terrestrial and marine biotas. Both historical (e.g., geological and evolutionary) and ecological (e.g., island size and distance to mainland) factors contribute to complex patterns of endemism (and species richness in other Caribbean islands) (Hedges 1996, Woods and Sergile 2001).

Moreover, changes in climate during the late Quaternary modified the distribution, size, and abiotic characteristics of Puerto Rico and the other Caribbean islands, significantly shaping the ecosystems and species of that time and today. The arrival of the first people to Puerto Rico happened about 4,000 years ago and Europeans about 500 years ago. The frequent occurrence of tropical storms and hurricanes (Landsea et al. 1999) is a constant hazard whose disturbances have molded the composition and structure of biotas (Walker et al. 1991, Walker et al. 1996) and sometimes leads to devastating consequences in terms of loss of life and property. For instance, seven months after Hurricane Irene struck Puerto Rico in August 2011, the island was continuing to recover from the heavy rains, flooding, landslides and mudslides left by the hurricane. The Government of Puerto Rico and the Federal Emergency Management Agency cited the approval of more than \$83.9 million in federal grants for disaster aid (FEMA 2012). Effects can be long-lasting, such as with the diminishment of the coffee industry on the island after two strong hurricanes in 1928 and 1932 or the long lasting impacts to agriculture and infrastructure after hurricanes Hugo (1989) and Georges (1998).

After hurricane Georges the National Weather Service reported enormous damage to Puerto Rico's utility infrastructure. Electricity was lost to 96% of the island's 1.3 million customers, while

water and sewer service was lost to 75% of the islands 1.83 million customers. It was estimated that at least 50% of the electrical poles and cables were damaged. Many roads were impassable by floods or destruction. A large number of road signs were twisted and destroyed, while electric post and cables were strewn on the ground, along with trees and foliage. Damage to roads was estimated at \$21,995,975. Telephone service was affected as 8.4% of telephone customers lost their service.

Hurricane Georges also caused extensive damage to the agricultural sector. The island lost 75% of its coffee crop, 95% of the plantain and banana crops, and 65% of its live poultry. Loss to equipment, manufacturing, and agriculture was estimated at \$212.9 million daily. Damage to houses was significant, especially those constructed of wood with wood-zinc system roofs. In all 28,005 houses were totally destroyed and 72,605 houses of all type were partially damaged. On the small island of Culebra, 74 houses were totally destroyed and 89 were partially affected. Public schools suffered an estimated \$20-\$25 million dollars in damage. All of the islands 401 shelters were opened during the storm and housed 29,107 people. An estimated \$1,673,529,890 in damages was caused to municipalities and \$233,496,484 in damages to commonwealth agencies. Thus, the total damage in Puerto Rico was estimated at \$1,907,026,374 (National Weather Service 2012; FEMA 2012).



Past hurricane damage in Puerto Rico. 1899 San Ciriaco Hurricane in Arecibo (top); 1998 -- A family in the Barriada of the Villa del Sol in Toa Baja, survey the wind and flood damage from Hurricane Georges to their home along with FEMA and Civil Defense Officials.

Global climate change is projected to increase the vulnerability of tropical island states to natural hazards and Puerto Rico is particularly sensitive to these changes. This vulnerability is multi-faceted and stems from factors such as small geographic size that increases sensitivity, location in regions prone to natural hazards (e.g. hurricanes, earthquakes, tsunamis), high population densities, high costs to maintain infrastructure, limited access to natural resources and capital, and the influence of external forces such as terms of trade, economic liberalization and migration flows (Gable et al. 1990, Pelling and Uitto 2001, Lewsey et al. 2004, Mimura et al. 2007). For the Caribbean region as in many other islands and coastal regions, changes in atmospheric and sea surface temperature, precipitation and sea level rise are of particular concern. A general, informed understanding of observed and projected conditions is critical to planning for the future and to anticipate the types of adaptation measures that should be developed in Puerto Rico. Given this imperative, the PRCCC's Working Group 1 worked from January 2011 to July 2012 to assess observed and potential future climatic change in Puerto Rico.

Report Organization

The members of Working Group 1: Geophysical and Chemical Scientific Knowledge are all highly respected in their fields of physics, chemistry, oceanography, climatology, hydrology, geology, engineering and meteorology both locally and abroad. The reviewers of this report were local experts from Puerto Rico, from the continental United States, and from overseas such as other Caribbean islands and the United Kingdom. Through a number of small sub-working group meetings, large working groups meetings, full PRCCC meetings, and a conference in San Juan, *Climate Change in the Caribbean 2011: Puerto Rico and the U.S. Virgin Islands*, the members met in-person to discuss the report compilation, data analyses, and peer-reviewed published studies. However, the majority of report writing and discussions occurred via email and dropbox research library correspondences. Additional correspondences occurred via the PRCCC listserv,

the PR-CC-L. The Working Group 1 report is organized by geographic scale – in that we start by discussing the global climate changes we are seeing and expecting to see in the future and narrowing down in scale through the Caribbean climatology and trends and finally to Puerto Rico's observed trends and projected changes. The logic for this order was stressed by Working Group members in that when discussing large coupled atmospheric and oceanic phenomena it is important to look at Puerto Rico's climate conditions in the context of the greater Caribbean and North Atlantic regions. In the report, each of the climate parameters analyzed (air and sea surface temperature, precipitation, extreme events, storms and hurricanes, sea level rise, and ocean acidification) are described specific to Puerto Rico in terms of their historically observed trends and the projections based on multiple sources. The information compiled is from literature review using a variety of databases as well as through the networks of our PRCCC members and from efforts to reach out to other Caribbean scientists and experts. As such some relevant studies may not have been received. The Working Group members and the PRCCC as a whole recognize that the information contained in this report is the best available knowledge as of July 2012 and will need to be continuously edited and expanded over the years as new and improved information becomes available.

Important Note: Climate change projections are based on simulations by Dr. Mark Jury with University of Puerto Rico, international climate modeling groups that have submitted their data to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), as well as other impact assessments from the Caribbean that have been conducted after the IPCC AR4 in 2007. The expertise of climatologists, oceanographers, meteorologists, biogeochemists, and physicists have further informed and refined the historic trends and climate projections summarized in this report. Impact assessments for the Caribbean basin have been conducted by the United Nations Development Program (UNDP), the Caribbean Community Climate Change Center (5C's), and in the peer-reviewed independent literature, as well as by the U.S. Global Climate

Research Program's 2009 report, *Global Climate Change Impacts in the United States* (Karl et al. 2009) – which is the first official U.S. climate assessment to include Puerto Rico and other small island states.

The information compiled here for possible future climate conditions is from the best available knowledge in July 2012. Much of the data come from global climate models, which are not able to resolve the small-scale atmospheric dynamics present over the islands and as such cannot “see” the islands at a high resolution. Therefore the projections are given over ocean surfaces rather than over land and very little work has been done in downscaling these projections to individual islands (with the exception of the Caribbean Community Climate Change Centre's dynamical downscaling through Dr. Campbell and the soon to be completed statistical downscaling by Dr. Katherine Hayhoe at Texas Tech University).

These limitations are somewhat mitigated by the maritime climate experienced in Puerto Rico. This means that the climatological conditions on the island are strongly influenced by the dynamics occurring in the Atlantic Ocean and Caribbean Sea, which are better resolved by the existing generation of GCMs. Assessments are also difficult because some climatic processes are still not well understood, such as midsummer drought in the Caribbean and how climate change impacts ENSO. Furthermore, there is insufficient information on future SST changes to determine the regional distribution of cyclone changes. Large deviations among models make the regional distribution of sea level rise uncertain and the number of models addressing storm surges is very limited. Despite all these limitations, the currently available data is useful for the Puerto Rico's first comprehensive vulnerability assessment to climate change and subsequent adaptation strategy recommendations for decision making because of Puerto Rico's sub-tropical maritime climate, sufficient data to assess observed trends, and the proven utility of the existing climate projections for decision-making as used by other island nations in the Caribbean.

CHANGES IN GLOBAL CLIMATE

Climate is Always Changing

When the term “climate change” is heard it is often assumed that the changes we are seeing are a new phenomenon and that the change itself is the reason behind the concerns the international scientific community has expressed. This is a misperception. The earth's climate has always changed and will continue to change. The concern lies with the rate of change, how fast we are seeing changes as compared to how fast they occurred in the past, and whether humans and nature will adapt to appropriately to the changes. Furthermore, the cause of this climatic change is linked to human actions; the burning of fossil fuels for energy which releases heat-trapping gasses into the atmosphere. These emissions have led to a rapid warming of the earth's climate.

The World is Warming

The past three decades have been Earth's warmest since reliable surface temperature records began to be kept in 1850, with a global average increase of about 1°C (5°F) over that period. (This warming is what originally led discussions about climate change to be termed “global warming” For more information on terminology see box *What is Global Warming and Climate Change?*). Furthermore, temperature trends based on Arctic ice cores, tree rings, paleo-coral studies, and documentary evidence indicate that the Earth's temperature in the late 20th century may have been the highest in at least the last 1,000 years. The most recent paleoclimate data reinforce this conclusion using longer records, new proxies, new statistical techniques, and a broader geographic distribution of paleo data (NOAA 2012). Here in Puerto Rico, as will be demonstrated in this report, our annual average temperature rose by about 1°C (1.8 °F) from 1900 to 2010, according to analyses by researchers at the University of Puerto Rico of daily measurements gathered from a subset of the island-wide network of weather stations.

According to the Intergovernmental Panel on Climate Change (IPCC), global average temperatures have risen by 0.6°C (1.1°F) since 1970 and can be expected to rise another $1\text{--}4^{\circ}\text{C}$ ($1.8\text{--}7.2^{\circ}\text{F}$) by the end of the 21st Century, depending on future societal practices and the amount of greenhouse gas emissions released into the atmosphere. This temperature increase was recently reaffirmed by the Berkeley Earth Surface Temperature analysis. Using the largest data set available to date the Berkeley team found that over the past 250 years the earth experienced a rise of approximately 1.5°C and about 0.9°C in the past 50 years (Brillinger et al. 2012).

Scientific modeling suggests that the surface temperature will continue to increase beyond the

year 2100 even if concentrations of greenhouse gases are stabilized by that time (figure 3). In other words, even if all greenhouse gas-emitting activities (e.g., burning of fossil fuels for energy and transportation, deforestation activities) were halted immediately, the planet would still experience decades of climate impacts due to the inertia inherent in the global climate system (Meehl et al. 2005).

Climate change is often thought of as a global systemic problem; systemic as its causes are initiated anywhere on earth, and the effects felt worldwide (Frederick and Gleick 1999, Wigley 1999). While climate change is a global problem, it already has and is predicted to continue manifesting locally in Puerto Rico.

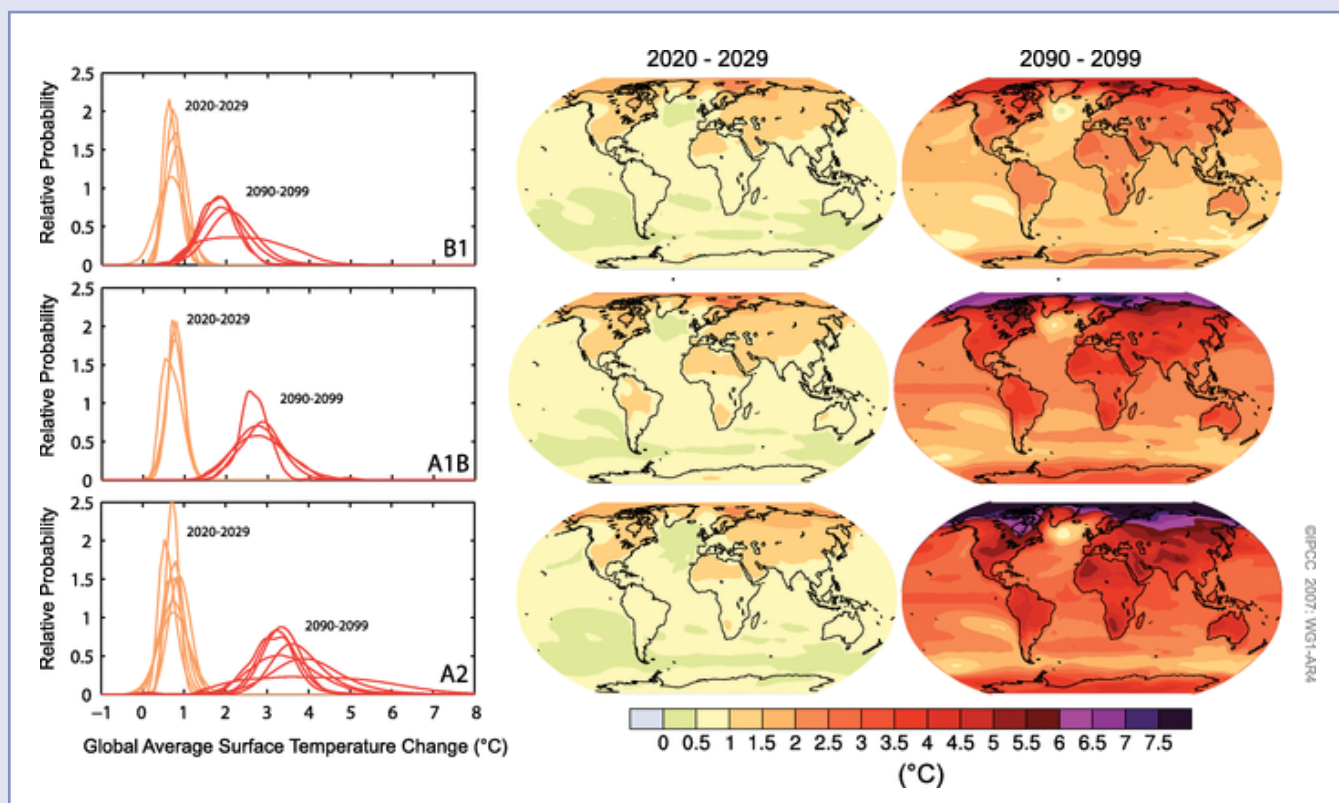


Figure 3 Projected surface temperature changes for the early and late 21st century relative to the period 1980–1999. The central and right panels show the AOGCM multi-model average projections for the B1 (top), A1B (middle) and A2 (bottom) SRES scenarios averaged over the decades 2020–2029 (centre) and 2090–2099 (right). The left panels show corresponding uncertainties as the relative probabilities of estimated global average warming from several different AOGCM and Earth System Model of Intermediate Complexity studies for the same periods. Some studies present results only for a subset of the SRES scenarios, or for various model versions. Therefore the difference in the number of curves shown in the left-hand panels is due only to differences in the availability of results (IPCC 2007).

At the national level in the United States, several reports have documented recent climate change as well as the potential impacts. The 2009 U.S. Global Change Research Program report entitled *Global Climate Change Impacts in the U.S.* (Karl et al. 2009) illustrated that the average mainland U.S. temperature has increased by 1.1°C (2°F) since about 1960, precipitation has increased by 5%, and the frequency of heavy precipitation has also increased by a factor of two. The growing season has lengthened on average by one week since 1960, mainly due to a retreat of the date of the last spring frost. Large portions of the U.S. are now experiencing a shorter, less intense wintertime on the basis of a decrease in extremely cold temperatures.

Since temperature is a basic control of the Earth's climate, climate change is not just limited to increasing temperatures, but changes in other fundamental aspects of climate. In the Caribbean region the projected changes of most concern include rising air and sea temperatures, decreasing annual rainfall, changing rainfall patterns, more frequent, heavy rain events, stronger hurricanes and rising sea level.

CHANGES IN CARIBBEAN CLIMATE

Caribbean Climatology

The climate of the Caribbean is characterized as sub-tropical with relatively dry winters and wet summers (Taylor and Alfaro 2005). The dominant large-scale atmospheric influence on the climate is the North Atlantic subtropical high (NAH). Island orography and elevation are significant modifiers of the climate at the sub-regional scale. Cuba, Jamaica, Hispaniola and Puerto Rico, the larger and more mountainous islands of the Greater Antilles, receive heavier rainfall at higher elevations, with a rain-shadow effect on their southern coasts that are distinctively arid. The smaller islands to the east tend to receive less rainfall, but are still well watered. For this region, rainfall totals generally increase going northward. The dry belt of the Caribbean is found over the southwestern islands of the Netherlands Antilles.

Precipitation Variability in the Caribbean

The dominant mode of variability in precipitation is a decadal oscillation (Jury 2009, Jury and Gouirand 2011). It is related to interactions between the global ocean and regional atmosphere and is influential in Puerto Rico and the southeastern Antilles islands. It is driven by a tri-pole pattern of SST and upper level zonal winds that involve shifts in the Hadley circulation and the subtropical jet stream every eight to eleven years. This decadal mode of climate variability also plays a role in the frequency of hurricanes in the region.

A secondary climate mode is associated with the El Niño Southern Oscillation (ENSO) (Stephenson et al. 2007). ENSO is a coupled ocean-atmosphere phenomenon consisting of periodic anomalous conditions in atmospheric circulation patterns and ocean temperatures in the tropical Pacific. These anomalous conditions can affect climatic conditions around the globe. In the Caribbean the primary affect is opposing precipitation anomalies in the Caribbean Antilles and northern South America. The southeastern Caribbean becomes drier than normal in response to a positive ENSO signal (known as El Niño) because of a change in the zonal overturning atmospheric circulations (known as the Walker Circulation). However the shifts in atmospheric circulation also lead to wetter than average early rainfall seasons (May to July) during the summer following an El Niño event (Chen et al. 1997, Giannini et al. 2000, Wang and Enfield 2001, Chen and Taylor 2002, Taylor et al. 2002b, Spence et al. 2004a, Ashby et al. 2005). The signal reverses during La Niña events with drier than average early rainfall seasons. The late rainfall season (August, September, October, November) tends to be drier in El Niño years and wetter in La Niña years (Giannini et al. 2000, Martis et al. 2002, Taylor et al. 2002a, Spence et al. 2004b, Ashby et al. 2005, Jury et al. 2007), thus accounting for the overall tendency for lower (higher) than average annual precipitation during positive (negative) ENSO phases in the Caribbean basin.

Additionally, as shown in figure 4, there is spatial variability across the Caribbean in response to the ENSO phase. The warm phase of ENSO, or El Niño, tends to increase rainfall in the eastern Caribbean in early summer, while it reduces rainfall in the

western Caribbean in late summer. The effect on winter rains is minor except near Florida. (Enfield and Alfaro 1999) showed that opposing SST anomalies in the tropical Atlantic further enhance the ENSO influence on Caribbean rainfall. Tropical cyclone activity diminishes over the Caribbean during El Niño summers due to upper westerly wind shear over the central Atlantic (Gray 1984).

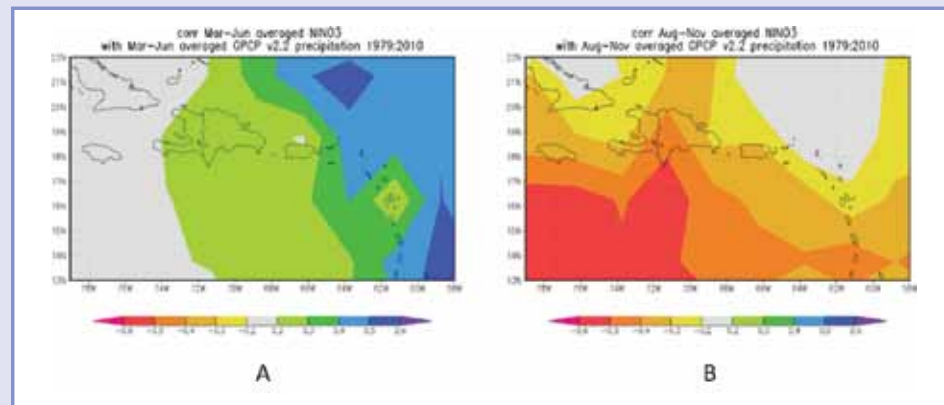


Figure 4 Correlations between NINO3 SST and early (A) and late summer rains (B) from GPCP. NAO correlations were near zero. The warm phase of ENSO, or El Niño, tends to increase rainfall in the eastern Caribbean in early summer, while it reduces rainfall in the western Caribbean in late summer.

The effect on winter rains is minor except near Florida. (Enfield and Alfaro 1999) showed that opposing SST anomalies in the tropical Atlantic further enhance the ENSO influence on Caribbean rainfall. Tropical cyclone activity diminishes over the Caribbean during El Niño summers due to upper westerly wind shear over the central Atlantic (Gray 1984). The effect of ENSO on the climate of the Caribbean is also influenced by another important mode of climatic variability, the North Atlantic Oscillation (NAO). The NAO is characterized by opposing variations of barometric pressure between Iceland and the Azores. These oscillations in turn can modulate the influence of ENSO (Giannini et al. 2001). A positive NAO phase implies a stronger than normal North Atlantic High which amplifies the drying during a warm ENSO. On the other hand, a negative NAO phase amplifies the precipitation in early summer following an El Niño.

Recent Climatic Trends in the Caribbean

According to the 2001 National Climate Assessment, average annual air temperatures in the Caribbean islands increased by more than 0.6°C or 1.0°F over the 21st century ((USGCRP

2001). Similarly, IPCC AR4 found that, for the Caribbean islands, average annual temperatures have increased by more than 0.5°C over the period 1900-1995; the seasonal data are consistent with this overall trend. Observed trends in precipitation in the Caribbean are less clear. Whilst Neelin et al. (2006a) identified a small but statistically significant drying trend during the months of June, July, and August (JJA) in recent decades, Peterson et al. (2002) found no statistically significant trends in mean precipitation (Neelin et al. 2006b). However, recent changes in the Caribbean climate were examined

using the Climate Explorer statistical analysis tool and in addition have been previously analyzed for the ocean environment in (Jury 2011) (figure 5). The linear trend analysis shows more warming (figure 5a) and drying in the eastern Caribbean (figure 5b), according to NCEP reanalysis data that include station, ship and satellite data interpolated by a weather forecast model. For Puerto Rico, the NCEP reanalysis indicates a positive trend of 0.01°C yr⁻¹ for surface air temperature and a negative trend of -0.02 mm day⁻¹yr⁻¹ for precipitation since 1948. Both trends are significant above the 95% confidence level. Trends in different seasons are similar.

The IPCC Special Report on Extremes (IPCC 2012) stated that it is very likely that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, at the global scale. There have been statistically significant trends in the number of heavy precipitation events in some regions. It is likely that more regions have experienced increases than decreases, although there is strong regional and subregional variations in these trends.

Peterson et al. 2002 found that for the Caribbean region there was an 8% increase in the number of very warm nights and a 6% increase in the number of hot days for the period 1958-1999. There was also a corresponding decrease of 7% in the number of cold days and 4% in the number of cold nights.

Donnelly and Woodruff's (2007) proxy reconstruction of the past 5,000 years of intense hurricane activity in the western North Atlantic suggests that hurricane variability has been strongly modulated by El Niño during this time, and that the past 250 years has been relatively active in the context of the past 5,000 years (Donnelly and Woodruff 2007). Nyberg et al. (2007) suggest that major hurricane activity in the Atlantic was anomalously low in the 1970s and 1980s relative to the past 270 years. As with Donnelly and Woodruff, their proxy measures were located in the western part of the basin (near Puerto Rico), and in their study, hurricane activity was inferred indirectly through statistical associations with proxies for vertical wind shear and SSTs. According to the U.S. Global Change Research Program, Atlantic tropical storm and

hurricane destructive potential as measured by the Power Dissipation Index (which combines storm intensity, duration, and frequency) has increased. This increase is substantial since about 1970, and is likely substantial since the 1950s and 60s, in association with warming Atlantic sea surface temperatures. There have been fluctuations in the number of tropical storms and hurricanes from decade to decade and data uncertainty is larger in the early part of the record compared to the satellite era beginning in 1965. Even taking these factors into account, it is likely that the annual number of tropical storms, hurricanes and major hurricanes in the North Atlantic have increased over the past 100 years, a time in which Atlantic sea surface temperatures also increased. The evidence is not compelling for significant trends beginning in the late 1800s as uncertainty in the data increases as one proceeds back in time. There is also evidence for an increase in extreme wave height characteristics over the past couple of decades, associated with more frequent and more intense hurricanes (USGCRP 2009).

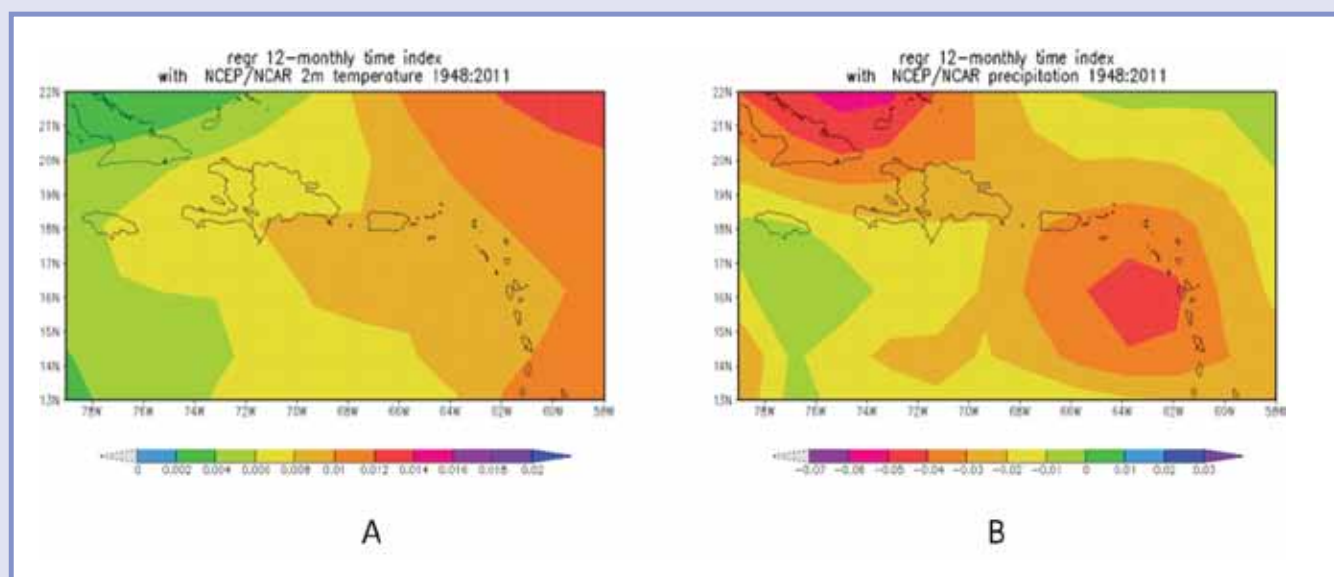


Figure 5 Linear trends in surface air temperature (A, °C/yr) and rainfall (B, mm/day/yr) from NCEP reanalysis. Note rain scale is reversed.

What is difference between global warming and climate change?

Global warming, which is not considered a technical term, refers to the long-term increase in Earth's average temperature. Whereas, climate change refers to any long-term change in Earth's climate, or in the climate of a region or a city. This includes warming and also cooling, changes in rainfall averages and downpour events, frequency and intensity of tropical storms and hurricanes, rising or falling sea levels, changes in the pH of our oceans, and other changes.

Climate change is a long-term in the statistics of the weather (including its averages). For example, it could show up as a change in climate normals (expected average values for temperature and precipitation) for a given place and time of year, from one decade to the next.

There are two reasons we would see a long-term increase in Earth's average temperature or a long-term change for a certain climate parameter: Natural variability and human-induced change. Climate change is a normal part of the Earth's natural variability, which is related to interactions among the atmosphere, ocean, and land, as well as changes in the amount of solar radiation reaching the earth. The geologic record including significant evidence for large-scale climate changes in Earth's past. Certain naturally occurring gases, such as carbon dioxide and water vapor, trap heat in the atmosphere causing a greenhouse effect. The greenhouse effect is good for humans and ecosystems as it warms us at a temperature that sustains life on Earth, as opposed to the other planets in our solar system whose greenhouse effect or lack thereof depending on the planet, makes the planets either too cold or too hot to inhabit. Burning of fossil fuels, like coal, oil, and natural gas is adding carbon dioxide to the atmosphere. The current level is the highest in the past 650,000 years. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change concludes that "most of the observed increase in the globally average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."

Where can I find more information?

United States Global Change Research Program

www.globalchange.gov

NOAA National Climatic Data Center site on Global Warming:

www.ncdc.noaa.gov/oa/climate/globalwarming.html

NASA Goddard Institute for Space Studies recent research:

www.giss.nasa.gov/research

Global Change Master Directory

gcmd.gsfc.nasa.gov/Resources/pointers/glob_warm.html

Future Caribbean Climate

Projections of the future climate of the Caribbean region are possible but have uncertainty for three reasons. The first reason is the **internal or natural variability** of the climate system, which makes prediction challenging over timescales shorter than a few decades. The second reason is **scientific uncertainty**, encompassing both what we don't know as well as what we cannot yet represent accurately in our models. The third reason is **socio-economic or scenario uncertainty**, since future change will be driven by emissions from human activities that in turn will be determined by trends in population, technology, and legislation (Hawkins and Sutton 2007, 2011). In order to prepare for future climate change, it is important to understand what kind of changes are expected or possible. We can develop scenarios future emissions based on a set of plausible assumptions about future human actions and develop projections of the climate changes that would result.

According to the IPCC AR4, over the coming century projected temperature increases for the Caribbean are projected to be slightly below the global average of 2.5 - 4°C (4.5 - 7.2°F) by 2100 (IPCC 2007), but slightly above the tropical average. Also, most IPCC AR4 models projected decreases in annual precipitation and a few increases, varying from -39 to + 11%, with a median of -12%. The annual mean decrease is projected by the IPCC AR4 to be spread across the entire region. December, January, February in the Greater Antilles is expected to see increased precipitation and June, July, August to see a region-wide decrease (IPCC 2007). A number of research groups in Puerto Rico, the Caribbean, and elsewhere have begun to study future

climate scenarios to identify possible impacts on the region. Such studies help define the range of possible future change and illuminate ways in which these changes will impact human and natural systems. This report section summarizes the results of a literature review performed from September 2010 to July 2012 by Working Group 1 of published and unpublished studies to compile currently available information on climate change and impacts for the Caribbean, the Greater Antilles, and Puerto Rico.

As a result of the three sources of uncertainty in future projections listed above, studies describe a wide range of potential changes in the Caribbean regional climate system. This is particularly true for precipitation. Projection uncertainty is pervasive across all models and is reflected in the range of potential impacts described in climate assessments (Turner 2003, Stanton and Ackerman 2007, Bueno et al. 2008, Karl et al. 2009). Climate models also show little agreement on how climate change will impact large-scale atmosphere-ocean circulation patterns such as the El Niño Southern Oscillation (ENSO) (Stoner et al. 2009), although there is some indication of El Niño-like conditions becoming more common in a warmer world (Meehl 2009). Given the role that ENSO plays in the Caribbean precipitation regime and hurricane activity, any changes to ENSO will be of great importance to the region and merit further study. In addition, although there is uncertainty in the magnitude of precipitation changes, a majority of GCMs used in the IPCC AR4 report show future decreases in precipitation due to broader regional responses of sea surface temperatures to anthropogenic climate change (Biasutti et al. 2012).



Previous Modeling Efforts for the Caribbean

University of the West Indies – Mona Climate Studies Group and the Cuban Meteorological Institute (2003)

In 2003 the Caribbean Modelling Initiative used a regional, simplified climate model, PRECIS (Providing Regional Climates for Impact Studies), to evaluate possible future regional climatic changes in the Caribbean (Campbell et al. 2010a). PRECIS is a dynamical downscaling model driven by the HADAM3P GCM and ECHAM GCMs but can be forced at its boundaries by other GCMs. It has a resolution of up to 25km and can be used for any part of the Globe. Using IPCC SRES Scenarios A2 (high emissions) and B2 (low emissions) they simulated historic conditions (i.e., 1970-present) and future (i.e., end of century) conditions and reported absolute or percent change between the present and future. They found that irrespective of

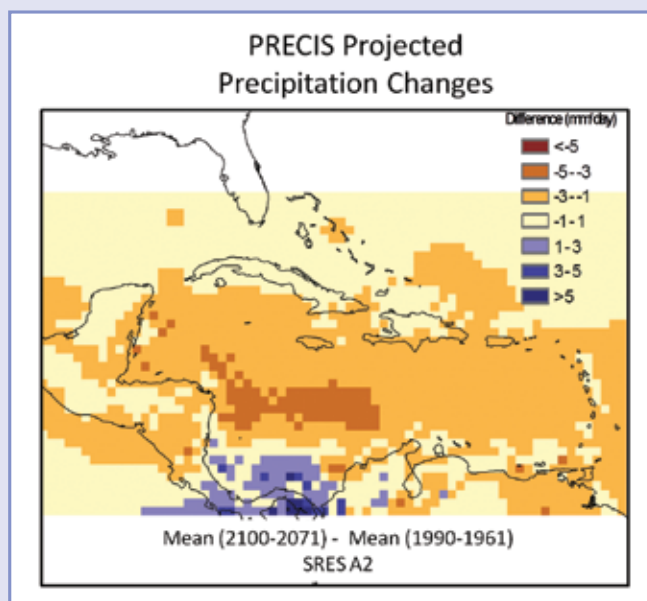


Figure 7: PRECIS Projected Precipitation Changes for SRES A2

scenario the Caribbean was expected to warm (warming between 1°C and 5°C; 1.8°F and 9°F) with greater warming under A2 (high emissions) scenario. The warming was consistent with projections for other parts of the globe and far exceeds natural variability (figure 6).

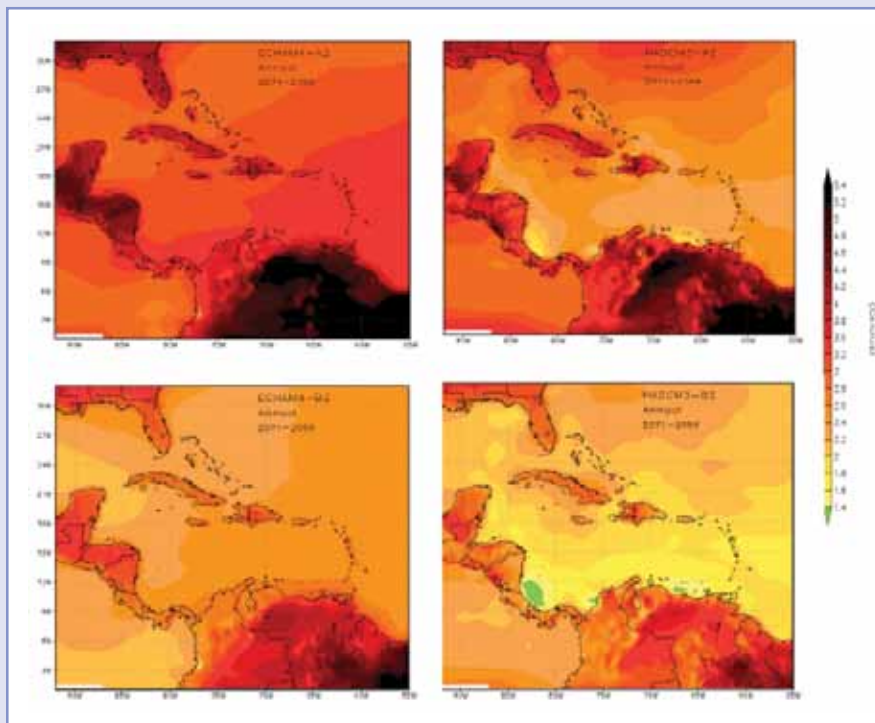


Figure 6 Mona Climate Studies Group found that irrespective of scenario the Caribbean was expected to warm (warming between 1°C and 5°C) with greater warming under A2 (high emissions) scenario. The warming was consistent with projections for other parts of the globe and far exceeds natural variability.

For precipitation, the Caribbean Modelling Initiative found there to be a general tendency for drying by the end of the century (drying between 25-30%) (figure 7) with a possible wetter future for the northern Caribbean's dry season (NDJ: November –January and FMA: February-April) and drying exceeds that of natural variability for the wet season (June-October) (figure 8). They note, however, that in some regions of the Caribbean all simulations projected drier conditions while in other areas of the Caribbean all simulations projected wetter conditions.

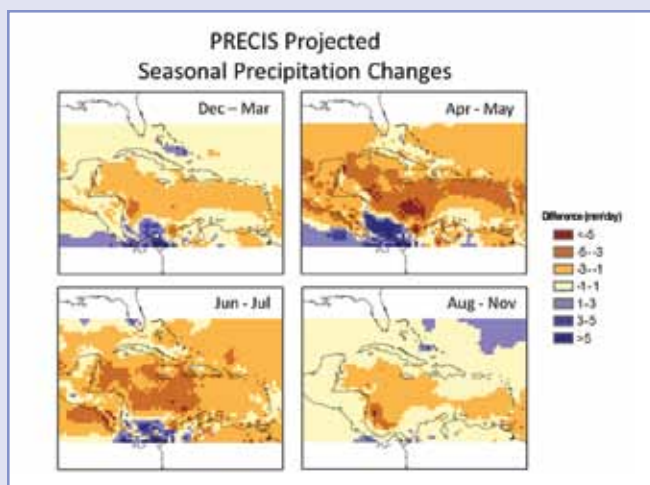


Figure 8: PRECIS projected seasonal precipitation changes for the Caribbean

University of Puerto Rico, Santa Clara University and Oak Ridge National Laboratory Study (2007)

Researchers from the University of Puerto Rico – Mayagüez, Santa Clara University and the Oak Ridge National Laboratory used a GCM (the Parallel Climate Model or PCM) to investigate possible climate change in the Caribbean under three future emission scenarios (Angeles et al. 2007). The results showed that for the period 2041 to 2058 increases in sea surface temperatures of approximately 1°C (1.8°F) are possible along with increases in precipitation during the Caribbean wet seasons (early and late rainfall seasons) and a strengthened vertical wind shear. They note that the PCM underpredicts SSTs so this is a conservative estimate. Strengthened vertical wind shear along with SSTs greater than 26.5°C (79.7°F) provides favorable conditions for possible future increases in tropical storm frequency.

University of Oxford and United Nations Development Program (2009)

Simpson et al. (2009) used 14 GCMs to create climate projections for 3 emissions scenarios (A1B, A2, and B1) for the 15 CARICOM countries of the Caribbean. Under these scenarios, the results indicate average air temperatures will rise in the future in all seasons. Typical

projected temperature increases in CARICOM countries are consistent with global trends (i.e. the Caribbean region largely tracks projected global temperature changes). However, the temperature increase is less in coastal regions and islands with greater warming over landmasses. This is related to the thermal inertia of the ocean and the greater internal heat capacity of water compared to land. All countries warm by at least 0.7°C (1.26 °F) by the time global temperatures have increased 2.0 °C (3.6 °F) above historic conditions (figure 9). According to these projections, there is little uncertainty that the trend of temperature is upwards, the main uncertainties are in the timing and extent.

Total annual rainfall was projected to decrease through all CARICOM countries by between 10 to 20% according to the ensemble mean, with larger declines as temperatures increase. The exception is in the north, particularly over the Bahamas, where the projections suggest hurricane-season rainfall will increase slightly. However, examination of standard deviations indicates that while the majority of projections simulate rainfall decreases, a few projections simulate rainfall increases.

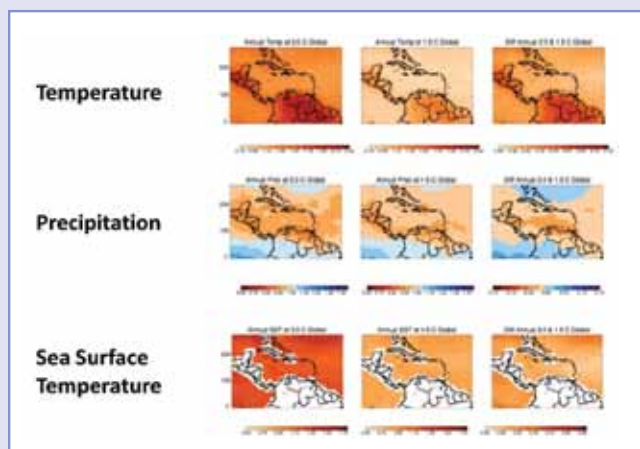


Figure 9: Changes in regional average annual temperatures (top), precipitation (middle), and sea surface temperatures (bottom) compared to present day values at thresholds of 2.0°C and 1.5°C and differences between the two; note different scales. Precipitation projections show fractional changes in total annual rainfall; reds indicate drying, blues indicate increased rainfall.

The United Nations Development Programme (UNDP) Climate Change Country Profiles Project (2010)

The UNDP Climate Change Country Profiles Project (McSweeney et al. 2010) uses existing data to generate a collection of country-level analyses of recent climate observations and the multimodel projections made available through the World Climate Research Program's Coupled-Model Intercomparison Project. They produce "off the shelf" analysis of the data to provide basic observed and model out-put summaries. Their analyses have included the Caribbean and the Dominican Republic model outputs include Puerto Rico. Using IPCC Emissions Scenarios A2, A1B, and B1 and 15 GCMs, results for the Caribbean show:

- All projections indicate substantial increases in the frequency of days and nights that are considered "hot" in current climate. And all projections indicate decreases in the frequency of days and nights that are considered "cold" in current climate. Cold events are expected to become exceedingly rare, not occurring at all in most projections. (The project considers a "hot" day or night one that the temperature exceeded on 10% of days or nights in current climate of that region and season.)
- The mean annual temperature is projected to increase by 0.5 to 2.3°C (0.9 and 4.14 °F) by the 2060s and 1.1 to 3.6°C (1.98 and 6.48 °F) by the 2090s. The projected rate of warming is most rapid in winter (December, January, February).
- Projections of mean annual rainfall from different models in the ensemble are broadly consistent in indicating decreasing rainfall, largely due to decreases in wet season (June, July, August) rainfall. Projected changes in the wet season vary from -78% to +21% by the 2090s. Annual changes range from -55% to +20%.

- The proportion of total rainfall that falls in heavy events is projected to decrease by most models by the 2090s.

Caribbean Community Climate Change Center (2010)

The Caribbean Community Climate Change Center commissioned a study (Campbell et al. 2010b) that combined the HadRM3P and PRECIS regional models to show annual temperatures are projected to increase over the Caribbean under all emissions scenarios. The models project greater than 2°C (3.6°F) increase in annual average temperature over the Caribbean, with the greatest warming for the larger islands of Cuba, Jamaica, Hispaniola, Central America and northern South America across all seasons. The rainfall response varies with season with one of the more robust changes being an intensification of a gradient pattern in November-January, in which the northern Caribbean (i.e., north of 22°N) gets wetter and the southern Caribbean gets drier. There is also a drying signal from June-October.

Puerto Rico Climate Change Council (2011)

The PRCCC used the visualization tool Climate Wizard (Girvetz et al. 2009) to assess recent climatic trends and possible future changes in the Caribbean based on output from 16 GCMs used in the IPCC AR4. The output of the ClimateWizard Change Map displays the 50th percentile or median projection for temperature and precipitation change averaged over the period 2080-2099 compared to 1961-1990 (figures 10, 11 and 12). The results are displayed for the A2 emissions scenario, corresponding to high future emissions of greenhouse gasses (GHG). The results show warming across the Caribbean, although less-so compared to continental regions due to the marine influence over the islands.

Overall the higher emissions scenario projects more warming and less precipitation for the region. The average warming for the Antilles is 2.8°C (5.04 °F) for the A2 scenario versus 1.7°C (3.06 °F) for the B1 emissions stabilization

scenario. The median precipitation projection indicates drying for most of the region with the exception of some areas in the southern Caribbean near the Panamanian Isthmus. The mean change for the median projection for the A2 scenario is a decrease of 15.8% compared to the 1961-1990 average precipitation and the mean change for the B1 scenario is a decrease of 8.5%.

Given the uncertainty in precipitation projections, the results shown in figure 12 are noteworthy in that the 80th percentile projection (that is, leaving out the 20% of model results that showed

the greatest future drying) shows a consensus amongst the models for drying in the Caribbean by the end of the century (for the high emissions scenario). Baisutti et al. (2012) show similar results using a slightly lower emission scenario (A1b). They tie the regional drying to the broader dynamical response of the tropical circulation to greater relative increases in SST in the tropical Pacific and Atlantic compared to the sub-tropical Caribbean (figure 13).

Table 1 shows a summary of the six Caribbean climate modeling studies.



Figure 10 ClimateWizard visualization of ensemble median output for average projected terrestrial temperature change from 2070-2099 compared to 1961 – 1990. Ensemble projection is for the IPCC A2 SRES Emission Scenario.



Figure 11 ClimateWizard visualization of ensemble median output for the median projection for percent departure from mean annual precipitation from 1961-1990.



Figure 12 ClimateWizard visualization of ensemble median output for the 80th percentile projection for percent departure from mean annual precipitation from 1961-1990.

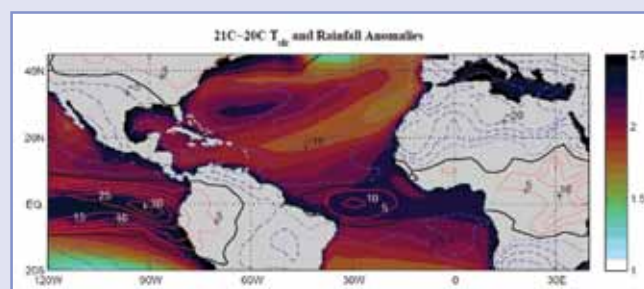


Figure 13 Ensemble mean temperature (shaded colors) and precipitation (colored contours) differences between the periods 2075-2099 and 1975-1999 for the A1b emissions scenario. Temperature changes are shown in degrees Celsius and precipitation changes are given in percent change from 20th century values. Reprinted with permission from Biasutti et al. (2012).

PROJECT	No. of GCMs	No. of DS	TEMPERATURE	PRECIPITATION	SEA SURFACE TEMPERATURE
Caribbean Community Climate Change Centre (5C's)	1	2	~2°C	Northern Carib Southern Carib	
Simpson et al. (for 2°C Global Warming)	14 (AR4)	0	> 0.7°C up to 2°C	-5% to -10% mean Up to +30% for some GCMs	> 0.5°C up to 1.7°C
PRCCC	16 (AR4)	0	~2°C	-10% to -20%	
UNDP	16 (AR4)	0	Hot Days 1°C – 3.6°C	-55% to +20% ann -78% to +20% wet Heavy Rain	
UPR-M	1	0		Wet Season	~1°C (mid-century)
UWI-CMI	2	1	1°C to 5°C	-25% to -30% ann Dry Season Wet Season	

Table 1 Summary of six Caribbean modeling studies for climate change projections described in the text, including the PRCCC. GCMs = Global Climate Models DS = Downscaled Models; AR4 = GCMs that were used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Knowledge Gaps and Future Research Needs for Caribbean Climate Change Studies

All previous studies have recommended a more detailed analysis of projections, together with research to downscale the information from the global models. Doing so would provide improved spatial detail and develop more specific information regarding the uncertainties associated with certain parameters, such as rainfall. Future research should also examine changes in the most intense climate events, such as those that produce heavy rainfall. Additional

and updated dynamical downscaling studies could improve understanding of the local and regional processes that drive precipitation events. Larger ensemble experiments such as perturbed physics experiments using single GCMs or simplified climate models could improve efforts to quantify uncertainty (and perhaps reduce uncertainties) in key physical parameters (e.g. ENSO, SST). Statistical downscaling could also improve projections of well-simulated climate variables such as surface air temperatures and sea surface temperatures.

PUERTO RICO'S CLIMATE

This section discusses the observed climatology of the island and expands on the summary of climatic trends in Puerto Rico using information from (Bush 1995), Lugo et al. (2011), Mendez (2010), Jury et al. (2011), and the NOAA National

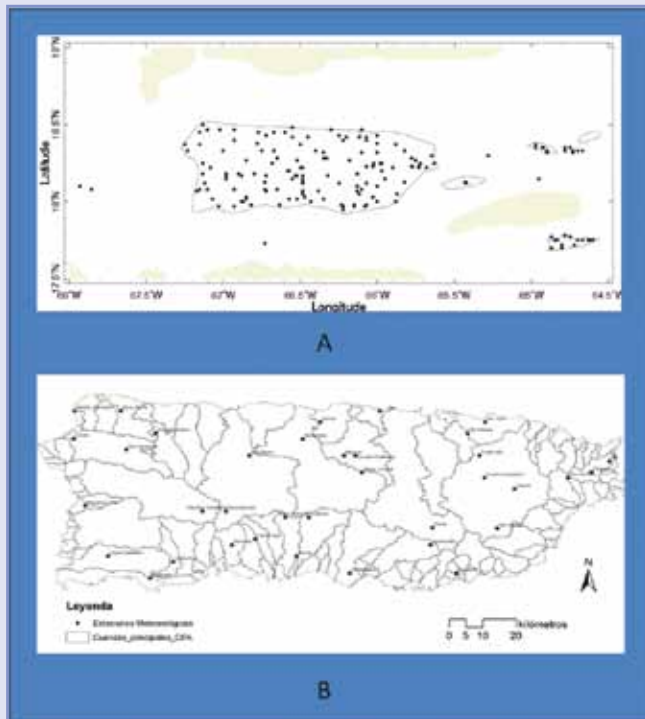


Figure 14: (a) NOAA GHCN station network over Puerto Rico and adjacent islands used in the PRCCC analysis; (b) Stations used in the Mendez (2010) analysis

Weather Service. The Jury analysis conducted for the PRCCC uses the NOAA GHCN station network over Puerto Rico (figure 14a) and the Mendez (2010) analysis is based on 36 precipitation stations and 16 temperature stations in Puerto Rico (figure 14b).

Puerto Rico is part of the Antilles island chain that between the Atlantic Ocean and the Caribbean Sea. This chain extends in a southeasterly arc toward the island of Trinidad and South America. Puerto Rico lies within the northeast trade wind belt and experiences a sub-tropical maritime climate typical of Caribbean islands, with warm temperatures and high summer precipitation (Daly et al. 2003, López-Marrero and Villanueva Colón 2006). Mendez (2010) estimated an island-wide average temperature of 24.9°C (76.8°F) over the period

1948-2007 based on 16 stations. Variability for all stations was below 2.5%. The stations which have recorded the highest annual average temperature are Fajardo (26.2°C; 79.2 °F), San Juan (26.8°C; 80.2°F) and Gurabo Substation (26.7°C; 80°F). The coolest average annual temperatures are observed at high elevation stations (Pico del Este (18.6°C; 65.5°F), Adjuntas Substation (21.5°C; 70.7°F) and Cayey (22.9°C; 73.2°F)) where local data indicates that temperature decreases approximately -0.6°C (-1.1°F) per 100m (328.1 ft) of elevation. The NOAA National Climatic Data Center has climatological normals and all time records across Puerto Rico and the U.S. Virgin Islands and shows that for a shorter time period (1981- 2010) than the Mendez (2010) analysis San Juan's annual average high was 87.6° F (30.9° C), Fajardo's was 87.2° F (30.7° C), and Gurabo's was 87.7° F (30.9° C).

The annual cycle of temperature in Puerto Rico is typical of the tropics in general and the Caribbean in particular. The cooler months are from December to March (as expected for coastal locations in the northern hemisphere). Beginning in April, temperature gradually increases to reach its peak in July or August followed by a steady, gradual decline beginning in September (Mendez 2010). Ocean temperatures in this sub-tropical climate are high and nearly constant with a minimum of 26°C (~79°F) in March to a maximum of 29°C (~84°F) in September (figure 15). Nearshore temperatures can be somewhat warmer and more variable (Bush et al. 1995). The warm ocean also plays a large role in the island's generally high humidity levels.

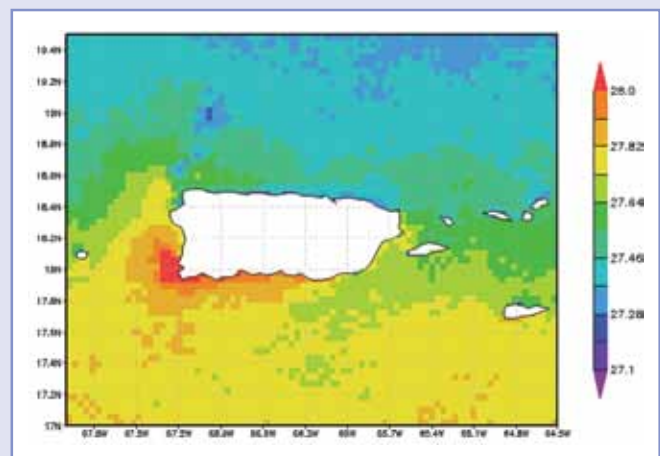


Figure 15 Mean sea surface temperatures around Puerto Rico at 4 km resolution from NOAA satellite in the past decade.

Although Puerto Rico is an island located entirely within the trade wind zone, distinct climate transitions exist from the mountainous interior and the exterior coasts of the main island (Bush et al. 1995). The central belt of mountains that run along the center of the island acts as a primary control on local temperature and precipitation variability. The most apparent topographic effect is the cooler temperatures at high elevations. Average temperatures in the interior mountains are $\sim 5^{\circ}\text{C}$ (9°F) cooler than coastal and urban San Juan. However the mountains also have an important effect on local circulation patterns. As the prevailing trade winds reach the island (figure 16), the marine air is forced to rise over the mountains. As the air rises, it cools and condenses; creating a cloud band that extends westward across the island (figure 17b; July weather radar rainfall). This orographic effect is enhanced by a confluent circulation that occurs during daytime hours, leading to large annual precipitation amounts in the central mountains and over the western portion of the island. The combination of the island-induced local circulation and the orographic effect of the mountains also leads to much drier conditions along the southern coast.

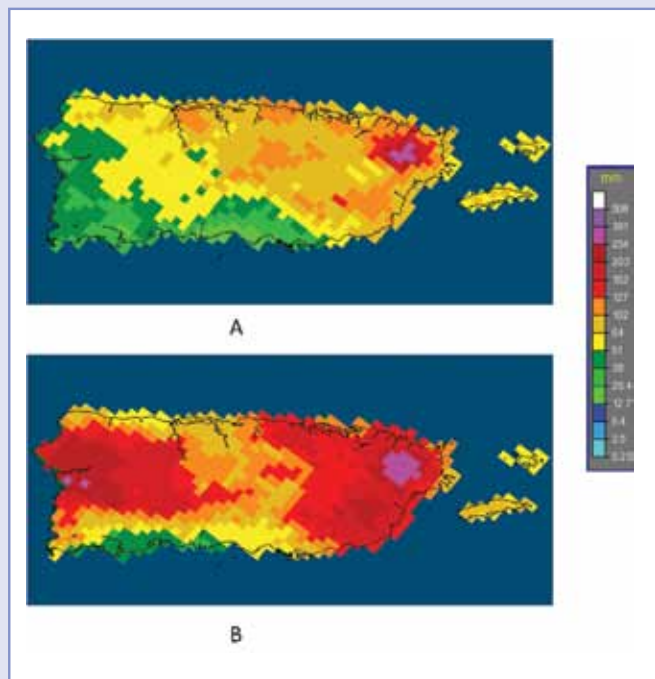


Figure 17: Mean monthly January (a) and July (b) rainfall at 1 km resolution from weather radar in the past decade.

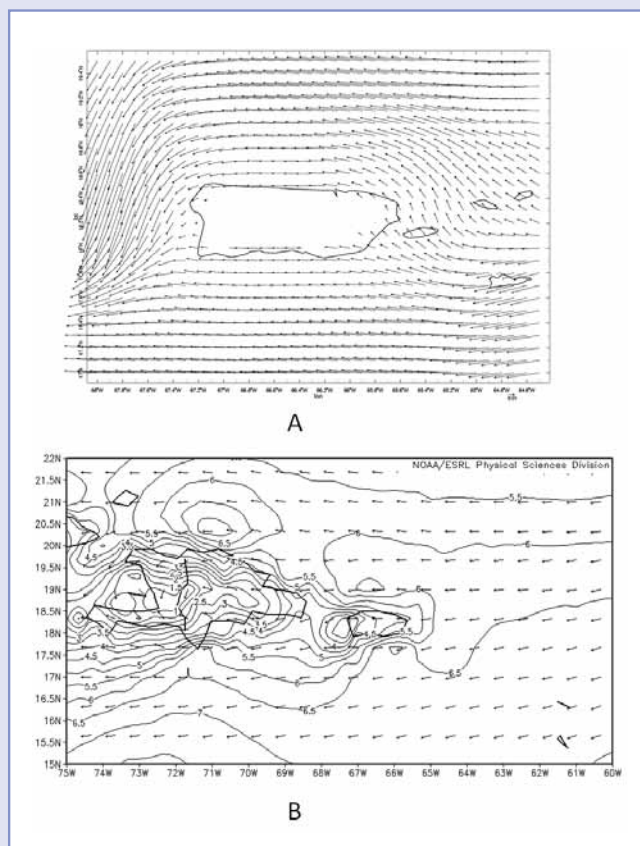


Figure 16: (A) prevailing winds around Puerto Rico; (B) 30-yr mean wind pattern from high resolution reanalysis model (NARR), with isotachs in m/s.

Generally rainfall increases from the coast inland, with more precipitation in higher elevations in the north and the eastern Sierra de Luquillo (Mendez 2010). The resulting differences in precipitation across the island can be quite large.

While the island-wide average annual rainfall is 1752 mm/yr (69 in/yr), local amounts can vary from as little as 800 mm/yr in the south (31.5 in/yr) to 4000 mm/yr in the Caribbean National Rain Forest on the northeast portion of the island (157.5 in/yr) (Mendez 2010). The NOAA National Climatic Data Center climatological normals map for mean annual precipitation (figure 18) shows the spatial differences in rainfall for Puerto Rico from the period 1981-2010.

Although the total amount of precipitation varies considerably, the seasonal cycle of precipitation is similar across all regions of the island. Typically the dry season is from December to March, with February being the driest month (figure 19a). A

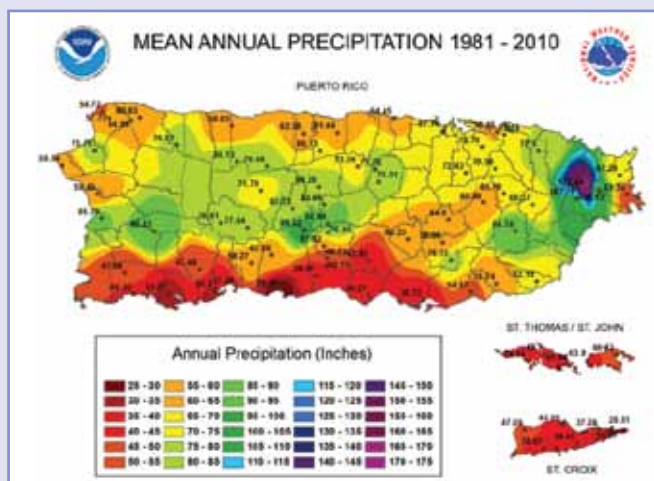


Figure 18: Mean Annual Precipitation from 1981-2010, courtesy of NOAA National Weather Service San Juan Office.

seasonal maximum in precipitation occurs in the month of May (figure 19b) followed by decreasing amounts in June and July before rising, reaching a fall peak in the months of October and November (figure 19c). Trade wind showers in the dry season are present over the northeastern half of the island while the southern coast is generally drier (Figure 16a; January weather radar rainfall). Figure 20 shows the frequency of stations reporting each month as either the driest month or the wettest month (Mendez 2010).

Rainfall is a frequent occurrence across the island, as reported for example in a USGS study which found 209 days with measurable precipitation during an average year in San Juan (Anderson 1976). Droughts are infrequent, even though certain areas of the main island experience drier conditions such as Guanica and other areas along the south coast. Persistent low rainfall over the island was observed in the years 1966-1968, 1971-1974, 1976-1977, 1993-1994 and 1998. The drought of 1971-1974 was the most severe in terms of its duration and streamflow reductions, while that of 1993-1994 was the most severe in terms of the impact on the island's water supply.

The rainfall distribution is punctuated by hurricanes, tropical storms, and westerly troughs (Bush et al. 1995). In July-August fast moving African easterly waves and hurricanes pass near Puerto Rico, but in September-October these same

systems slow down and cause localized flooding almost every year. Puerto Rico lies directly in the Caribbean hurricane belt. The hurricane season lasts from June through November, with a peak in August and September. Additionally, Puerto Rico is visited by a tropical depression (*onda tropical*) on the average of once every 2.5 years (Bush et al. 1995).

The earliest recorded storm in Puerto Rico was on the feast day of San Roque, August 16, 1508. (Picó 1969) reports six hurricanes and storms with significant effects on PR between 1893 and 1956. The San Ciriaco hurricane of August 8, 1899, is considered the worst natural disaster in Puerto Rico's history. This great hurricane killed more than 3,300 people, left 25 percent of the island's population homeless, destroyed more than \$7 million worth of the coffee crop (over \$225 million in 2012 dollars), and extensively damaged other cash crops, including sugarcane and plantain (Bush et al. 1995). Since then, several other hurricane events have affected the island, with the San Felipe Hurricane in 1928 leaving no area of the island untouched (Bush et al. 1995). Hurricanes Hugo (1989) and Georges (1998) were the most severe in terms of wind effects. Two hurricanes, San Nicolas, in 1931 and San Ciprian, in 1932, passed directly over the San Juan metropolitan area (Lugo et al. 2011). A more recent analysis of Puerto Rico's destructive hurricanes is offered by (Jury et al. 2011). Tracks of all category 3-5 hurricanes passing within 100 nm of Puerto Rico since 1860 (figure 21) shows that many develop to the east-south-east and pass over the smaller Antilles before reaching Puerto Rico. The paths diverge west-north-west and tend to pass over Hispaniola and Florida. About half of these cases are African easterly waves that develop over the Ethiopian highlands and pass Senegal about two weeks earlier. Hence it will be important to 'keep an eye' on climate changes over West Africa.

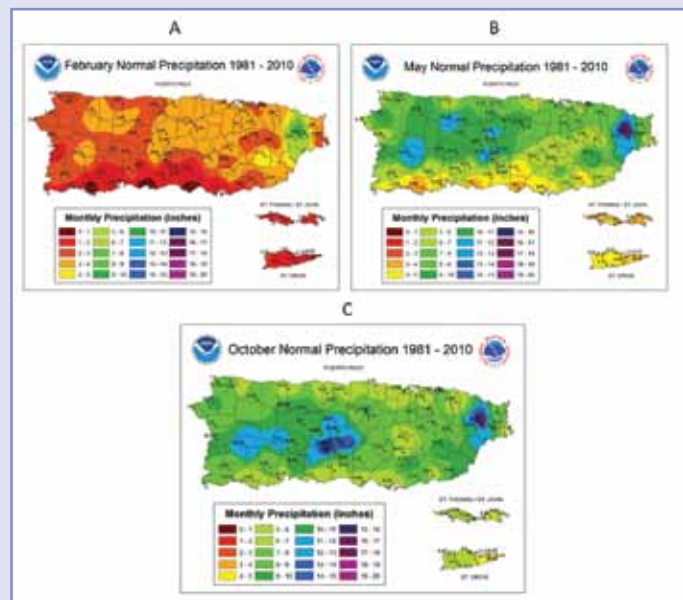


Figure 19: Normal Precipitation for 1981-2010 for months of (a) February, (b) May, and (c) October, courtesy of NOAA National Weather Service San Juan Office.

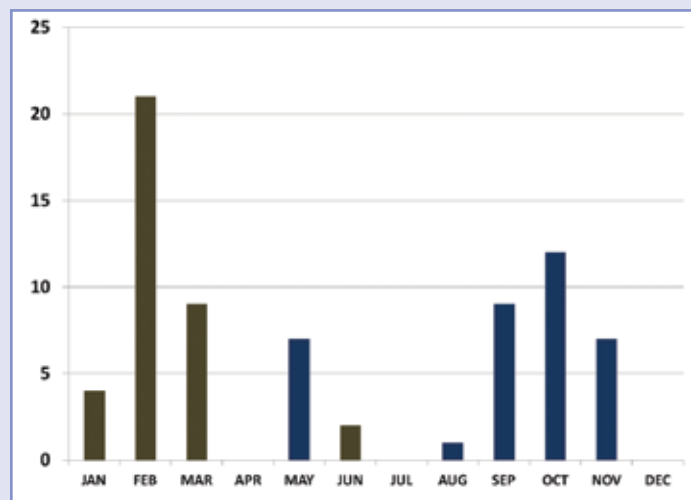


Figure 20: Frequency of stations (n=36) reporting each month as either the driest month (brown) and wettest month (blue). Based on analysis in Mendez (2010).



Figure 21: Tracks of all category 3,4,5 hurricanes passing within 100 nm of Puerto Rico in July-October season since 1860, based on NOAA hurdat data.

Analysis Methods from Dr. Mark Jury for the PRCCC

Analyses using high resolution grid-interpolated station data, reanalysis products and low resolution IPCC general circulation models were specifically conducted for the PRCCC by Dr. Mark Jury of the University of Puerto Rico. A number of well documented datasets are available that make use of 'smart interpolation' techniques to understand past climate and remove unwanted effects such as changes in site, elevation, instrumentation, etc. If only raw station data are considered, there are significant instrumentation anomalies before 1950. Raw island-averaged temperatures show an upward step $>1^{\circ}\text{C}$ around 1980. Thus it is essential to use quality controlled datasets. The gridded fields at $<50\text{km}$ resolution are of two types: direct observations adjusted using metadata information on instruments and site elevation, and quality control measures (CRU3, GPCC), and numerical model reanalysis using observations and satellite estimates in the past 30 years (NCEP, ECMWF, CFS). The value of the grid-interpolated analyses is in the area-averaging which helps limit the impact of stochastic climate variability, particularly for isolated short-lived floods. Furthermore, they include data from millions of satellite overpasses and marine weather observations from ships and buoys. This is important because Puerto Rican climate is largely of a marine nature.

Table Description of Gridded Products

Title	Description	Resolution (km)	Starting year
RADAR	NOAA National Weather Service weather radar gridded product using gauge correction	1	2000
WRF	Current operational mesoscale model of National Weather Service	1-10	2000
MODIS	Moderate-resolution Imaging Spectrometer SST, vegetation	4	2000
cMorph	Center for Disease Control and Prevention multi-satellite microwave IR morphed rain estimate	25	2000
NARR	N. American Regional Reanalysis with ETA model	30	1979
CFS-R	Climate Forecast System ETA model reanalysis	30	1979
GPCC	Global Precipitation Climatology Center land station reanalysis v5	50	1900
CRU3	Climate Research Unit land station reanalysis version 3	50	1900
CPC	Climate Prediction Center GHCN land station interpolation	50	1948
SODA	Ocean subsurface data reanalysis version 2.4 with ECMWF wind	50	1958
Hurdat	NOAA – MIT reanalysis of hurricane tracks and intensity	50	1861
ECMWF	European Community Medium-range Weather Forecast interim reanalysis	70	1979
HadSST	UK Hadley Center SST gridded reanalysis version 2	100	1880
GPCP	Global Precipitation Clim. Project blended gauge + satellite rain v2.2	100	1979
MIROC	Coupled GCM version 5 of Frontier System Japan for CMIP5	100	1900
CCSM4	NCAR Community Climate System Model version4 for CMIP5	120	1900
NCEP	NCEP operational data reanalysis by MRF model	180	1948
CSIRO	Australian CSIRO coupled GCM version 3.6 for CMIP5	180	1900
GISS	Goddard Inst Space Science coupled GCM version 2R for CMIP5	200	1900
NCDC	USA NCDC NOAA SST gridded reanalysis version 3	200	1860

HISTORIC TRENDS AND CLIMATE PROJECTIONS BY PARAMETER

This section discusses the observed, historical trends and projected changes of the island for seven climate parameters (air temperature, precipitation, extreme events, sea surface temperature, sea level, and ocean acidity) and uses data from CariCOOS, NOAA, IPCC, and PRCCC partner analyses. Climate trend information differs from the known climatology or “climate normals” of Puerto Rico that were previously described, in that climate trends can be used to detect climate changes. Climate normals were not designed to be metrics of climate change as they are long-term averages versus long-term changes. More simply, the climate trends described here in section 5 are the historic observations of how we may be departing from the known climate normals of Puerto Rico that were described in section 4 and what changes we are expecting to see in the near future (years 2050 to 2100).

Air Temperature

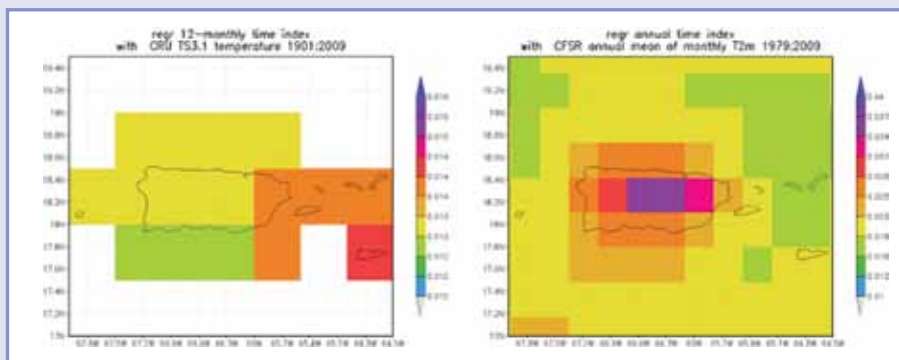
Observed Air Temperature Trends in Puerto Rico

Mendez (2010) showed that twelve of sixteen stations in Puerto Rico had significant increases in annual average temperature from 1948 to 2007. Statistically significant ($p < 0.05$) increases in monthly average temperature trends are observed for most months and stations. From these results, Mendez (2010) concluded that the annual temperature increased over this period throughout the island of Puerto Rico. The warmest years were 1998 (observed in 6 stations) and 2007 (observed in 3 stations).

Using gridded products (see box on previous page), Dr. Mark Jury mapped the linear trend of surface air temperature with two different datasets using the Climate Explorer

statistical analysis tool. There is faster warming in the east in the longer dataset (1901 - 2009), and faster warming over the center of the island in the shorter dataset (1979 - 2009). Temperature trends are significant above 98% confidence level. Trends are similar in different seasons (figure 22 and figure 22). Climate Forecast System Reanalysis Temperature trends shows that the central (elevated) parts of Puerto Rico have a faster rate of warming than the coast. Air temperatures in the trade wind inversion (~850 hPa, 1500m) over Puerto Rico are rising faster than the global average. This is due to an accelerated Hadley circulation, with a trend of sinking motions over the Caribbean and rising motion over South America as indicated by the trend analysis of NCEP reanalysis data in Figure 24. The additional sinking motion causes heating by compression at the bottom of the layer, so the trade wind inversion has strengthened. The rate of warming in the 1-2 km layer is 3 x greater than surface air temperatures.

Both global and local changes can drive temperature trends. Historic temperature trends in Puerto Rico based on station data include large-scale influences of global climate change as well as land cover change as reflected in increasing daily minimum temperatures (Duchon 1986). In Puerto Rico, there is some indication that the enhanced coastal warming may be at least in part due to the urban heat island effect (Velazquez-Lozada et al. 2006; Gonzalez and Comarazamy 2009). Stations located in San Juan show that both maximum and minimum temperatures are on the rise in heavily urbanized areas where there is conversion of



Figures 22 (left) and 23 (right): Linear trends in surface air temperature for CRU3 station interpolated observations (left, °C/yr) and from CFS reanalysis (right °C/yr). Climate Forecast System Reanalysis Temperature trends shows that the central (elevated) parts of Puerto Rico have a faster rate of warming than the coast

natural vegetation to urban dwellings (Gonzalez and Comarazamy 2009). Velazquez-Lozada et al. (2006) also found warming in the San Juan metropolitan area, with a trend of $0.06^{\circ}\text{C}/\text{yr}$ from 1960-2000. Throughout the tropics, population movements, urban growth, and industrialization are causing conditions that result in elevated temperatures within urban areas when compared to that in surrounding rural areas, a phenomenon known as the urban heat island (UHI) (Murphy et al. 2010). Murphy et al. (2010) demonstrated that San Juan experiences greater temperature when compared to the surrounding forested and

open, rural areas by as much as 4.7°C (8.5°F). Using projections of future development and temperatures they suggest that if the present pattern of development continues, over 140 km^2 of land that showed no signs of the urban heat island effect in 2000 will have an average annual temperature increase between $+0.4$ and $+1.55^{\circ}\text{C}$ ($+0.72$ and 2.79°F) by 2050. Furthermore, more than 130 km^2 of land area with a current UHI between $+0.4$ and $+1.4^{\circ}\text{C}$ ($+0.7^{\circ}\text{F}$ and $+3.5^{\circ}\text{F}$) in 2000 will have an average UHI greater than $+1.55^{\circ}\text{C}$ ($+2.79^{\circ}\text{F}$) by 2050 (Murphy et al. 2010).

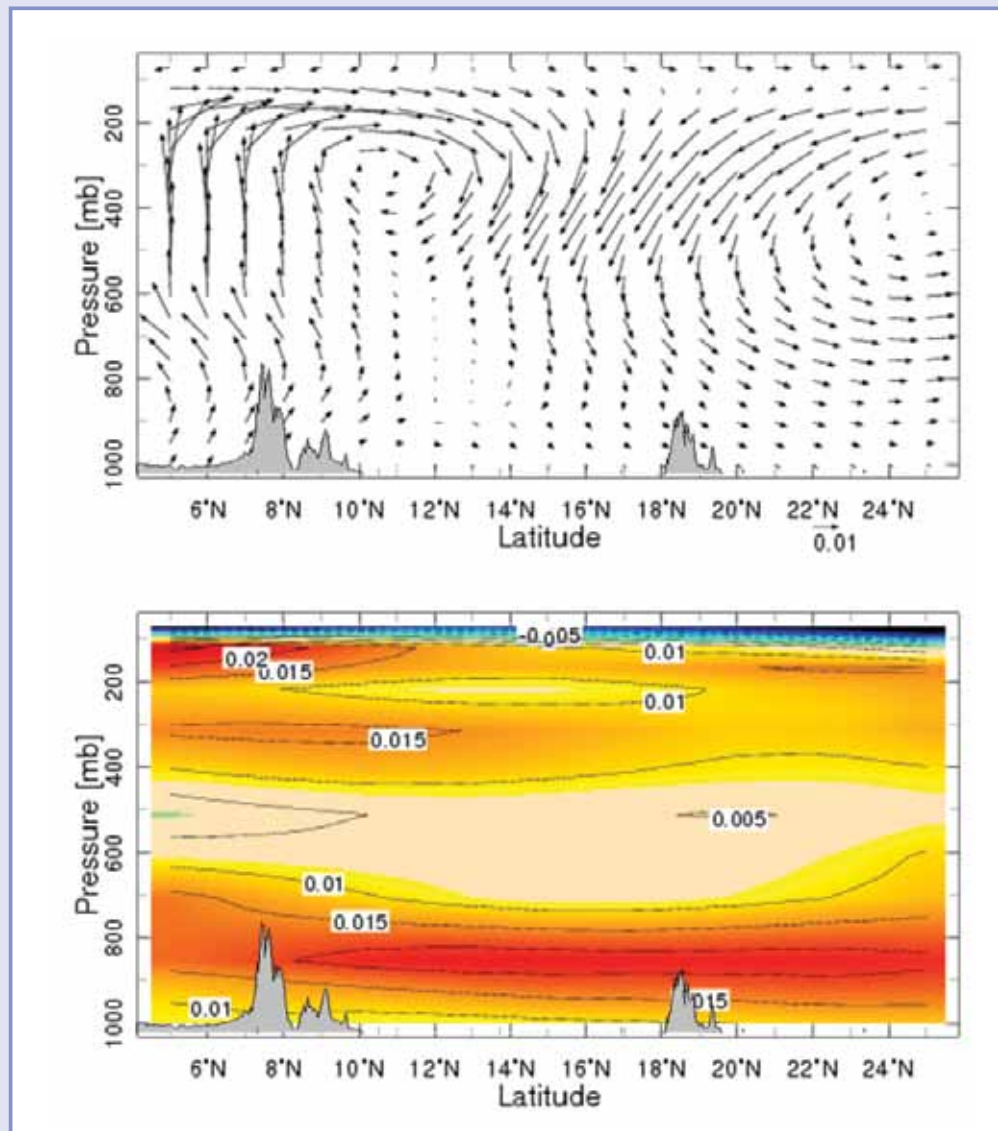


Figure 24: The analysis is of linear trends in the meridional atmospheric Hadley circulation (top, $\text{m/s}/\text{yr}$) and air temperature ($^{\circ}\text{C}/\text{yr}$), as N-S height sections across Puerto Rico from NCEP reanalysis 1948-2009. Adapted and updated from Jury and Winter (2009).

The amount of warming that may be attributed to larger-scale warming can be deduced by comparing observed trends over Puerto Rico with those from other islands in the region. Centella et al. (1999) found annual average temperature increases of 0.5°C (0.9°F) for the island of Cuba since 1950. On the islands of Trinidad and Tobago Singh (1997) found an increase of 1.5°C (2.7°F) between 1946 and 1995. It appears, therefore, that Puerto Rico does follow a larger-scale trend in warming, although some locations on the island are warming faster than others. As part of the PRCCC Assessment Dr. Mark Jury also compared annual temperature anomalies for Puerto Rico and global land surface anomalies (50°S-60°N, all longitudes, land only) using the Hadley Center CRUTEM3 dataset. The results indicate that Puerto Rico's temperature anomalies were lower than the global anomalies in the early portion of the observation record, but are higher than the global anomalies in the most recent period. This indicates a greater range of climate change for Puerto Rico compared to the global range of climate change.

Projected Changes in Temperatures

The CMIP5 coupled general circulation model projections that will be used in the next IPCC assessment report (AR5) are now available (Taylor et al. 2011b). These models have increased resolution and dynamic vegetation, compared with the earlier CMIP3 models used in the IPCC AR4 assessment, reported in the earlier section of this report. These models have been evaluated for the Caribbean and for Puerto Rico. While they perform reasonably well for many features of the observed climate, certain models better match the annual cycle of climate due to better representation of Antilles Island wind shadows which generate larger amplitude seasonal and diurnal cycling. Most of the CMIP5 models, like their predecessors, are biased towards a North Atlantic high pressure cell that is too strong - with trade wind evaporation causing below normal sea surface temperatures east of Puerto Rico. In this analysis of CMIP5 models, use is made of an all-model ensemble average based on the 'rcp6

forcing' scenario. This assumes an approximate doubling of CO₂ by the end of this century, consistent with the earlier CMIP3 A1B scenario, a 'middle of the road' projection.

Figure 25 shows the results of observed trend analysis of the San Juan weather station as well as model outputs of surface temperature from an area-averaged observation product CRU3 and from the CMIP5 coupled model CCSM4 projection with the rcp6 scenario. The analysis shows that the historic trends of temperature for the whole of Puerto Rico are consistent with the global climate models: a rise of 0.012 to 0.014°C/yr (0.022 to 0.025°F/yr). On the other hand, the trend for San Juan is 0.022°C/yr (0.04°F/yr). If this trend continues San Juan's average temperature will increase to 27°C (80.6°F) in 2050 (as compared to 25.5°C or 77.9°F in 1950). This is consistent with the historic analyses by Mendez 2010. San Juan's temperature trend is higher than the rest of the island due to urbanization and measurement changes.

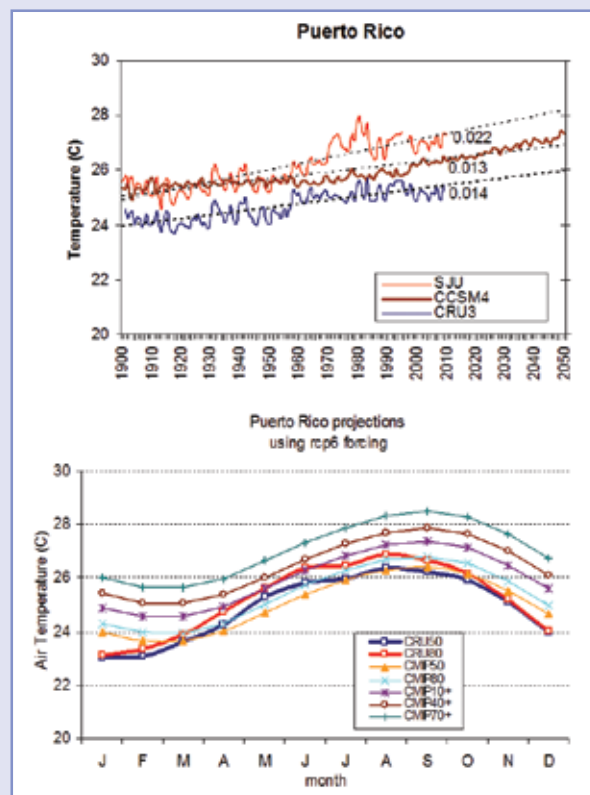


Figure 25: Comparison of surface air temperature from area-averaged observation product CRU3, San Juan station and CMIP5 coupled model CCSM4 projection with rcp6 scenario. Puerto Rico area is defined as 18-18.5N, 67-65W. Linear trends for area averages show a 0.012-0.014°C/yr temperature increase. San Juan trend is higher due to urbanization and measurement changes.

Station Data and Limitations

About 100 rainfall and 60 temperature observing stations in Puerto Rico have daily data back to 1900. Many of these stations have gaps in the records, and have shifted many kilometers and hundreds of meters in altitude, thus creating variable spatial and temporal distributions that pose problems in station-based interpretations. For example, an all-island average temperature analysis will have lower values in mid-20th century due to an increase in mountain stations at that time. In early and late 20th century there were more coastal stations and warmer temperatures. These effects can be removed by either taking a sub-set of stations that have no gaps or shifts, or by 'smart' interpolation using elevation models and metadata. It is important to recognize the station data limitations that exist.

Knowledge Gaps and Future Research Needs

Continual monitoring of temperature weather stations is critical to expanding our understanding of these trends in the future. Longer datasets allows us to increase certainties about the geographic distribution of the temperature trends in Puerto Rico. In terms of temperature projections, analyses that incorporate all GCMs and obtain larger ensemble experiments will allow for better quantification of uncertainty in the range of possibilities. Additionally, there is a need to capture more local and regional processes in the modeling work and so it is highly recommended that Puerto Rico develop higher resolution projections in the form of dynamical and statistical downscaling to obtain more refined temperature projections for future assessments.

Summary of Observed and Projected Temperatures for Puerto Rico

Over the 20th century, average annual air temperatures in the Caribbean islands have increased by more than 0.6°C or 1.0°F. In Puerto Rico, station analyses show significant increases

in annual and monthly average temperatures and a rise of 0.012°C/yr to 0.014°C/yr (0.022 to 0.025°F/yr) was observed from 1900 to present. Therefore, Puerto Rico does follow the larger-scale trend in warming, although some locations on the island are warming faster than others. Urban heat islands exist in Puerto Rico where temperatures are higher in developed areas than in rural, vegetated areas. For instance, San Juan's observed temperature trend is higher than the rest of the island at 0.022°C/year (0.04°F/year) since 1900. If this trend continues, San Juan's average annual temperature will have increased to 27°C (80.6°F) in 2050 (as compared to 25.5°C or 77.9°F in 1950). There is consensus on continued warming into the future amongst all modeling experiments. Over the coming century, projected temperature increases for the Caribbean are projected to be slightly below the global average of 2.5 - 4°C (4.5 - 7.2°F) by 2100, but slightly above the tropical average. Projected temperature increases are expected to be significant by late century at all locations. Projections for the Caribbean show a greater than >1.5°C rise in annual average temperature by 2100, with greatest warming over Cuba, Jamaica, Hispaniola, Central America and northern South America, where the increase is >2°C across all seasons. Projections for Puerto Rico show as little as 0.02°C/year warming through 2050, in other words at least 0.8 °C (1.44°F) by mid-century, and as much as 2-5°C (3.6-9°F) by the year 2100.

Precipitation

Observed Precipitation Trends in Puerto Rico

Analysis of weather station data for the period 1948 to 2007 found no clear trends in total annual rainfall for the island as a whole. 14 stations showed increases (38.9%), 12 stations showed decreases (33.3%) and others showed no significant trend (27.8%) (Mendez 2010). The long-term rainfall record for Old San Juan reflects a decreasing trend over a 107-year period (Lugo et al. 2011). Similarly, there are many other stations with 100-yr records and most show this decline.

While no clear trend exists for the entire island, there is evidence for changes in the spatial distribution of rainfall. Although the analysis by Mendez (2010) found mixed trends in annual precipitation, there was an indication that the southern region of Puerto Rico, which is also the driest region, had positive trends in annual rainfall while the western and a portion of the northern

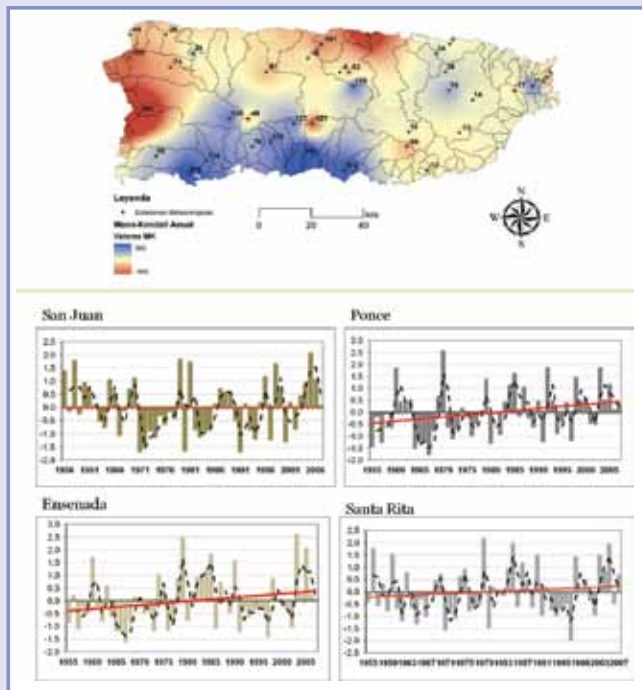


Figure 26: Precipitation trends for Puerto Rico (Mendez 2010)

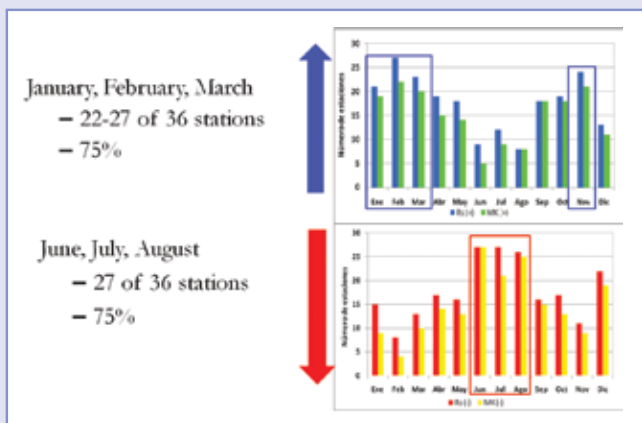


Figure 27: Data from rain gauges show that winter months (top) have experienced increasing rainfall while rainfall has been decreasing during the summer months (bottom).

region showed decreases (figure 26). Seasonal trends were also observed: a majority of stations (72.2%) showed negative trends in summer

(June, July, August) precipitation and a majority of stations (72.9%) showed positive trends in winter (January, February, March). However, no temporal trends are observed for spring or autumn precipitation (Mendez 2010) (figure 27).

Specific to the San Juan Metropolitan Area, from 1955 to 2009, 218.8 rainy days were observed for an average year (rainy days are defined as >0.01 mm of rain per 24 hours). San Juan station had 264 observed rainy days, Rio Piedras, 217 days, Trujillo Alto 181 days, Gurabo 191 days, and Canóvanas 233 days (figure 28). It has also been observed that the year with the least amount of dry days in San Juan was 2009. For Rio Piedras and Gurabo it was 2008. When comparing the average number of dry days per year from 1955 to 2009, San Juan exhibited 102 dry days on average per year with less dry days in the last decade (82 dry days during the years 2000-2009). Rio Piedras station showed 148 dry days per year from 1955-2009 with 100 dry days for the last decade, and finally Gurabo station showed 165 dry days per year from 1955-2009 with the last decade exhibiting a decrease in dry days as well (148 dry days).

Conversely, other datasets exhibit drying trends

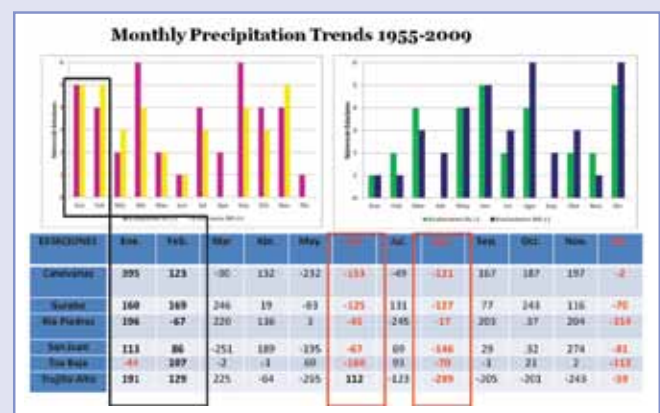


Figure 28: Monthly precipitation trends 1955-2009. Red numbers and boxes show stations and the corresponding months with decreasing precipitation trends.

throughout the year. Linear trends in observed rainfall in the CRU3 observed and CFS reanalysis datasets were mapped per grid cell (figure 29) by Dr. Mark Jury for the PRCCC. Decreases of -0.01 mm/day/yr are noted in the longer CRU3 record while significantly faster drying trends are evident in the shorter CFS reanalysis (-0.1mm/day/yr).

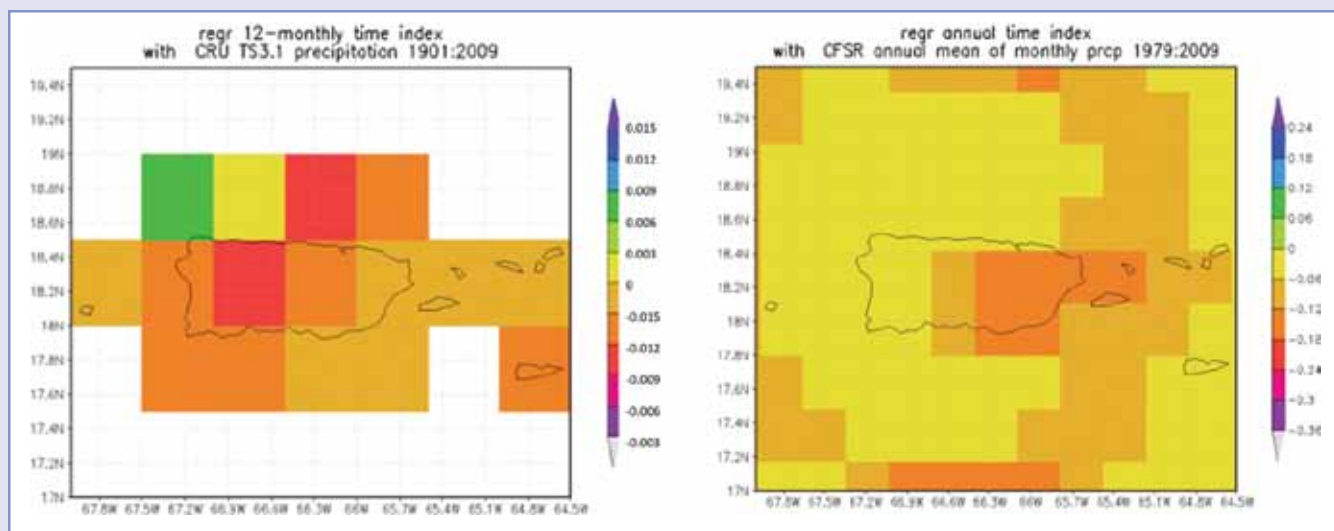


Figure 29: Linear trends in rainfall (mm/day/yr) in the CRU3 observations (left) and CFS reanalysis (right). There is a weak drying trend in both long and short records that exceeds 90% confidence. Note scale is inverted.

These decreases are found to be similar in all seasons, as opposed to the analysis by Mendez (2010) showing an increase in precipitation during winter months. Linear trends in river run-off from independent USGS records show a -1.27 mm/yr decline, though landuse change plays a large role in river run-off (figure 30).

Projected Precipitation Changes in Puerto Rico

In order to simulate future climate change, global climate models need to accurately represent observed climate. Whilst GCMs simulate temperature well, precipitation is more challenging, especially in the tropics. For example, most models from the IPCC AR4 predict a decrease in precipitation across the Caribbean region annually whilst also underestimating current precipitation amounts in the region (Neelin et al. 2006a, Christensen et al. 2007). The trend in tropical precipitation during June, July and August (JJA) from a select number of IPCC AR4 models was investigated by Neelin et al. (2006). It was shown in this study that not only is Caribbean precipitation projected to decrease, the Caribbean is one of the few tropical regions where there is large agreement between models.

The PRCCC analysis of CMIP5 results uses an all-model ensemble average based on the 'rcp6 forcing' scenario. This assumes an approximate

doubling of CO₂ by the end of this century, consistent with the earlier CMIP3 A1B scenario, a 'middle of the road' projection. The annual cycle of precipitation from observations and two CMIP5 models is analyzed in the period 1980-2010 below (figure 31). In addition the observed trend of annual rainfall over the 20th century and in one CMIP5 model projection is studied. Past and future trends are similar, there is a decrease of rainfall of -0.0012 to -0.0032 mm/day /yr.

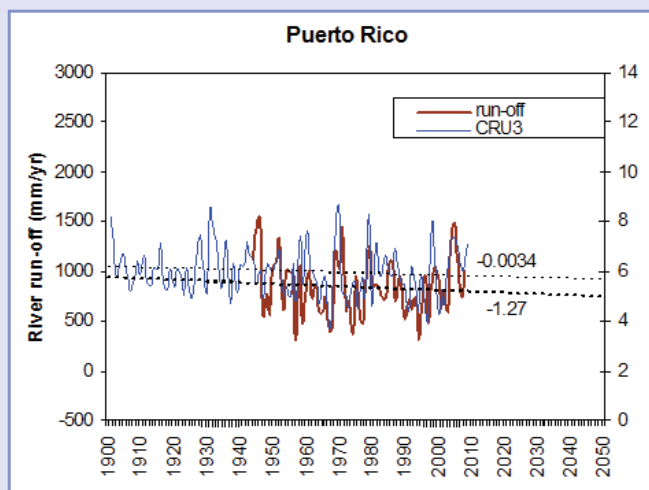


Figure 30: Comparison of annual river run-off from US Geological Survey observations and rainfall from area-averaged observation product CRU3.

The CMIP5 coupled general circulation model projections that will be used in the next IPCC assessment (AR5) are now available (Taylor et al. 2011a). These models have increased resolution and dynamic vegetation, compared with the earlier CMIP3 models used in the IPCC AR4 assessment, reported in the earlier section of this report. These models have been assessed for validity in the Caribbean and for Puerto Rico. While they

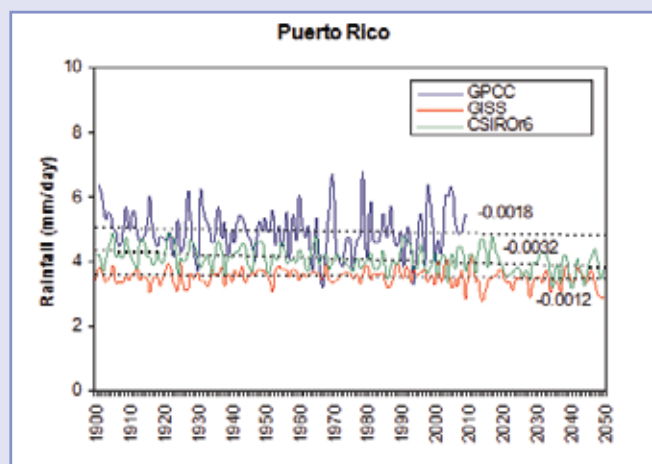


Figure 31: Comparison of annual rainfall from area-averaged observation product GPCC, and two CMIP5 coupled models: GISS and CSIRO with rcp6 scenario.

perform reasonably well for many features of the observed climate, certain models better match the annual cycle of climate due to better representation of Antilles Island wind shadows which generate larger amplitude seasonal and diurnal cycling. Most of the CMIP5 models, like their predecessors, simulate the North Atlantic high pressure cell as too strong - with trade wind evaporation causing below normal sea surface temperatures east of Puerto Rico. In this analysis of CMIP5 models, use is made of an all-model ensemble average based on the 'rcp6 forcing' scenario. This assumes an approximate doubling of CO_2 by the end of this century, consistent with the earlier CMIP3 A1B scenario, a 'middle of the road' projection. Figure 32 shows the results of observed trend analysis of the San Juan weather station as well as model outputs of precipitation from an area-averaged observation product CRU3 and from the CMIP5 coupled model CCSM4 projection with the rcp6 scenario. The analysis shows that the historic trends of precipitation for

the whole of Puerto Rico is -0.001 mm/day/yr and will continue through 2050 (figure 32).

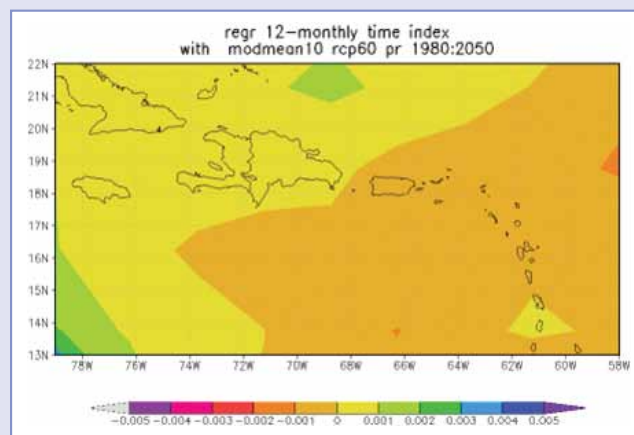


Figure 32: Linear trends in rainfall (mm/day/yr) predicted from CMIP5 model ensemble average using the rcp6.0W/m² forcing scenario in the period 1980-2050. The trend over Puerto Rico is -0.001 mm/day/yr . Trends in different seasons are similar.

Knowledge Gaps and Future Research Needs

Continual monitoring of precipitation weather stations is critical to expanding our understanding of these trends in the future. Longer datasets allows us to increase certainties about the geographic distribution of the precipitation trends in Puerto Rico. In terms of precipitation projections, analyses that incorporate all GCMs and obtain larger ensemble experiments will allow for better quantification of uncertainty in the range of possibilities. Additionally, there is a need to capture more local and regional processes in the modeling work and so it is highly recommended that Puerto Rico develop higher resolution projections in the form of dynamical and statistical downscaling to obtain more refined temperature projections for future assessments.

Summary of Observed and Projected Precipitation Changes

Observed trends in precipitation in the Caribbean as a whole are unclear from the literature. Most models from the IPRCC fourth assessment report predict a decrease in precipitation across

the Caribbean region. An analysis for the PRCCC shows that since 1948 the Caribbean Basin has seen decreasing precipitation (-0.01 to -0.05 mm/day/yr), with a greater drying trend for the Eastern Caribbean. Specifically for Puerto Rico, one analysis of weather station data for the period 1948 to 2007 found no clear trends in total annual rainfall for the island as a whole, while another analysis showed decreases in rainfall from -0.01 to -0.1 mm/day/yr. Regionally within the island, there are indications that the southern region of Puerto Rico has experienced positive trends in annual rainfall while the western and a portion of the northern region showed decreases. Additionally, seasonal trends with observed showing negative trends in summer and positive trends in winter. In

order to simulate future climate change, global climate models need to accurately represent observed climate. There is a lot of uncertainty in the magnitude of precipitation changes in the Caribbean, though a majority of GCMs used in the IPCC fourth assessment report show future decreases in precipitation are likely. Model projections range from -78 to -10% (with a few GCMs showing +30%) and current evidence suggests drier conditions are more likely than wetter for Puerto Rico, a contrast to the global precipitation signal. Specifically the PRCCC analysis found that past and future trends are similar, a decrease of rainfall of -0.0012 to -0.0032 mm/day /yr, that are projected to continue through 2050.



What is the IPCC and USGCRP?

The Intergovernmental Panel on Climate Change (IPCC) is the leading international body for the assessment of climate change. It was established in 1988 by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts. The United Nations General Assembly endorsed the action by WMO and UNEP in jointly establishing the IPCC. The IPCC is a scientific body that reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. It does not conduct any research nor does it monitor climate related data parameters. The IPCC is an intergovernmental body that is open to all member countries of the United Nations and WMO (currently 195 countries are members of the IPCC). Their findings are based on observations, paleoclimate analyses and model simulations informed by understanding the climate system. Because the IPCC does not carry out research and their findings are approved by United Nations countries, many of the major findings of the most recent assessment report, the Fourth Assessment Report (AR4) are now considered conservative and optimistic. For instance, recent indications point to higher average sea level rise estimates than those previously reported by the IPCC AR4.

The United States Global Change Research Program (USGCRP) coordinates and integrates federal research on changes in the global environment and their implications for society. The USGCRP began as a presidential initiative in 1989 and was mandated by Congress in the Global Change Research Act of 1989 (P.L. 101-606) which called for a "a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change." Thirteen departments and agencies participate in the USGCRP, which was known as the U.S. Climate Change Science Program from 2002 through 2008. During the past two decades, the United States, through the USGCRP has made the world's largest scientific investment in the areas of climate change and global change research. The vision of the USGCRP is for a nation, globally engaged and guided by science, meeting the challenges of climate and global change. The mission is to build a knowledge base that informs human responses to climate and global change through coordinated and integrated federal programs of research, education, communication and decision support.

Extreme Weather Events

Extremes are a natural part of even a stable climate system, but because social-ecological systems have adapted to their historical range of extremes, the majority of events outside this range have primarily negative impacts and therefore it is highly important to assess observed trends and projected changes of these extremes.

Globally there is evidence from observations gathered since 1950 of change in some extreme events. Extreme events are rare, which means there are few data available to make assessments regarding changes in their frequency and intensity. The more rare the event the more difficult it is to identify long-term changes.

A January 2001 workshop held in Kingston, Jamaica brought together scientists and data from around the Caribbean region, including Puerto Rico. ("The Caribbean Regional Climate Change Workshop"). Together the scientists analyzed daily weather observations from 18 of the 21 meteorological services in the Caribbean. They found that the extreme intra-annual temperature range was decreasing and that the number of very warm days and nights has been increasing dramatically since the late 1950s while the number of very cool days and nights have been decreasing. Additionally, extreme precipitation increased while the maximum number of consecutive dry days decreased. Indices of some of the variables show relationships with hurricanes and sea surface temperatures, but the scientists did not find one factor dominating all the observed changes (Peterson et al. 2002).

Extreme Temperatures in Puerto Rico

According to a National Weather Service San Juan office analysis by Odalys Martinez (2012), in the nearly 113 years of record keeping in the San Juan Metro Area, a greater frequency of days with maximum temperature equal to or above 90 °F (32.2 °C) has been observed during the last few decades (figure 33). In fact, during 2010 and 2011, about 100 days with temperature equal to or above 90 °F were observed; this is the same number of days observed per decade during 1900 through 1949.

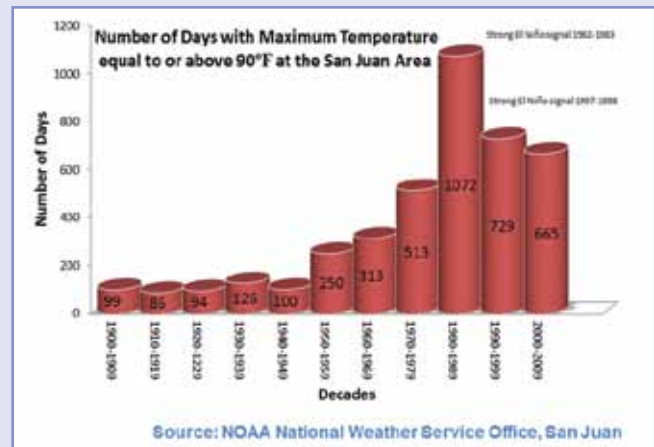


Figure 33: Number of Days with Maximum Temperature equal to or above 90°F in the San Juan Area

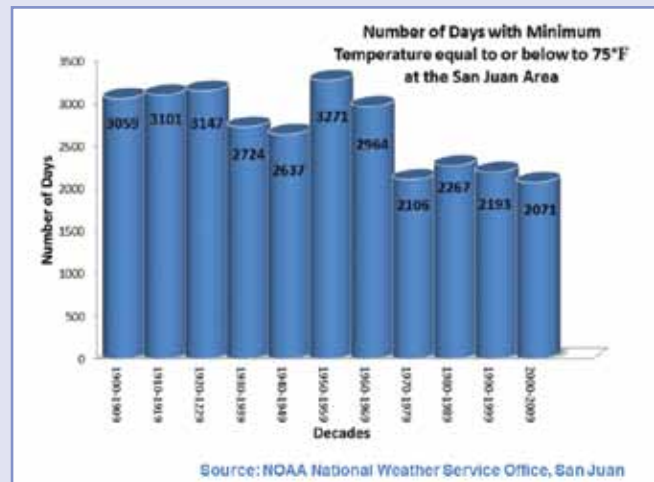


Figure 34: Number of Days with Minimum Temperature equal to or below 75°F in the San Juan Area.

During the 80's and 90's, the frequency of hot days is notably higher due to the presence of El Niño conditions across the Pacific basin. This increase in greater frequency of hot days is consistent with an analysis done by the U.S. Global Change Research Program. They found that the number of very warm nights in Puerto Rico has increased by 15 or more per year for Puerto Rico from 1950 to 2004 (USGCRP 2009). In terms of minimum temperatures, the NOAA National Weather Service's 113 yr record shows a lower frequency of days with temperature equal to or below 75 °F (23.9 °C) has been observed as well (figure 34). The signal of the urban heat island effect is included in the decrease of days with minimum temperature equal to or below 75 °F. An urban heat island is a metropolitan area which is significantly warmer than its surrounding rural areas. The temperature difference usually is larger at night than during the day.

Extreme Precipitation in Puerto Rico

Historically, droughts are not very common in Puerto Rico. The most important and long-lived droughts that have affected the whole island in recent decades occurred between 1966-1968, 1971-1974, 1976-1977, 1993-1994 and 1998. The drought of 1971-1974 was the most severe in terms of its duration and streamflow reductions, while that of 1993-1994 was the most severe in terms of the impact on the water supply.

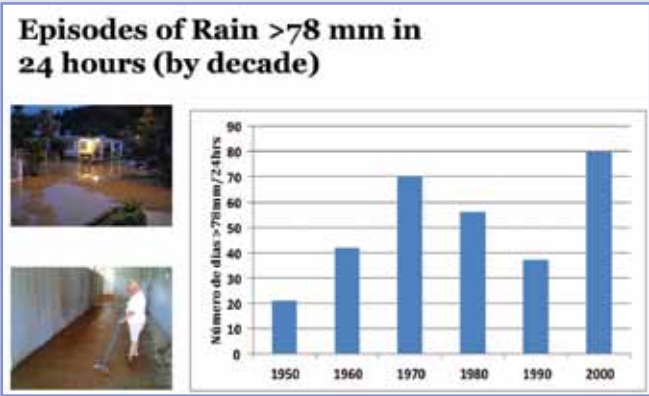


Figure 35: Episodes of rain over 78 mm in 24 hours by decade from 1950-2000

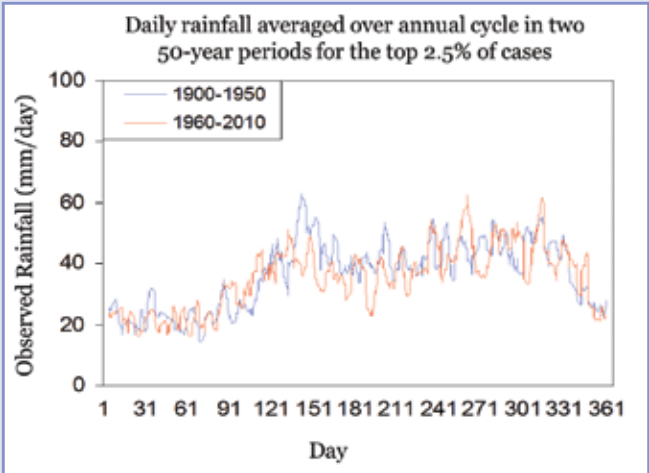


Figure 36: Daily rainfall averaged over annual cycle in two 50yr periods using data combined from Mayaguez, Manati and Manuabo for top 2.5% of cases. Notice the decrease in May floods (days 121-151).

One of the clearest precipitation trends in the United States is the increasing frequency and intensity of heavy downpours. The amount of rain falling in the heaviest downpours has increased approximately 20 percent on average across North America, the Hawaiian Islands, and Puerto Rico in the past century, and this trend is very likely to

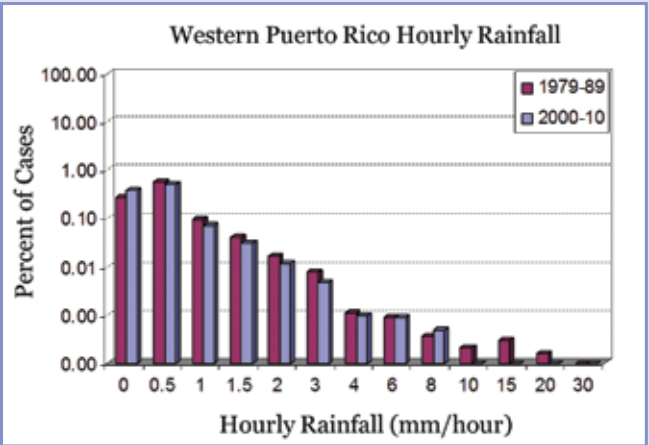


Figure 37: Hourly rainfall averaged over the western half of Puerto Rico from CFS-reanalysis, using data for two 10 yr periods, showing slight changes in the frequency distribution in the recent decade.

continue, with the largest increases in the wettest places (USGCRP 2009). In fact, from 1958 to 2007, Puerto Rico experienced a 37% increase in very heavy precipitation (USGCRP 2009). The San Juan metropolitan area has seen greater than 15% increase in more frequent rainfall events greater than 78mm of rain per 24 hours (3 in/24hrs) from 1955 to 2009. 70 episodes were observed in the 1970s, 55 episodes in 1980, 38 episodes in 1990, and 80 episodes in 2000 (not including 2010), according to the San Juan ULTRA Project (figure35).

An analysis was conducted for the PRCCC by Dr. Mark Jury, where daily rainfall was averaged over the annual cycle in two 50-year periods (1900 – 1950 and 1960-2010) using data combined from Mayaguez, Manati and Manuabo for the top 2.5% of rainfall event cases. The analysis showed a decrease in flooding events in May (figure 36).

Dr. Jury also performed an analysis of hourly rainfall events averaged over the western half of Puerto Rico from CFS-reanalysis, using data for two 10 yr periods (1979-1989 and 2000-2010), indicating a decline of flood events in the satellite era and a corresponding increase in light rain events (figure 37).

Projections for Extreme Precipitation Events

Regional downpours, defined as intense precipitation at subdaily (often subhourly)

timescales, are likely to increase in frequency and intensity in a warmer climate due to the greater capacity of warmer air to hold water vapor. In 2010, the IPCC stated that there has been a large increase in the available analyses of changes in extremes. This allows for a more comprehensive assessment for most regions. Projections concerning extreme events in the sub-tropics remain uncertain, however Nurse and Sem 2001; Solomon et al. 2007 all report a decrease in annual rainy days and higher risk of increased daily intensity of rainfall. Considering the IPCC MIROC model which simulates the annual rain cycle rather well, the projections show a significant increase in May rainfall that is at odds with the observed trend above for Puerto Rico (figure 38). The down-trend of sensible heat flux may inhibit late summer flood events from hurricanes. The CMIP5 MIROC5 model 1900-1950 simulation (50-) and 2000-2050 projection (50+) of the top 2.5% of monthly rainfall over an annual cycle (performed for the PRCCC by Dr. Mark Jury), indicate a significant increase of floods in May in through 2050. The model output shows no appreciable change in flood events during the hurricane season. Thus, while Puerto Rico may not have experienced an increase in May flood events in previous decades, the future may bring an increase as currently projected through 2050. However, McSweeney et al. (2010)'s model analysis shows a projected decrease in heavy rainfall events by the end of century (2090s) for the Dominican Republic and Puerto Rico.

Knowledge Gaps and Future Research Needs

The continued development and maintenance of high quality climate observing systems will improve our ability to monitor and detect future changes in climate extremes. Also, efforts to digitize, homogenize, and analyze long-term observations in the instrumental record with multiple independent experts and analyses would improve our confidence in detecting past changes in climate extremes. Weather observing systems adhering to standards of observation consistent with the needs of both the climate and the weather research communities would improve our ability

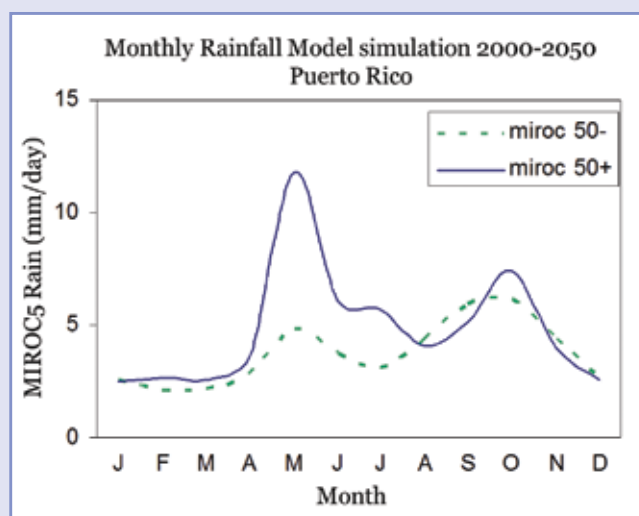


Figure 38: : CMIP5 MIROC5 model 1900-1950 simulation (50-) and 2000-2050 projection (50+) of top 2.5% of monthly rainfall cases over the annual cycle, indicating a significant increase of floods in May in the next 50 years. There is no appreciable change in flood events in the hurricane season.

to detect observed changes in climate extremes. Furthermore, the creation of annually-resolved, regional-scale reconstructions of the climate for the past 2,000 years would help improve our understanding of very long-term regional climate variability.

Summary of Historic Trends and Projections for Extreme Events

Globally there is evidence from observations gathered since 1950 of change in some extreme events. Extreme events are rare, which means there are few data available to make assessments regarding changes in their frequency and intensity. The more rare the event the more difficult it is to identify long-term changes. However, the IPCC Special Report on Extremes stated that it is *very* likely that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, at the global scale. There have been statistically significant trends in the number of heavy precipitation events in some regions. It is likely that more regions have experienced increases than decreases, although there is strong regional and subregional variations in these trends.

Caribbean trends show the extreme intra-annual temperature range was decreasing (becoming more uniform throughout the year) and that the number of very warm days and nights has been increasing dramatically since the late 1950s while the number of very cool days and nights have been decreasing. Additionally, extreme precipitation increased while the maximum number of consecutive dry days decreased.

These trends are consistent in Puerto Rico where we are experiencing a greater frequency of days with maximum temperature equal to or above 90 °F (32.2 °C) and a lower frequency of days with temperature equal to or below 75 °F (23.9 °C). And during 2010 and 2011, about 100 days with temperature equal to or above 90 °F were observed; this is the same number of days observed per decade during 1900 through 1949. Conflicting results exist for extreme precipitation events in Puerto Rico. One analysis for the San Juan region shows an increase while other regions are showing decreases in hourly rainfall events.

Models project substantial warming in temperature extremes by the end of the 21st century. It is *virtually certain*, according to the IPCC, that increases in the frequency and

magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century at the global scale. Additionally, it is *likely* that the frequency of heavy precipitation or the proportion of total rainfall to heavy falls will increase in the 21st century over many areas of the globe. This is particularly the case in tropical regions. And heavy rainfalls associated with tropical cyclones are *likely* to increase with continued warming. There is *medium confidence* that, in some regions such as the Caribbean, increases in heavy precipitation will occur despite projected decreases in total precipitation in those regions.

For Puerto Rico, climate projections for extreme events show a probable increase in extreme heat days and cold events are expected to become exceedingly rare. The projected rate of warming is most rapid in winter (December, January, February). Puerto Rico climate projections show a probable increase in regional downpours, particularly downpour events in May, despite the fact that the observed trends do not show an increase in May downpour events in Puerto Rico. It should be noted that one model shows a projected decrease in heavy rainfall events by the end of the century (2090s).



2011 downpour event in Mayagüez, PR: Flooding after only 30 minutes of rain. It is *likely* that the frequency of heavy precipitation events like this one will increase in the 21st century. *Photo Credits: Professor Aurelio Mercado, UPR.*



Sea Surface Temperatures (SST)

Observed Sea Surface Temperature Trends in the Northeastern Caribbean

Caribbean sea surface temperatures have warmed by 1.5°C over the last century (IPCC 2007). Rayner et al. (2003) described and assessed the Hadley Center sea ice and sea surface temperature (SST) data sets, which were developed at the Met Office HadleyCentre for Climate Prediction and Research. They worked for spatially complete, monthly SST analyses for the years 1871 to 1999 and found a clear trend of increasing SSTs globally (figure 39).

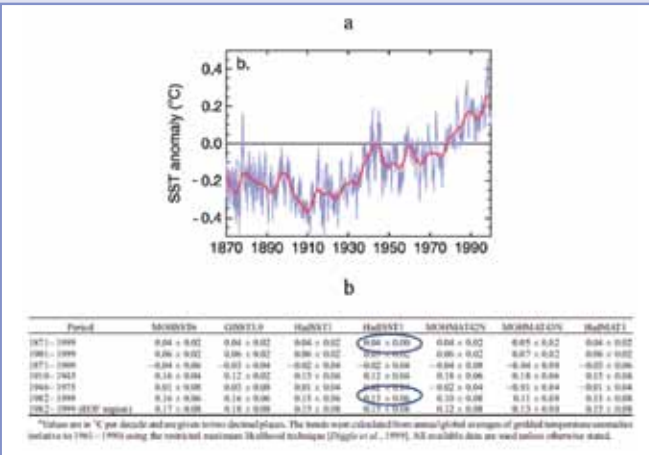


Figure 39: (a) Global average of the field reconstructed for 1870-1999. Blue curve is the monthly average, while the red curve has a 21pt binomial (near decadal) filter applied; (b) Global temperature trends (and their 2 standard deviation uncertainties) in surface temperature data sets. Courtesy of Rayner et al. (2003).

Dr. Julio Morell of the University of Puerto Rico’s Caribbean Coastal and Ocean Observing System (CariCOOS) compared this result with local observations through an analysis of sea surface temperatures around Puerto Rico for the PRCCC based on data collected from the Prediction and Research Moored Array in the Atlantic (PIRATA) buoy in the tropical Atlantic (15°N, 38°W) (<http://www.pmel.noaa.gov/pirata/>). Besides “in situ” he also explored estimates at these sites from a global weekly sea surface temperature data product, NOAA OI.v2 SST, operationally issued by NOAA. The two sources used for this study include annual SST from the Hadley center SSTv2 and the NCDC NOAA erSSTv3 because they have at least 30 years

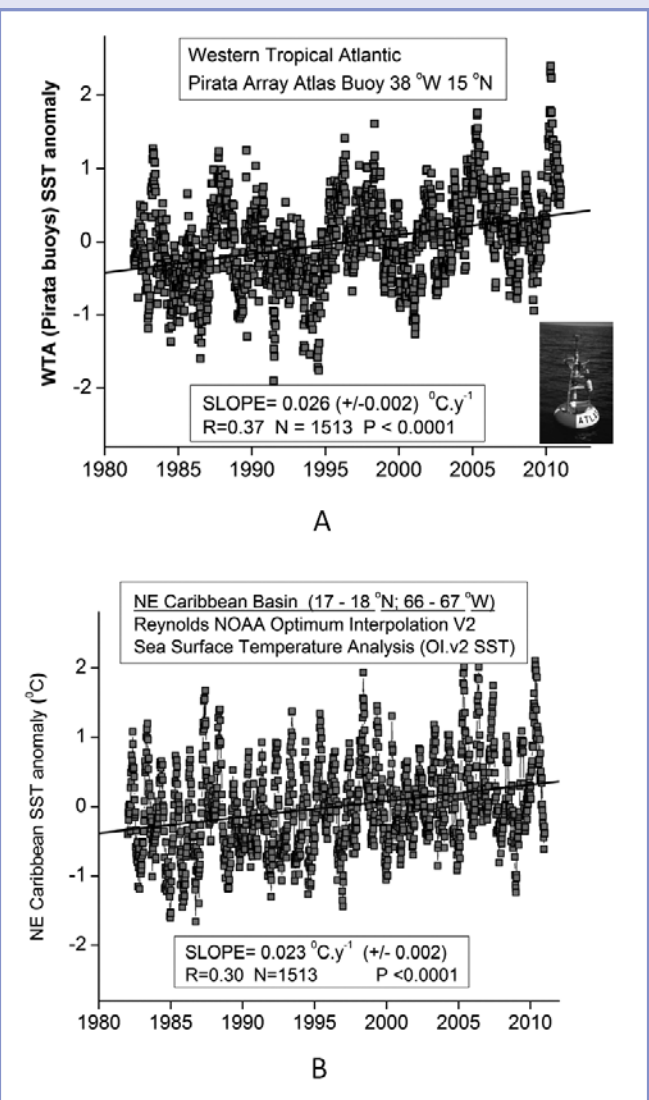


Figure 40: (a) PIRATA data analysis for sea surface temperature trends. The data yields a slope of 0.026 (+/-0.002)°C per year; (b) Reynolds NOAA Optimum Interpolation V2 Sea Surface Temperature Analysis anomaly data from OI.v2 SST product for the CaTS region (Northeastern Caribbean) from 1982 to 2011. A linear fitting of the data yields a slope of 0.023 (+/- 0.002)°C per year.

of data. A spatial map of linear trend regression is made and temporal plot of linear trend for a Puerto Rican area-average is analyzed. Sea surface and subsurface temperature measurements were collected with PMEL electronics coupled to a YSI (Yellow Springs Instruments) thermistor 46006 with a resolution of 0.001°C (±0.02°C). SST data (1981 to 2010) analysis of the West Tropical Atlantic PIRATA station data yields a slope of 0.026 (+/-0.002) °C per year (figure 40a).

A second data source to assess observed sea surface temperature trends for Puerto Rico was

used by Morell. The optimum interpolation sea surface temperature analysis product (OI.v2 SST) is operationally issued weekly for 1 degree grid for the global ocean. The product results from the analysis of direct measurements as well as satellite observation derived SST estimates. The latter is adjusted for biases using the method of Reynolds (1988) and Reynolds and Marsico (1993). A description of the OI analysis can be found in Reynolds and Smith (1994) and the modifications leading to the version here utilized can be found at: <http://www.ncdc.noaa.gov/oa/climate/research/sst/papers/whats-new-v2.pdf>. This method yielded a slope of 0.023 degrees (± 0.002) $^{\circ}\text{C}$ per year from 1982 to 2011 (figure 40b).

SST analysis was also conducted for the PRCCC by Dr. Mark Jury. Observed SST trends near Puerto Rico were assessed to be $0.008^{\circ}\text{C}/\text{yr}$ over the period 1900 to 2010. This trend is projected to

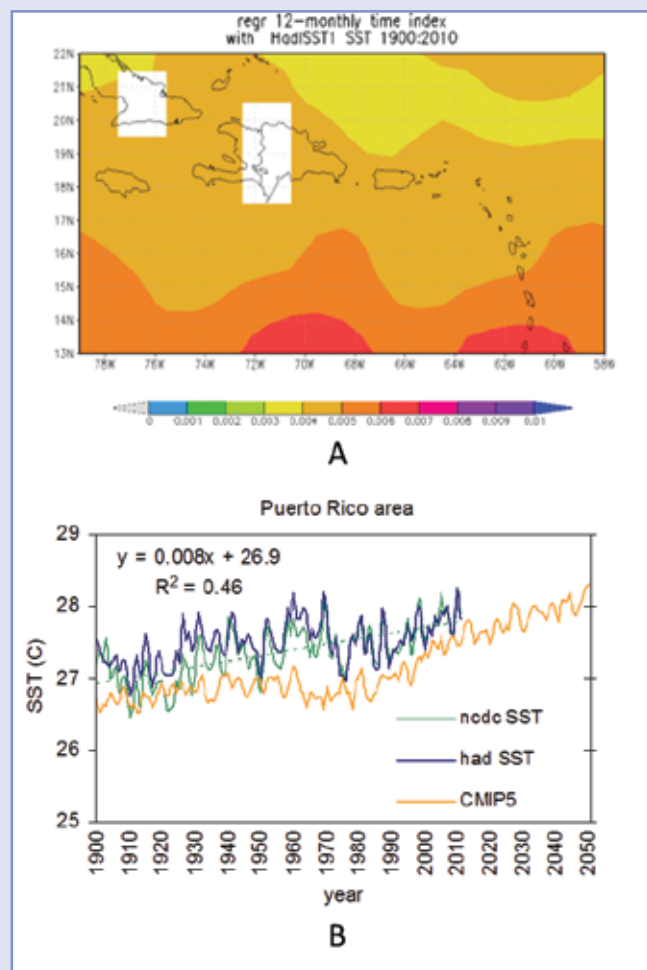


Figure 41: (A) Past trends in SST mapped over the Caribbean and for the Puerto Rico area; (B) including CMIP5 ensemble average projected data.

remain similar in the 21st century according to the CMIP5 ensemble average (figure 41). Part of the reason for the low rate of change is that **the ocean is warming much slower than the atmosphere**. Also in the Puerto Rico record, the 1970s are rather cool. If only data for recent decades are considered, then the SST trend is higher ($0.026^{\circ}\text{C}/\text{yr}$), a rate consistent with Winter et al (1998) for inshore waters on the southwest coast (1966-1995) and the analysis by Morell described above.

The map of SST trends (figure 41) shows that SST warming trends south of Puerto Rico are faster than to the north. Sub-surface temperatures are warming faster than the surface, particularly south of Puerto Rico. The higher rate of warming south of Puerto Rico (figure 42) is related to a significant weakening of trade winds (as they travel over the higher elevations of the central mountain range), evaporation and westward currents (Jury 2011). The Caribbean has warmed faster than the Atlantic.

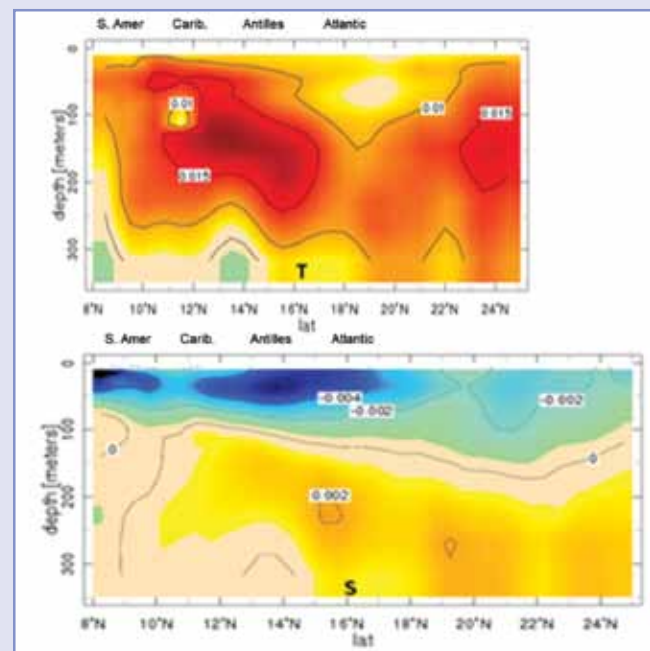


Figure 42: (top) Past trends in subsurface sea temperatures ($^{\circ}\text{C}/\text{yr}$) and (bottom) salinity (ppt/yr) in N-S depth section from SODA reanalysis 1958-2007. Courtesy of Jury (2011).

Future Sea Surface Temperature Projections for Puerto Rico

An analysis by Dr. Jorge Corredor from CariCOOS for the PRCCC used the OI v2 SST trend (0.023°C/yr) and climatology obtained at the Caribbean Time Series Station ($17^{\circ}36' \text{N } 67^{\circ}\text{W}$; 1994 – 2007 monthly data). Corredor found that an increase of 1.17°C (2.1°F) over a 50 year period can be expected. Additionally, SST above the threshold for coral bleaching will be exceeded over a third of the year (Hoegh-Guldberg 1999) and the threshold for deep convection storm formation will be exceeded throughout the year (Hoegh-Guldberg 1999) (figure 43).

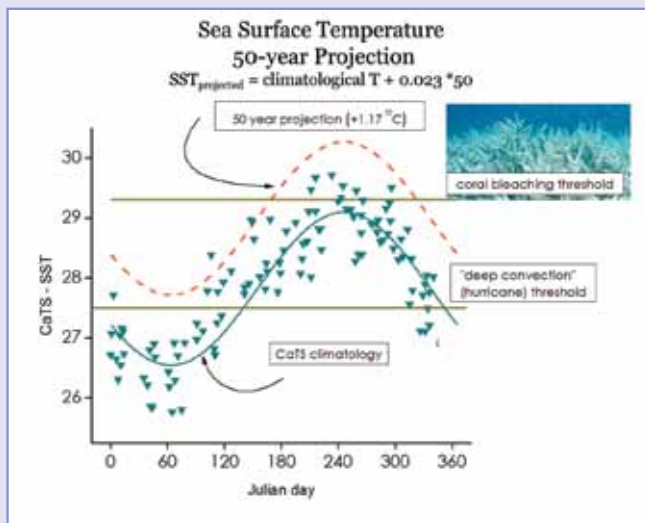


Figure 43: OI v2 SST trend (0.023°C/yr) and climatology obtained at the Caribbean Time Series Station ($17^{\circ}36' \text{N } 67^{\circ}\text{W}$; 1994 – 2007 monthly data). An increase of 1.17°C (2.1°F) over a 50 year period can be expected.

Summary of Historic Trends and Projections for Sea Surface Temperatures

Caribbean sea surface temperatures have warmed by 1.5°C over the last century (IPCC 2007). Three SST analyses were conducted for the PRCCC. The first used the West Tropical Atlantic Prediction and Research Moored Array (PIRATA) station data and found an increase of 0.026 (± 0.002) $^{\circ}\text{C}$ per year from 1981 to 2010. The second analysis used the optimum interpolation SST analysis product (OI.v2 SST), which is operationally issued

weekly for 1 degree grid for the global ocean, and found an increase of 0.023 degrees (± 0.002) $^{\circ}\text{C}$ per year from 1982 to 2011. The third analysis found observed SST trends near Puerto Rico to be 0.008°C/yr over the period 1900 to 2010 (figure 41). Different SST trends are found depending on the length of time analyzed. If only data for recent decades are considered, then the SST trend is higher. However, all three trends show a clear warming. SST warming trends south of Puerto Rico are faster than to the north and sub-surface temperatures are warming faster than the surface, particularly south of Puerto Rico. The higher rate of warming south of Puerto Rico is related to a significant weakening of trade winds (as they travel over the higher elevations of the central mountain range), evaporation and westward currents (Jury 2011). The Caribbean has warmed faster than the Atlantic. This observed warming trend is projected to remain similar in the 21st century according to two studies conducted for the PRCCC. One showing that an increase of 1.17°C (2.1°F) over a 50 year period can be expected. Additionally, SST above the threshold for coral bleaching will be exceeded over a third of the year.

Sea Level Rise

Observed Sea Level Rise Trends in Puerto Rico

The sea level at any moment is the sum of the mean sea level, plus the state of the tides, wave set-up, responses to air pressure and near shore winds, and may sometimes be affected by additional flows of water from the land. For scientific and societal purposes it is useful to group these influences under changes to average conditions and changes to extreme hazard events. Under climate change (both natural and anthropogenic) both mean conditions and extremes will change over a range of time scales and spatial scales (figure 44).

Globally speaking, global sea levels have been rising via thermal expansion resulting from warming of the oceans, as well as freshwater input from the melting of a majority of Earth's

glaciers and ice sheets. Global sea level on average has risen by 120 meters over the last 18,000 years. The average rate during the last 3,000 years has only been about 1-2 centimeters (cm) per century, but the past century saw an average of 17 ± 5 cm of sea level rise around the

interglacial age on Mona Island and measured the elevation of the last interglacial reef and since they are 4 to 6 meters above present, there are indications of little or no uplift. On the other hand, there is evidence of coseismic uplift during the Holocene (the past ~10,000 years) on

		Timeframe	Cause	Predictability
Net extreme event hazard	Recurring extremes (Storm surge, storm tide)	Hours-days	Wave, winds, storm strength, coastal and offshore form	Moderate from observations; future very uncertain
	Tide ranges	Daily-yearly	Gravitational cycles	Very predictable
	Regional sea level variability	Seasonal-decadal	Wave climates	Not well known
Net regional mean sea-level rise (SLR)	Regional net land movements	Decades-millennia	Tectonics and compression	Predictable once measured
	Regional eustatic sea level rise	Months-decades	Ocean warming, currents, climate	Existing effects observable, future effects uncertain
	Global mean sea level rise	Decades-centuries	Climate change (temperature, ice melt)	Short term extend current rates, future changes uncertain especially beyond 2011

Figure 44: Main contributors to net extreme event hazard and regional mean sea-level rise. Adapted from Jones et al. 2009.

the south and west coasts of Puerto Rico (Prentice and Mann 2005). In some areas in these two regions Prentice and Mann found evidence of young marine deposits, well above high-tide level. It is unknown, however, if these deposits represent coseismic events or tsunamis. In order to answer that question, last-interglacial marine deposits would need to be found in these areas of Puerto Rico in order to get a long-term uplift rate for the south and east coasts.

globe (Bindoff et al. 2007). The long-term rise has been driven by polar ice melt and thermal expansion of the oceans (Cayan et al. 2006). The United States Geological Survey has been researching the sea level history of Puerto Rico using interglacial sea level deposits. Their research has shown that sea levels around Puerto Rico over the past 120,000 years have decreased by more than 6 meters. Because sea level rise or fall is influenced by the rising or sinking of land masses, USGS also looks for tectonic “uplift” (land masses increasing elevation, slowing the rate of sea level rise) and “subsidence” (land masses sinking increasing the rate of sea level rise). The deposits USGS has analyzed are at (or no more than slightly above) the sea level at which they formed (+6 m, relative to present sea level, 120,000 years ago), indicating that on the northern and northwestern coasts of Puerto Rico uplift has been very minimal, if these coasts have been uplifted at all (Muhs 2004). USGS has also dated corals of the last-

During the 20th century the world’s oceans have been absorbing more than 80 percent of the heat added to the climate, causing ocean water to expand and sea levels to rise. Between 1993 and 2003 thermal expansion was the largest contributor to sea level rise. Melting glaciers and losses from the Greenland and Antarctic ice sheets have also contributed to recent sea level rise. The average global sea level has been rising steadily, at an average rate of 1.8 mm/yr since 1961 and at an increased rate of 3.1 mm/yr since 1993 (Pachauri et al. 2007). Relative or local sea level, which takes into account natural or human-caused changes in the land elevation such as tectonic uplifting and land subsidence (sinking), is showing an upward trend at sites monitored in the Caribbean. The current rate of sea level rise in the Caribbean is 10 cm (3.9 in) per century ((USGCRP) 2001).

Tide gauge records from Isla Magueyes (south coast of PR) and from San Juan (north coast of PR) contain the longest sea level time series in the U.S. Caribbean (figure 45). For the PRCCC, Dr. Jorge Capella of CariCOOS analyzed 56.7 years of monthly mean sea level for Isla Magueyes and 49.4 years for San Juan. Gaps in the time series were identified and filled, and sea level trends were calculated from the resulting time series.



Figure 45: CariCOOS tide observation stations used in analysis. Tide Observation Locations in PR. Active links to all NOAA tide gauge stations in the northeastern Caribbean Sea: http://www.caricoos.org/drupal/tides_map The long-term Isla Magueyes (at La Parguera, Lajas PR) and San Juan stations are circled in blue as these were the stations used for the relative sea level rise analysis conducted for Puerto Rico.

Regional trends and accelerations were then compared to global estimates and to local estimates published in the local press in 2007. Dr. Jorge Capella analyzed trend-acceleration estimate discrepancies through the spectral analysis of the time series. Full-series sea level trends up to September 2011 are 1.35 mm/yr at Isla Magueyes and 1.65 mm/yr at San Juan (figure 46 and 47), consistent with global trends. A deceleration of these trends during the last decade (2001-2011) results in current trends of 1.1 mm/yr at Isla Magueyes and 0.5 mm/yr at San Juan. Net changes in sea level between 2011 and 2100, extrapolated from existing data (full time series), are in the order of 5-6 inches. When comparing Puerto Rico's trend to the global 1.7-1.8 mm/yr trend during the 20th century we can deduce that Puerto Rico has experienced similar trends over the second half of the 20th century and that a slight trend acceleration has been observed over the latter part of the 20th century. However, when compared to the entire last decade Puerto

Rico has experienced a deceleration and the acceleration-deceleration changes could be caused by yet unresolved low-frequency dynamics of the system.

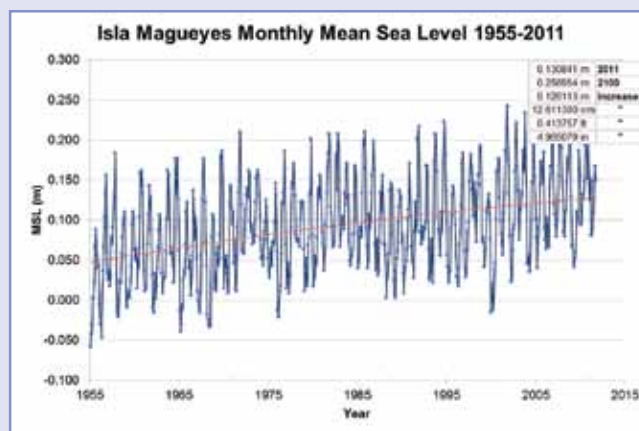


Figure 46: Tide gauge data from Isla Magueyes show that from 1955 to 2011 the south coast of Puerto Rico experienced a 1.35 mm/yr rise in sea levels. From 2001 to 2011 the South Coast experienced a 1.10 mm/yr rise. Source: Dr. Jorge Capella 2011, UPR/CariCOOS

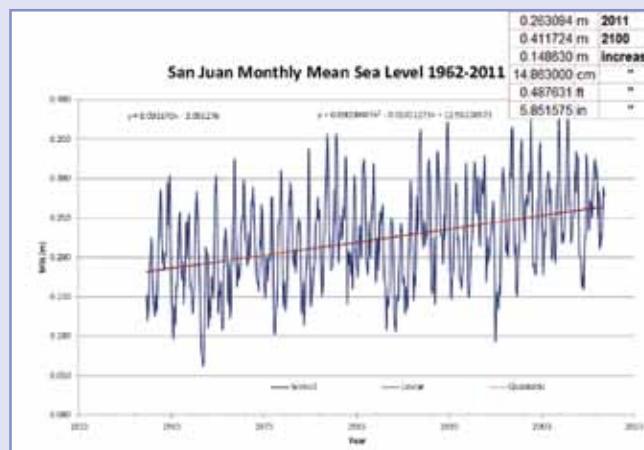


Figure 47: Tide gauge data from San Juan show that from 1962 to 2011 the North Coast of Puerto Rico experienced a 1.65 mm/yr rise in sea level. From 2001 to 2011 the rise was 0.50 mm/yr. Source: Dr. Jorge Capella 2011, UPR/CariCOOS.

A second sea level rise study was conducted for the PRCCC by UPR Professor Aurelio Mercado using two methods. First, a Low Pass Butterworth Filter with a sharp cut-off frequency at 1/10 cycles per year was used to analyse the NOAA tide gauge data. This means that oscillations with periods less than 10 years were filtered out. The results show that since about 2007 the low-passed curves flattened out and the low-frequency oscillations of periods of about 13 years seen in the past disappeared during the last decade. Using the last

common peak observed around 1995, the low-passed curves should have started to go down by around 2007. But instead both low-passed curves continued to go up slightly and flattened out, as mentioned, for at least five years now. The second method used was a least-squares fit starting in 1990. The results show that for the San Juan tide gauge the trend increases from 1.63 mm/year to 2.21 mm/year (figure 48). The Magueyes tide gauge also showed an acceleration

up from 1.5 mm/year to 2.67 mm/year, showing an acceleration in sea level rise as also detected by Dr. Capella. These accelerations are in accord with satellite data (since 1993) and with Sallenger et al. (2012) though not to the same magnitude of up to 6mm/year sea level rise as seen from 1970-2009 in the northeast hotspot for sea level rise in the Northeast of the continental United States (Sallenger et al. 2012).

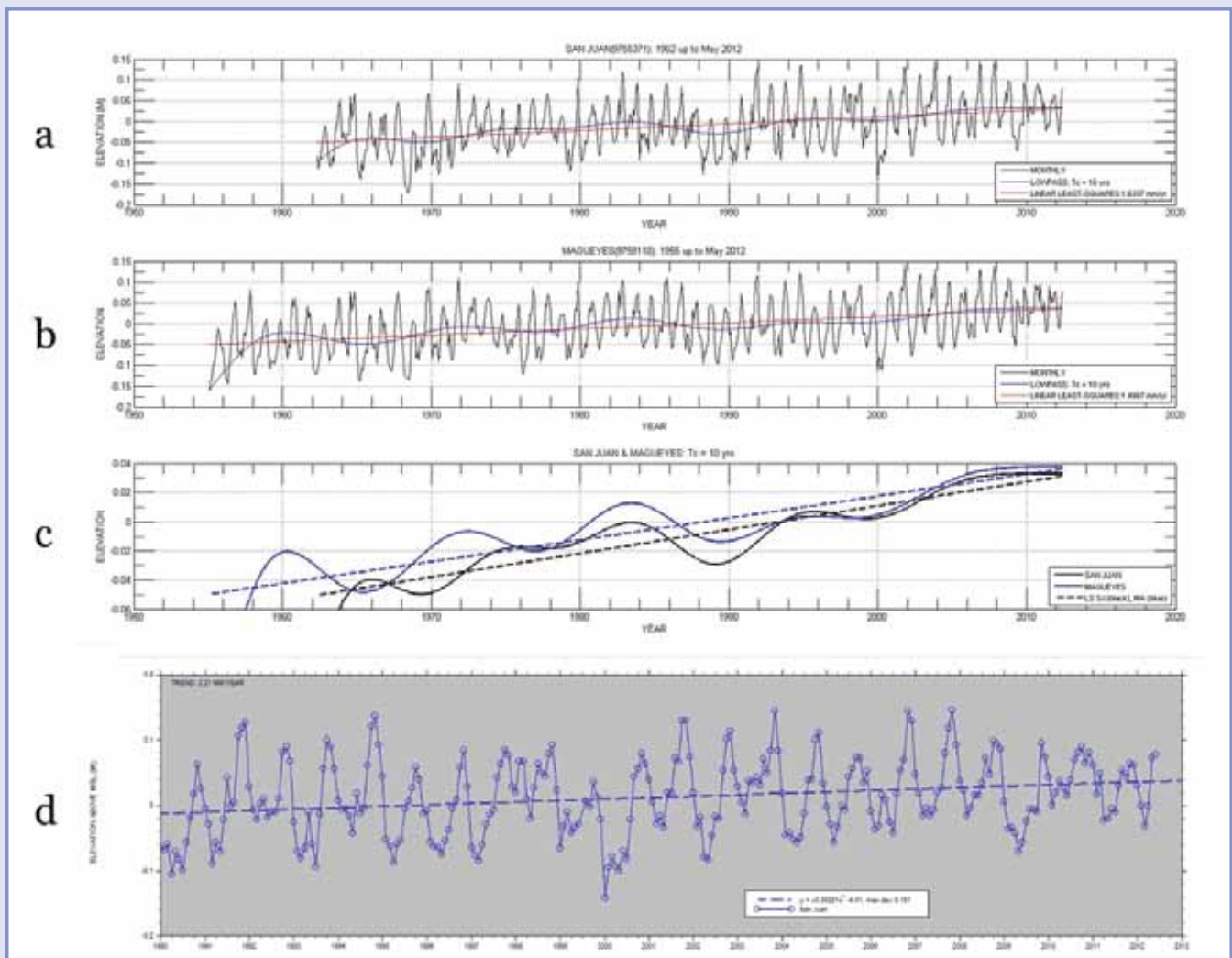


Figure 48: (A) San Juan 1962 to May 2012. Black is monthly data. Blue is Lowpass $T_c=10$ years, Red is Linear least-squares regression; (B) Magueyes (1955 to May 2012). Black is monthly data. Blue is Lowpass $T_c=10$ years, Red is Linear least-squares regression; (C) San Juan and Magueyes $T_c=10$ years. Black is San Juan and Blue is Magueyes. Dashed black line is least squares for San Juan and blue dashed line is least squares for Magueyes; (D) San Juan tide gauge data from 1990 to May 2012 showing a 2.21 mm/year acceleration.

A third sea level rise analysis was conducted for the PRCCC by Dr. Mark Jury. Tide gauge data was analyzed for Puerto Rico by combining the Isla Magueyes and San Juan data and including a MIROC (IPCC CMIP3) ocean model forecast with A1B scenario (mid-high IPCC emission scenario). He found the sea level increase in Puerto Rico to be 1.4 mm/yr, consistent with the analysis conducted by Dr. Jorge Capella (figure 49).

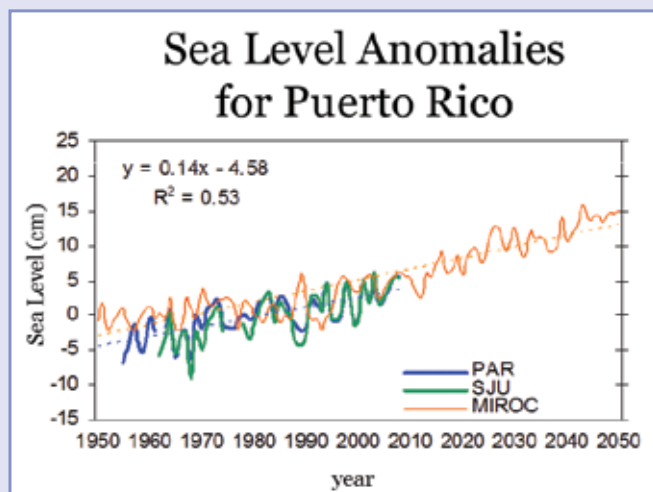


Figure 49: Observed and projected sea level anomalies for Puerto Rico. Blue line is sea level rise data for the south coast, green line is sea level rise data for the north coast, and the orange line is the MIROC ocean model forecast with A1B scenario (mid-high IPCC emission scenario).

As a result of the already observed sea level rise as well as weak shoreline management practices, coastal erosion is causing a retreat of the coastline of up to one meter per year (1.0 m/yr) in some sectors of Puerto Rico, according to a USGS report that considered sequences of past aerial photos (Thieler et al. 2007). See figure 50 for an example from Rincon on the west coast of Puerto Rico.

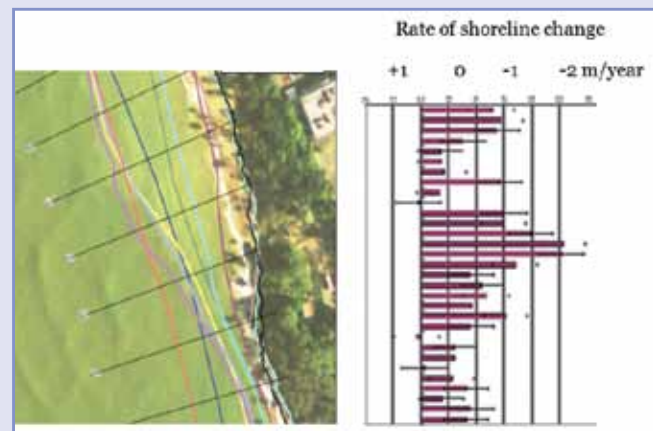


Figure 50: Coast lines approximately every 10 year near Rincon, PR, with matching coastal recession graph.

Future Sea Level Rise Projections for Puerto Rico

The extent of sea level rise is dependent on interactions between the climate system, thermal expansion of ocean water, the breakup of polar ice, melting of glaciers and permafrost and local geological height changes due to tectonic plate movement. The effects of rising sea level will be amplified by the short-term impacts of storm surges. The IPCC refined their 2001 projections for climate change for the fourth assessment report in 2007. Projected climate change for the second half of this century depends on the level of future heat-trapping emissions. The IPCC based its projections on six emission scenarios, running each one through sophisticated climate simulation programs. The models project that by the end of this century (2099), the global average sea-level will rise between 0.18 and 0.59 meters (0.6ft and 1.9ft) above the 1980–1999 average. An additional 0.1 to 0.2 meters of rise could derive from accelerated polar ice melt; providing an upper range of 0.79 meters.

Due to ongoing scientific uncertainty, the IPCC notes that the following factors are not fully reflected in its sea level rise models that were used for the fourth assessment report:

- **Carbon dioxide uptake.** Evidence suggests that warming tends to reduce land and ocean uptake of atmospheric carbon dioxide, increasing the portion of carbon dioxide emissions that remain in the atmosphere. This would result in further warming and cause additional sea-level rise.
- **Ice sheet instability.** Recent observations show that meltwater can run down cracks in the ice and lubricate the bottom of ice sheets, resulting in faster ice flow and increased movement of large ice chunks into the ocean. This process, and others related to ice flow dynamics, directly contributes to sea-level rise. Some models suggest a warming of $>3^{\circ}\text{C}$ above today's global average temperature that would initiate irreversible melting of the Greenland ice sheet, contributing up to 6

m of sea-level rise. The risk for crossing this threshold could occur within our generation, while the consequences would be felt by future generations.

The IPCC Special Report on Climate Extremes (2010) states that it is *very likely* that mean sea level rise will contribute to upward trends in extreme coastal high water levels in the future. There is *high confidence* that locations currently experiencing adverse impacts such as coastal erosion and inundation will continue to do so in the future due to increasing sea levels, all other contributing factors being equal. Similarly, according to the Australian climate impacts assessment, “many people imagine that sea level will rise gradually, like water rising in a bathtub. This is unlikely. Coastal waters will continue to be affected by extreme tides, storm surges and storm tides, which may become increasingly severe in many places as a result of climate change. These factors will interact with sediments in coastal systems. The combined effects of rising sea levels and changes in extremes will produce much greater risks in the coastal zone than any single factor” (Australia 2009).

The predicted rates for regional sea level rise in the Caribbean are the same as the global predictions (around 1.8 mm/year) (IPCC 2007). According to the IPCC 2007, “sea levels are likely to rise on average during the century around the small islands of the Caribbean Sea, Indian Ocean and northern and southern Pacific Oceans”.

Recent projections of global sea level rise (Pfeffer et al. 2008, Vermeer and Rahmstorf 2009, Grinsted et al. 2010, Jevrejeva et al. 2010) have generally been significantly higher than estimates from the 2007 IPCC Report. Combining climate modeling and paleoclimatic data, total sea-level rise of about 2.0 m by 2100 has been estimated as the maximum that could occur, with a best estimate of about 0.8 m (Pfeffer et al. 2008). Even newer estimates suggest that global sea level could rise approximately 3.26 meters from the melting of the West Antarctic Ice Sheet. If perturbations in

Earth’s rotation and shoreline migration are taken into account, the Pacific and Atlantic coasts of the United States, could be impacted by sea levels 25 percent higher than the global mean at the end of the century (Mitrovica et al. 2009). All these Figures are substantially higher than the model-based estimates in the IPCC Fourth Assessment

Sea-Level Rise Projections (for 2100)	
IPCC 2007 Fourth Assessment Report	0.18 m to 0.59 m, excluding accelerated ice discharges from the Greenland and Antarctica ice sheets
Puerto Rico linear trend projection	< 0.4 m (based on a “linear trend” projection)
Rahmstorf (2007)	0.8 m – 1.7 m
Pfeffer et al. (2008)	0.8 m (“best estimate”) – 2.0 m
Vermeer and Rahmstorf (2009)	0.75 m – 1.9 m
Grinsted et al. (2010)	0.9 – 1.3 m
Alley (2010)	1.0 m – 5.0 m
Hansen (2011)	5.0 m
U.S. Army Corps of Engineers	Federal Planning Guidance uses scenarios of 0.5m, 1.0 m, 1.5 m

Figure 51: Summary of projections for how high seas could rise by the year 2100 globally and in Puerto Rico

Report. See figure 51 for a summary of sea level rise projections for globally and in the Caribbean.

The U.S. Army Corps of Engineers (USACE) conducted an analysis for the PRCCC to project possible future sea level rise for the North and South coasts to 2165 (figures 52 and 53). The USACE sea level rise curves are computed using the global rate of sea level rise (1.7 mm/year), NOAA tide gauge data for Puerto Rico (1.65 mm/year rise for San Juan since 1962 and 1.35 mm/yr rise for Magueyes Island since 1955), and the estimated local vertical land movement rates of -0.02 mm/yr for San Juan and -0.49 mm/year for Isla Magueyes.

The Figures show a 50 year and 100 year planning horizon for adaptation with sea level rise estimates ranging from 0.07 to 0.57 meters (0.20 to 1.87 feet) above current mean sea level by the year 2060 and between 0.14 and 1.70 meters (0.40 to 5.59 feet) above current mean sea level by the year 2110. Due to the variability and uncertainty in the system it is important to project sea level rise across a range and plan for all possible future scenarios when possible, rather than just the lower bound conservative estimate.

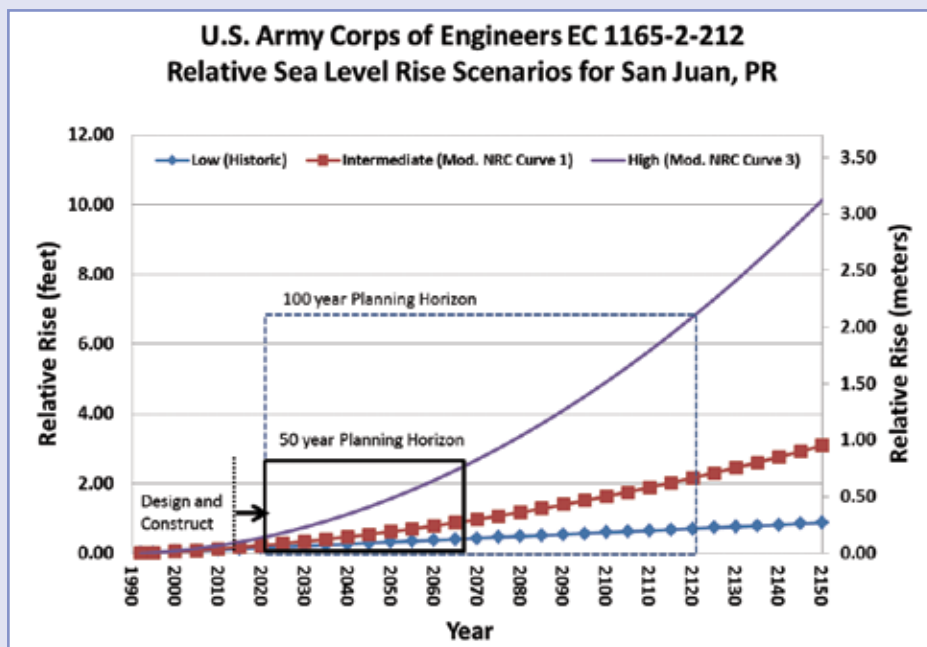


Figure 52

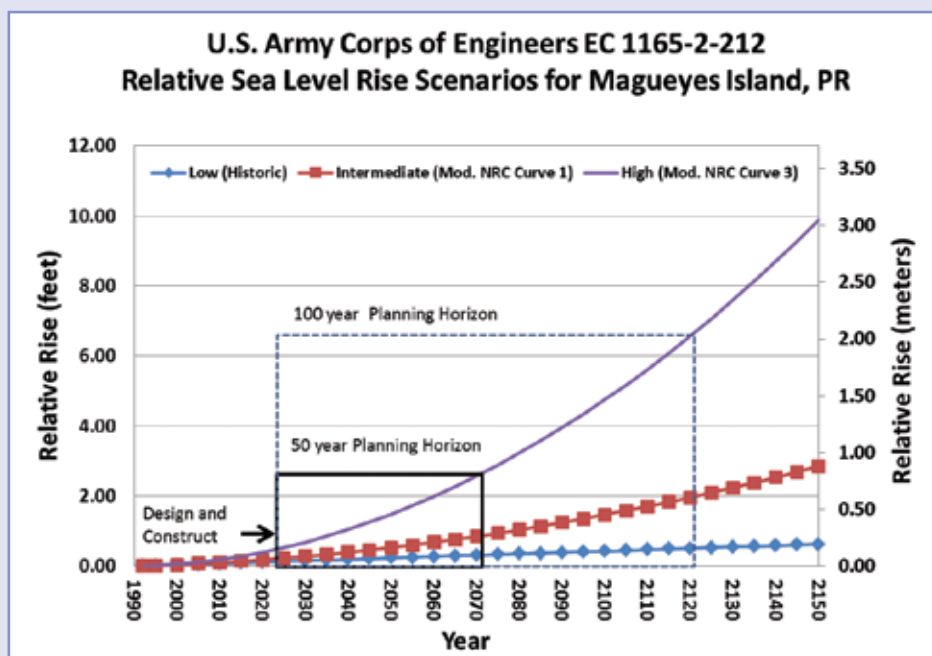


Figure 53

Figures 52 and 53: The U.S. Army Corps of Engineers' sea level rise curves are computed using the global rate of sea level rise (1.7 mm/year), NOAA tide gauge data for Puerto Rico (1.65 mm/year rise for San Juan since 1962 and 1.35 mm/yr rise for Magueyes Island since 1955), and the estimated local vertical land movement rates of -0.02 mm/yr for San Juan and -0.49 mm/year for Isla Magueyes. The Figures show a 50 year and 100 year planning horizon for adaptation with sea level rise estimates ranging from 0.07 to 0.57 meters (0.20 to 1.87 feet) above current mean sea level by the year 2060 and between 0.14 and 1.70 meters (0.40 to 5.59 feet) above current mean sea level by the year 2110.

Knowledge Gaps and Future Research Needs

The Puerto Rico Coastal Zone Management Program is funding a new sea level rise scenarios modeling effort to be conducted by a team of modelers from the University of Puerto Rico-Mayaguez led by Profesor Aurelio Mercado.

Project objectives are to use and improve mesh using the latest high-resolution NOAA/NGDC DEM for Puerto Rico especially made for coastal flood mapping and assuming “worst-case scenario flooding” where elevations are relative to mean high water (MHW), the team will use the dynamically coupled (two-way coupling; this refers to the procedure of periodically inputting radiation stresses from the wave model to the storm surge model and periodically inputting water elevations from the storm surge model to the wave model) models ADCIRC+ unSWAN with the above mesh to upgrade the Puerto Rico Storm Surge Atlas showing coastal inundation extensions as a function of hurricane category. The internal hurricane wind model in ADCIRC or a modified version can be used.

The modeling team will study the flooding implications of sea level rise. This will be carried out by increasing the water depths by 0.5 and 1.0 m, and running the models over the new vertical datum. Increasing the water depths by adding a constant to the vertical elevations will move the MHW shoreline a certain distance inland, allowing for farther penetration of the surge, including wind waves. The Atlas runs will be re-run with these two new starting elevations.

PRCZMP will use the results of the project to assess potential impacts of sea level rise on coastal communities, infrastructure and coastal ecosystems and biodiversity.

Summary of Observed and Projected Trends for Sea Level Rise

Both mean conditions and extremes of sea level will change over a range of time scales. Analyses of Puerto Rico’s tide gauges show a rise of at least 1.4 mm/year which is expected to continue and possibly will accelerate. If the trend continues linearly, with no rate acceleration, by 2100 the sea level around Puerto Rico will have risen by at least 0.4 meters. The risk of large sea-level rise already in the 21st century is now estimated to be much greater than the IPCC estimates of 0.18-0.59 meters. According to the Australian climate impacts assessment, “many people imagine that sea level will rise gradually, like water rising in a bathtub. This is unlikely. Coastal waters will continue to be affected by extreme tides, storm surges and storm tides, which may become increasingly severe in many places as a result of climate change. These factors will interact with sediments in coastal systems. The combined effects of rising sea levels and changes in extremes will produce much greater risks in the coastal zone than any single factor” (Australia 2009). Based on this information and future projections for sea level rise the PRCCC recommends planning for a rise of 0.5-1.0 meters by 2100. It is no longer a question of whether the coasts of Puerto Rico and many port cities in the Caribbean will be inundated, but rather it is a question of when and by how much.



Tropical Storms and Hurricanes

Observed Trends in Tropical Storms and Hurricanes in Puerto Rico

Warmer sea surface temperatures around the North Atlantic, Caribbean and Puerto Rico are likely to increase the intensity of pulsated rainfall, wind and storm surge events like hurricanes and tropical storms. For instance, the most active hurricane season ever recorded in the Atlantic Ocean – which included devastating storms like Hurricane Stan in Guatemala and Hurricane Katrina in New Orleans – occurred during the record breaking sea surface temperatures of 2005 (Trenberth and Shea 2006). The 2011 hurricane season was the third most active on record, tied with the 2010 season (Strachan 2012), and brought unusual amounts of rain to Puerto Rico during the late summer months.

mainly because the ocean is warming much slower than the atmosphere. Tropical cyclones within 500 km of Puerto Rico are plotted with sea surface temperatures in figure 54 (printed with permissions from Jury 2011). The acceleration of the Hadley circulation and related increase in upper westerly wind shear tend to suppress hurricane development and intensification.

The number of hurricanes reaching Puerto Rico has shown a decline over a period of 270 years from 1730 to 2005 (Nyberg et al. 2007), where “reaching” means hurricanes that have come close enough to cause a turbidity signal in coral growth (eg. Heavy run-off and strong currents). The analysis using proxy records shows that there have been on average 3 to 3.5 major hurricanes per year from 1730 to 2005 (figure 55).

A gradual downward trend is evident from an average of ~4.1 (1755 – 1785) to ~1.5 major

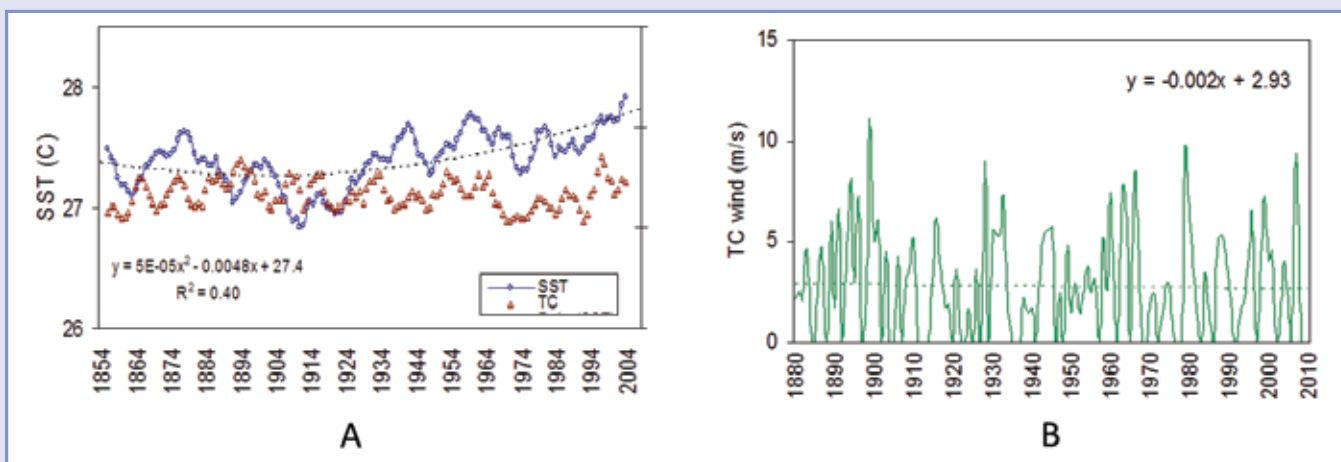


Figure 54: (A) NOAA hurdat number of tropical cyclones and SST within 500 km of Puerto Rico shown in red and blue respectively; (B) MIT observed mean wind anomaly fortropical cyclones passing within 100 km of Puerto Rico, showing weak downtrend since 1880.

Uncovering a clear long-term trend specific to Puerto Rico is challenging, however, due to data uncertainty being larger in the early part of the record compared to the satellite era beginning in 1965. The U.S. Global Change Research Program states that “even taking these factors into account, it is likely that the annual number of tropical storms, hurricanes and major hurricanes in the North Atlantic have increased over the past 100 years, a time in which Atlantic sea surface temperatures also increased. The evidence is not compelling for significant trends beginning in the late 1800s. Uncertainty in the data increases as one proceeds back in time” (CCSP 2008). Jury (2011) asserts that we have not seen a long-term increase in tropical cyclones in the Caribbean

hurricanes during the late 1960s to early 1990s, which experienced strong and few major hurricanes compared to other periods since 1730. Furthermore, the active phase of 1995-2005 is unexceptional compared to other high-activity periods and appears to represent a recovery to “normal hurricane activity” despite the increase in SST...indicating that increases in SST during the past 270 years have been offset by increased vertical wind shear which suppresses major hurricanes...A more rapid warming of the atmosphere relative to the ocean could have caused the anomalous calm period between the 1970s and 1990s” (Nyberg et al. 2007).

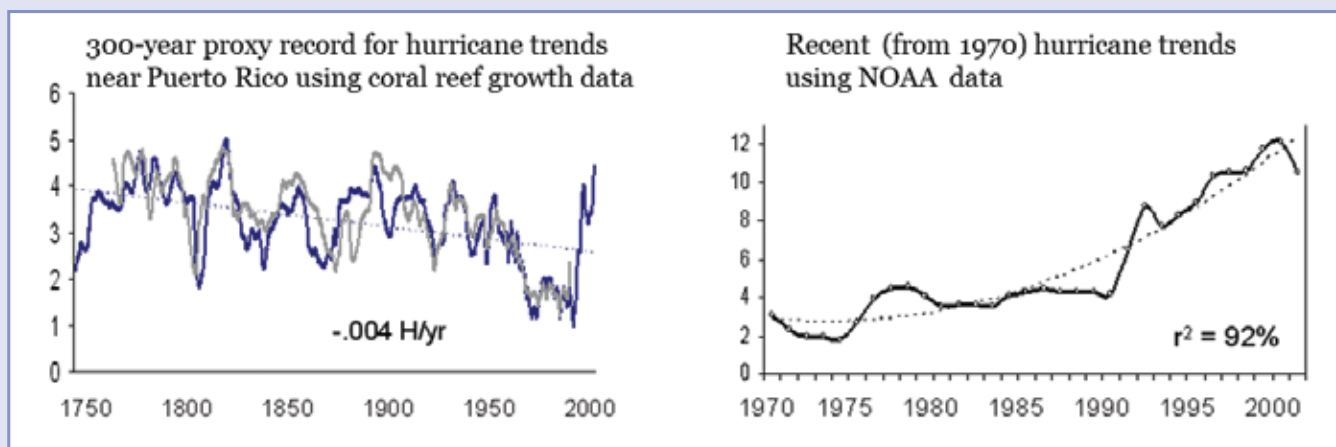


Figure 55: Intercomparison of hurricane trends near Puerto Rico, based on (left) coral reef growth in a 300-year proxy record (data from Nyberg et al. 2007), and NOAA hurdat data (right) over 30 yr. Notice that the coral reef growth data depicts a decrease in the number of hurricanes reaching Puerto Rico while the NOAA data shows an increase in different time eras.

Another study uses an inverse hurricane modeling technique to reconstruct flooding conditions for 29 overwash events (29 sediment layers) deposited over the past 5000 years at Laguna Playa Grande, a Puerto Rican lagoon located on the island of Vieques, to assess tropical cyclone frequency and intensity (Woodruff et al. 2008). This reconstruction indicates that although the Laguna Playa Grande record exhibits large-scale changes in hurricane frequency on centennial to millennial time scales, the magnitude of these events has stayed relatively constant. Over the last 5,000 years, no evidence exists for an anomalously large hurricane (or tsunami event) with the ability to transport coarse-grained sediment in greater amounts than historical hurricane events. A previous study by one of the authors (Donnelly and Woodruff 2007) showed that the category 5 San Felipe hurricane of 1928 appears to have been one of the most intense hurricanes to leave a deposit at the lagoon over the past 100 years. Their proxy reconstruction of the past 5,000 years of intense hurricane activity in the western North Atlantic also suggests that hurricane variability has been strongly modulated by El Niño during this time, and that the past 250 years has been relatively active in the context of the past 5,000 years (Donnelly and Woodruff 2007). Of course, the 29 Vieques events and the previous reconstruction are limited to those hurricanes that came close enough to the study sites to move sediment and therefore cannot be used solely to determined frequency and magnitude trends for Puerto Rico or the Caribbean.

For instance, another similar sediment-based study was conducted in Grand-Case Pond at Saint-Martin, north of the Lesser Antilles archipelago in the

Caribbean, that contradicts the hurricane record of the Vieques site. It's likely that this contradiction is due to two distinct storm paths in response to latitudinal shifts of the Intertropical Convergence Zone (ITCZ). The ITCZ position changes depending on climatic conditions and stronger storm activity over the Gulf coast and the inner Caribbean Sea is favored by a southern position of the ITCZ during dry periods. Another possibility is influences by the North Atlantic Oscillation. (Elsner et al. 2000) showed that when higher-than-average hurricane activity is recorded on the Atlantic coast, lower-than-average activity takes place in the Caribbean Sea and Gulf of Mexico, and vice versa. Researchers also did a comparison between the available records of hurricane landfalls during the last 5000 years in the Caribbean and Gulf of Mexico and found significant differences (Malaizé et al. 2011). Including data sets from Saint-Martin, the central coast and barrier reef of Belize, the Vieques lagoon, and compilation of several records from the U.S. coastline, they found that Saint-Martin hurricane frequency is higher (more than two times) within the 3700-2500 calendar years before present time interval (year cal. BP), than during 2500-1000 yr. cal. BP. A secondary peak was also observed between 750 and 300 yr. cal. BP. The studies from Belize show a close match with the Grand-Case record with an increase in hurricane activity between 5500 and 2500 yr. cal. BP, together with an exceptionally strong hurricane 500 years ago. By contrast with Vieques, the time intervals 3600-2500 and 1000-250 yr. cal. BP are two periods characterized by few intense hurricane strikes, whereas higher activity is recorded in between. On the U.S. coast, high activity is suggested during Medieval times, i.e. roughly between AD 900 and 1100.

Future of Hurricanes in Puerto Rico

In 2007, the IPCC stated, “there has been a large increase in the available analyses of changes in extremes. This allows for a more comprehensive assessment for more regions...projections concerning extreme events in the tropics remain uncertain. The difficulty in projecting the distribution of tropical cyclones adds to this uncertainty. Changes in extra-tropical cyclones are dependent on details of regional atmospheric circulation response, some of which remain uncertain.” Few models have simulated tropical cyclones in the context of climate change than those simulating temperature and precipitation changes and sea level rise, mainly because of the computational burden associated with high resolution needed to capture the characteristics of tropical cyclones. Accordingly, there is less certainty about the changes in frequency and intensity of tropical cyclones on a regional basis than for temperature and precipitation changes. Based on a range of models, it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures. There is less confidence in projections of a global decrease in numbers of tropical cyclones. The apparent increase in the proportion of very intense storms since 1970 in some regions is much larger than simulated by current models for that period (IPCC 2007: 9.5, 10.3, 3.8).

Despite the uncertainty surrounding El Niño, it is “likely” that hurricane rainfall and wind speeds will increase in the Caribbean in response to global warming (Kunkel et al. 2008), leading to an increase in the frequency of the most intense storms (Knutson et al. 2010).

Intense hurricanes and associated extreme wind events will more likely than not become more frequent due to expected warming of the upper ocean in the tropical cyclone genesis regions (IPCC 2007). That is, once formed, the fraction of hurricanes that become intense is expected to increase, along with the overall destructive

power. However, because future changes in other critical factors for tropical cyclones, including wind shear, the vertical temperature gradient in the atmosphere, and trends in ENSO and the Atlantic Multidecadal Oscillation are uncertain, it is unclear whether the total number of tropical storms will increase. However it is likely that the most probable tracks or trajectories of hurricanes will shift northward, as ocean water temperatures increase and intense hurricanes may change in the future.

The uncertainty about the effects of global warming on hurricane frequency (Landsea et al. 1996, Emanuel 1997, Henderson-Sellers et al. 1998, Emanuel 1999, Meehl et al. 2000) arises from the fact that the ocean is warming slower than the atmosphere. Therefore the uptake of heat energy necessary for hurricane development has to work against a downward gradient. Studying the effect of global warming at a time of doubled CO₂, (Bengtsson et al. 1997) concluded that there were significantly fewer hurricanes (especially in the Southern Hemisphere), but little change in the spatial distribution of storms. Nested high-resolution models (18 km) indicate a 5-11% increase in surface winds and a 28% increase in near-storm precipitation (Knutson et al. 1998, Knutson and Tuleya 1999) recent overall assessment regarding changes in hurricane strength suggests a 5-10% increase in tropical storm wind speed by the end of the 21st century (Henderson-Sellers et al. 1998).

The highest frequency of cyclones in the Caribbean occurs over the Gulf Stream east of Florida. There has been considerable decadal variability of hurricanes during this century (Reading 1990, Landsea et al. 1995, Diaz and Pulwarty 1997). Among other factors, decadal variability is affected by ENSO as well as changes in the meridional overturning thermohaline circulation (THC), the large-scale oceanic circulation in the Atlantic that involves the Gulf Stream. For example, (Gray et al. 1997) show that a weakening of the THC in the latter half of the century resulted in cooling of the Atlantic ocean along coast of NW Africa, increase in the low-level pressure gradient between this region

and the central Sahel, and a resulting reduction in the strength of the easterly waves that originate off the coast of Africa and propagate into the tropical Atlantic. These easterly waves are responsible for hurricane activity in the Caribbean. Therefore, changes in THC help regulate hurricane occurrence in the Caribbean as reflected in the correlation map (figure 56) with late summer rainfall.

Current global climate models are rather poor in simulating tropical cyclones, due in part to the coarse spatial resolution of these models.

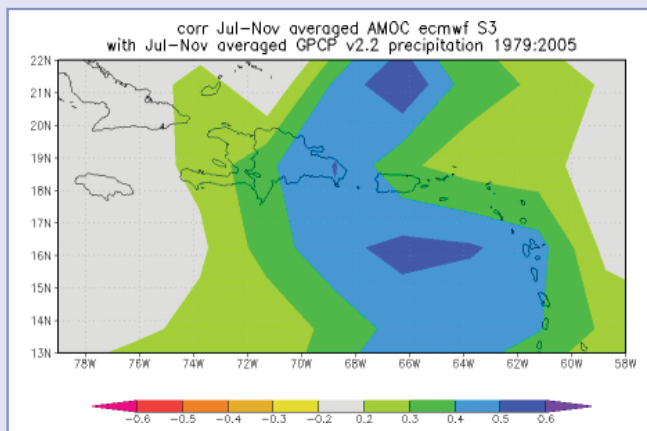


Figure 56: Cross-correlation between Global Precipitation Climatology Project (GPCP) precipitation data and the Atlantic Ocean subsurface meridional overturning thermohaline circulation (THC) in July–November season.

Short-term studies suggest that the frequency of strong tropical cyclones has increased globally in recent decades in association with increases in sea-surface temperature (Saunders and Lea 2008), and that anthropogenic GHG emissions are the main driver of observed changes in SST in tropical cyclogenesis regions (Santer et al. 2006).

A comprehensive reanalysis of satellite records has found significant upward trends in the strongest cyclones in all world regions during the last 30 years, with the largest increase occurring over the North Atlantic (Elsner et al. 2008). Another study has shown that the trend of increasing numbers of category 4 and 5 hurricanes for the period 1970–2004 is directly linked to the SST trend (Hoyos et al. 2006). It is important to note that the Atlantic Multi-decadal Oscillation underwent an upturn since the 1970s that contributes much of the observed

short-term trend in Caribbean–Atlantic basin hurricanes. The longer IPCC fourth assessment report climate simulations suggests that global warming will decrease tropical cyclone frequency, but that an increase in the frequency of the most intense events is to be expected (Emanuel et al. 2008). Similar results have been obtained by simulations with a high-resolution version of the ECHAM5 global climate model (Bengtsson et al. 2007). In summary, substantial uncertainties about past and future changes in cyclone activity remain, and the scientific debate on this subject is expected to remain very active.

In a related matter, the winter season brings storm waves to Puerto Rico’s north coast. Waves or swell from these huge North Atlantic storm centers easily traverse the 1,500 or so kilometers that separate the north coast of Puerto Rico from the northeastern coast of the United States. Although most of these westerly cold fronts pass quickly eastward, some storms may linger for several days, generating huge waves that actually outrank hurricane waves in terms of surge impact on the north coast (Snow 1943, Dickson 1978, Fitzgerald et al. 1994, Bush 1995).

Because climate change will affect both the ocean and atmosphere, we can assume that the winter swells, Puerto Rico experiences will change in some form. Intensity and frequency of swell producing storms near Bermuda has been studied for Puerto Rico. In New England it was found that storm waves were more frequent and intense, while fewer affected the Mid-Atlantic States, due to a northward shift in storm track (see also NECIA 2006). Ocean buoys in the past decade offer new data which has been analyzed for peak events such as in March 2008 (figures 57 and 58). In this case of high northwesterly swells at Puerto Rico, the jet stream makes a loop over Bermuda, and there is interaction between the cold northwesterly winds and the warm Gulf Stream. It takes about 2 days for the swells to reach Puerto Rico from Bermuda, leaving adequate time for warnings.

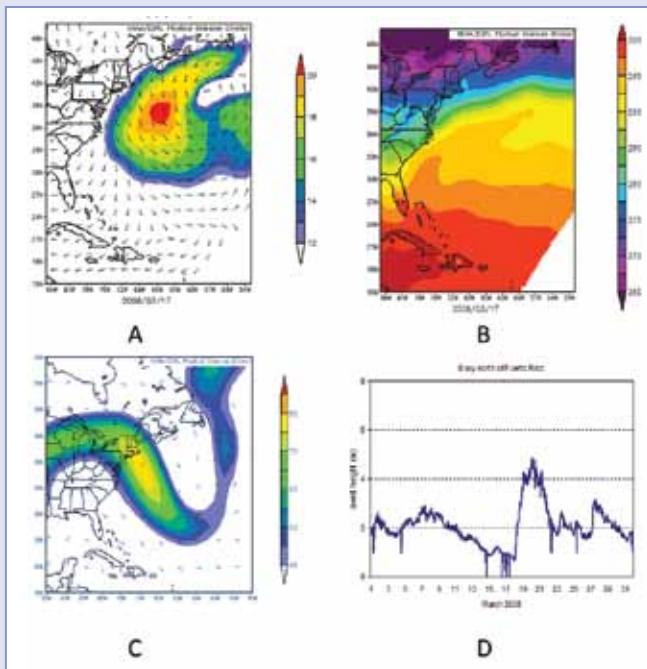


Figure 57: (A) surface winds from NARR for 17 March 2008, (B) surface temperatures (K), (C) upper level winds showing looping jet stream, and (D) hourly swell data from a buoy north of Puerto Rico for March 2008.

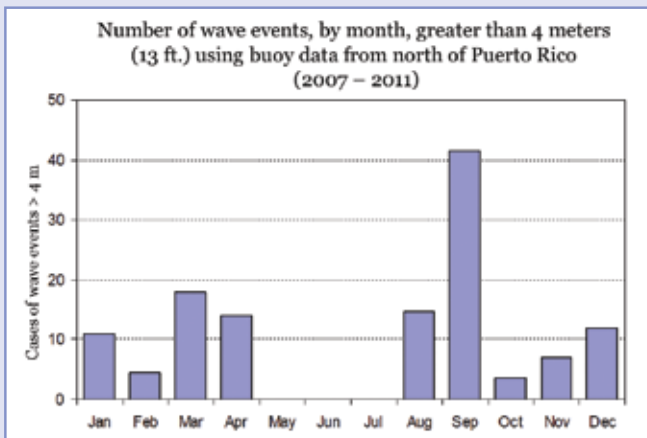


Figure 58: Monthly cases of waves above 4m measured at the buoy north of Puerto Rico (21N,65W) in the past 5 years.

Although ocean waves from winter storms are important, it is Caribbean hurricanes that pass south of the island which cause the most severe wind damage, sediment budget alteration and coastal erosion (coupled with poorly designed shoreline hardening structures). For example Hurricane David on 31 August 1979 caused certain western beaches (ie. Joyuda, Rincon) to lose more than 100 meters of horizontal extent as millions of cubic meters of sand were swept away by large southwesterly swells and currents. Many of these beaches never recovered from that event.

Knowledge Gaps and Future Research Needs

Due to the destructive nature of hurricanes coupled with modern societies propensity to develop in high-risk areas, more research is needed on past hurricane observations and future projections. In order to better understand the hurricane trends for Puerto Rico the tropical storms and hurricanes database that is kept by the Puerto Rico State Climatologist (records from 1515-2004) should be kept up-to-date and include more detailed information on past storm events using information from the written record, proxy records (paleo studies), and NOAA data. Additionally, more local studies that use oceanic heat content to assess past and future hurricane trends are needed. The oceanic heat content (OHC) is a variable to measure the amount of warm water available for the tropical cyclone to convert into energy. OHC has been shown to be a much better predictor than SST alone ([Zebiak 1989, Wada and Usui 2007a, Palmer and Haines 2009, Shay and Brewster 2010, Law 2011] as cited in Law 2011) and results suggest that Tropical Cyclone Heat Potential (TCHP), not SST, plays an important role in tropical cyclone intensity and its intensification (Wada and Usui 2007b).

Summary of Observed and Projected Trends for Tropical Storms and Hurricanes

Proxy reconstruction of the past 5,000 years of intense hurricane activity in the western North Atlantic suggests that hurricane variability has been strongly modulated by El Niño during this time, and that the past 250 years has been relatively active in the context of the past 5,000 years. Nyberg *et al.* (2007) suggest that major hurricane activity in the Atlantic was anomalously low in the 1970s and 1980s relative to the past 270 years. According to the U.S. Global Change Research Program, Atlantic tropical storm and hurricane destructive potential as measured by the Power Dissipation Index (which combines storm intensity, duration, and frequency) has increased. This increase is substantial since about 1970, and is likely substantial since the 1950s and 60s,

in association with warming Atlantic sea surface temperatures. There have been fluctuations in the number of tropical storms and hurricanes from decade to decade and data uncertainty is larger in the early part of the record compared to the satellite era beginning in 1965. Even taking these factors into account, it is likely that the annual number of tropical storms, hurricanes and major hurricanes in the North Atlantic have increased over the past 100 years, a time in which Atlantic sea surface temperatures also increased. The evidence is not compelling for significant trends beginning in the late 1800s as uncertainty in the data increases as one proceeds back in time. There is also evidence for an increase in extreme wave height characteristics over the past couple

of decades in the North Atlantic, associated with more frequent intense hurricanes and in the future there may be an increase in the intensity of winter swells reaching Puerto Rico's coasts. Current global climate models are rather poor in simulating tropical cyclones, due in part to the coarse spatial resolution of these models, however the IPCC fourth assessment report's climate simulations suggests that the North Atlantic and Caribbean will experience a decrease in tropical cyclone frequency, but an increase in the frequency of the most intense events. Other models concur. Due to the substantial uncertainties about past and future changes in cyclone activity the scientific debate on this subject is expected to remain very active.



Ocean Acidification

Trends in Ocean Acidification

As a result of the fossil carbon released to the atmosphere from human activities, seawater pH and carbonate saturation state (Ω) have decreased and will continue to decrease as the ocean continues to absorb carbon dioxide (CO_2). The oceans are currently taking up about one ton of anthropogenic CO_2 per year for each person on the planet (IPCC 2001). During the Industrial Revolution (1800) the concentration of atmospheric CO_2 was an about of 280 parts per million (ppm), and the global ocean pH averaged 8.16 (Ruttiman 2006). Currently, atmospheric CO_2 concentration has reached 395 ppm (Tans and Keeling 2012), and the average pH of the oceans has dropped to 8.05 (IPCC 2007). This is equivalent to an increase of CO_2 concentration of about 35% and a decrease in pH of 0.1 units (IPCC 2007). If we continue as business as usual path of fossil carbon release to the atmosphere, by the next century the average pH of oceanic waters will decrease by 0.3 – 0.4 units below the level of pre-industrial times (Kleypas et al. 2006b). The oceans play an important role in the uptake of anthropogenic CO_2 as it eventually absorbs an about 50% of the antropogenic CO_2 released to the atmosphere. As shown by the Hawaii Ocean Time

Series program long term increases in atmospheric CO_2 are clearly linked to an increase in CO_2 dissolved in surface water and corresponding decreases in pH (figure 59).

When CO_2 from the atmosphere dissolves in seawater, it reacts with water and produces carbonic acid (H_2CO_3). The carbonic acid dissociates and causes an increase in hydrogen ions (H^+) and bicarbonate (HCO_3^-). This chemical process has been named ocean acidification. Some of the free H^+ reacts with carbonate ions (CO_3^{2-}) causing a decrease in the concentration of these ions and in the saturation state (Ω) of seawater with respect to calcium carbonate minerals. As a result of the decrease in surface seawater carbonate saturation state, the rate of calcification in marine calcareous organisms and precipitation of carbonate minerals such as calcite, aragonite, and high-magnesium calcite decreases as well.

The saturation state of seawater with respect to carbonate mineral phases (calcite, aragonite, magnesium calcites) is defined as the ratio between ionic product of calcium and carbonate and the stoichiometric solubility product based on ion concentrations and has been described by the following equation:

$$(1) \quad \Omega = [\text{Ca}^{+2}][\text{CO}_3^{2-}]/K_{\text{SP}}^*$$

This measurement tells us about the thermodynamic capability for the mineral to precipitate or to dissolve. In other words, how easy it is to calcify. If Ω is greater than one, the mineral phase with respect to calcium carbonate will have favorable conditions to precipitate because the mineral is supersaturated, if Ω is less than one will be difficult to precipitate and could be subject to net dissolution because it is undersaturated, and is if Ω is one the system is said to be in equilibrium (net precipitation equals the net dissolution with respect to calcium carbonate mineral phases). Currently, in the tropics the aragonite saturation state of surface seawater ranges from 3 to 3.5 and it is expected to decrease for the next century from 2 to 2.5 (Orr et al. 2005, Atkinson and Cué 2008).

Potentially adverse consequences arising from the decrease of surface seawater calcium carbonate saturation state could imply serious problems for

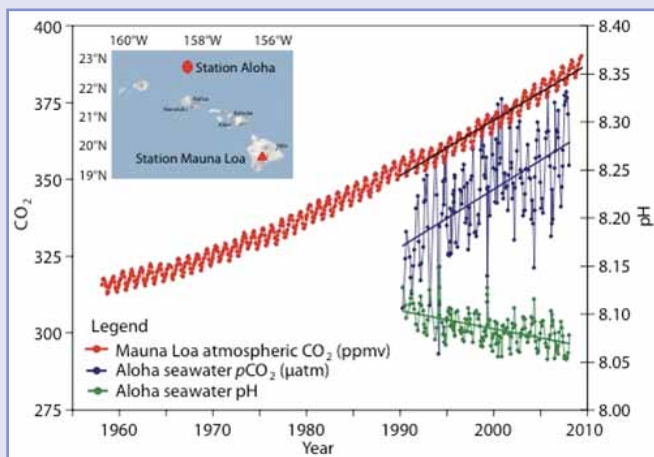


Figure 59: Time-series from 1960 to 2010 shows in red atmospheric CO_2 (ppmv) at Mauna Loa and in dark blue partial pressure of CO_2 at Ocean Station ALOHA. The Mauna Loa time series constitutes the longest record of direct measurements of CO_2 in the atmosphere. Mauna Loa data courtesy of Dr. Pieter Tans, NOAA/Earth System Research Laboratory and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/) (<http://www.esrl.noaa.gov/gmd/ccgg/trends/>); Hawaii Ocean Time-Series (HOT)/ALOHA data courtesy of Dr. David Karl, University of Hawaii (<http://hahana.soest.hawaii.edu>).

marine calcifying organisms that use carbonate minerals as principal components to produce their skeletons and shells (figure 60). In addition, some of the most fundamental biological and geochemical processes such as marine calcifying rates, physical strength of calcareous skeletons of corals reef, shells growth, recruitment success, reproduction, survivorship, and food web dynamics in general, may be adversely affected by a decrease in the availability of carbonate ions. As a result, species that undergo calcification may become displaced by species that do not. By some estimates, calcification rates will decrease as much as 60% by the end of this century. Laboratory experiments have conclusively shown that lowering carbonate ion concentration reduces calcification rates in tropical reef builders by 7–40%. These rapid changes do not allow for natural adaptation to occur in ecosystems that have experienced only moderate changes in ocean chemistry over most of geological time. Marine

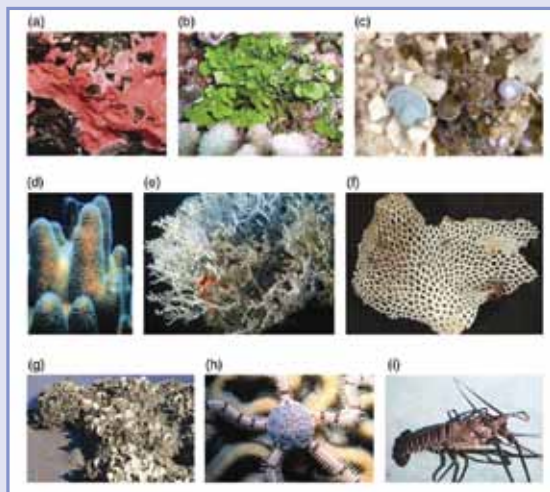


Figure 60: Representatives of major benthic calcifiers: (a) coralline algae (photo by Nancy Sefton; courtesy NOAA/CORIS); (b) Halimeda (photo by James Watt; courtesy NOAA/NMFS); (c) benthic foraminifera (courtesy P. Hallock); (d) reef-building coral (*Dendrogyra cylindrus*; Cmdr William Harrigan, NOAA Corps; courtesy Florida Keys National Marine Sanctuary); (e) deep-water coral (*Lophelia pertusa*; from 413 m depth off North Carolina. Large red crab is *Eumunida picta*; urchin below it is *Echinus tyloides*; courtesy S.W. Ross, K. Sulak, and M. Nizinski); (f) bryozoan (courtesy NOAA/Ocean Explorer); (g) mollusc (oyster reef; courtesy South Carolina Department of Natural Resources); (h) echinoderm (brittle star; Larry Zetwoch; Florida Keys National Marine Sanctuary); (i) crustacean (lobster; Dr. James P. McVey, NOAA Sea Grant Program). The calcification responses of many of these groups have not been investigated (figure printed with permissions from J. Kleypas. Source: Kleypas, J.A. et al. 2006. Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18–20 April 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the U.S. Geological Survey, 88 pp.)

organisms at risk from ocean acidification are coralline algae, green algae, benthic foraminifera, reef-building coral, deep-water coral, bryozoans, mollusks like oysters, echinoderms like the brittle star, and crustaceans such as lobsters (figure 60).

Status of Ocean Acidification in the Caribbean

Ocean acidification effects will have a great impact in coral reef development areas, as in the Great Caribbean region. This region spans the entire Caribbean and comprises one of the major carbonate platforms on the world. Puerto Rico forms part of this area and can become one of the last refuge habitats in the ocean for marine calcifying and non-calcifying organisms. In order to protect and better understand the consequences of ocean acidification in Puerto Rico we need determine the present state of knowledge concerning this problem. Figure 61 displays the data from the Hawaii Ocean Time Series on pH since 1985 (left) and the available pH data for the south coast of Puerto Rico since 2009 (right). Figure 62 shows NOAA data for 1989 and 2008 for the Caribbean aragonite saturation states, showing clear decline.

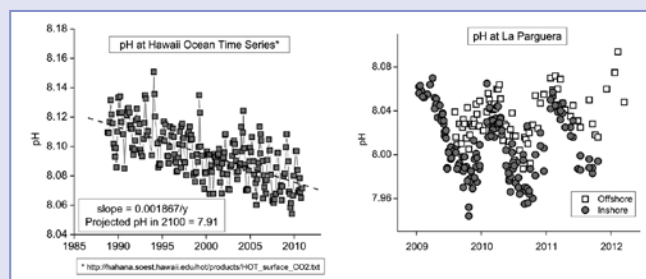


Figure 61: pH data from the Hawaii Ocean Time Series since 1985 (left) and the available pH data for the south coast of Puerto Rico since 2009 (right)

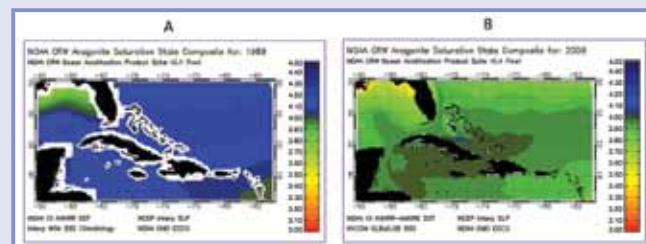


Figure 62: Caribbean Aragonite Saturation States for 1989 and 2008, showing clear decline. Aragonite saturation state refers to whether calcium carbonate is saturated (1), subsaturated (<1), or super saturated (>1). Ocean acidification causes decreased aragonite saturation states which in turn decreases coral viability. Source: coralreefwatch.noaa.gov/satellite/oa/saturationState_GCR.html

Future Saturation State Scenarios for the Caribbean

Figure 63 shows annual seawater aragonite saturation state (Ω_{arg}) from Enrique mid-shelf reef (red line) compared to the offshore Caribbean Sea estimations using OAPS model (blue line). Historical context estimates using the oceanic water values (black dashed lines) shows that during preindustrial times (PIR) the Ω_{arg} value was approximately 4.6. After the Pre-Industrial Revolution (PIR) the increase in CO_2 emissions have decreased the Ω_{arg} and for 2050 is expected to decrease around 3.4 and for the next century to 2.8. Currently, in tropical oceanic surface waters of the Caribbean, Ω_{arg} typically ranges from 4 to 3.7 and is believed to be adequate to support robust calcification. However, these values are declining within the Caribbean region at a rate of about 3% per decade. Maximum values are in early spring and winter. During the summer and fall these values considerably decrease due to the “local effects”. Currently it is unknown if future saturate state scenarios will continue to follow the same rate of decline in the Caribbean as it will be largely dependent on the amount of carbon dioxide emitted to the atmosphere and oceans today and in the near future.

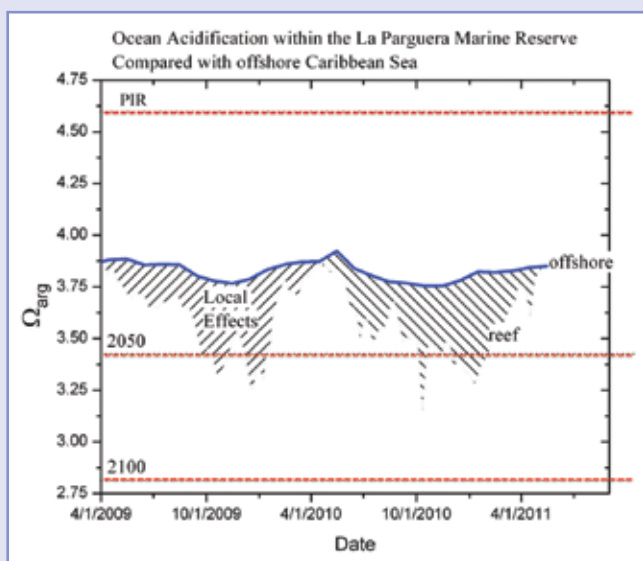


Figure 63: The figure shows measurements of annual seawater aragonite saturation state (Ω_{arg}) at Enrique reef compared to offshore model-based estimations (blue line) (Courtesy of Dwight Gledhill, modified by Melissa Meléndez).

Knowledge Gaps and Future Research Needs

At the present time the scientific community cannot answer questions about the consequences of high atmospheric CO_2 concentration and sink capacity of the oceans. In addition how all the abiotic and biotic processes will be respond with the decrease in pH and carbonate saturation state. Certainly, the scientific information concludes that ocean acidification represents an enemy to marine calcifying organisms and will affect the population dynamics, community structure, survival rate, fitness, marine food webs, life history patterns, organism interactions, recruitment, and many other components of carbonate and non-carbonate marine ecosystem. Furthermore, some of the effects that cause pH decrease in scleractinians corals are poorly understood and need more effort from the scientific community, society, as well as political attendant.

Some scientists reported different areas that need further research. For example, the effects of decreasing aragonite saturation state on deep-sea, bioherm-forming scleractinians are not well understood and further experimentation is warranted (Guinotte et al. 2006). (Guinotte and Fabry 2008) said that the effects of a reduction in calcification rates on recruitment, settlement, and juvenile life stages of most marine calcifiers, including the majority of scleractinian corals, are not well known. (Kleypas et al. 2006a) argues that the effects of changing calcification and dissolution on reef ecosystems functioning are still unknown. Additionally, Kleypas et al. (2006a) mentioned the effects of reduced carbonate saturation state on bioerosion rates and the conditions controlling sediment dissolution (including suspended sediment) and the potential impact on coral reef carbonate chemistry are poorly understood or unknown. Another issue that Seibel and Fabry (2003) reported is that, no up-to-date quantitative data exists to test that the reduced calcification decreases a calcifying organism's fitness or survivorship, then such calcareous species may undergo shifts in their latitudinal distributions and vertical depth ranges as the CO_2 /carbonate chemistry of seawater changes.

Summary of Observed and Projected Trends for Ocean Acidification

Currently, atmospheric carbon dioxide concentration has reached 395 ppm globally and because half of the carbon dioxide released both naturally and by humans is taken up by the oceans, average pH of the oceans has dropped from 8.16 to 8.05 since the year 1800. This change in seawater chemistry is equivalent to an increase of carbon dioxide concentration of about 35% and a decrease in pH of 0.1 units. As a result, there has been a global decrease in surface seawater

carbonate saturation states and thus, the rate of calcification in marine calcifying organisms and the precipitation of carbonate minerals like calcite and aragonite are decreasing as well. The Caribbean and Puerto Rico saturation states of carbonate minerals reflects this global trend. For example, the values of aragonite saturation states are declining within the Puerto Rico-Caribbean region at a rate of about 3% per decade. Currently it is unknown if future saturation state scenarios will continue to follow the same rate of decline in the Caribbean as it will be largely dependent on the amount of carbon dioxide emitted to the atmosphere and oceans today and in the near future.



References - Working Group 1 Report

- (USGCRP), U. S. G. C. R. P. 2001. Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. Cambridge University Press.
- (USGCRP), U. S. G. C. R. P. 2009. Global Climate Change Impacts in the U.S. Cambridge University Press [online: www.globalchange.gov/usimpacts]
- Anderson, H. R. 1976. Ground water in the San Juan metropolitan area, Puerto Rico. .in U. S. G. S. W. R. Investigations, editor. U.S. Department of Interior, U.S. Geological Survey, Fort Buchanan, Puerto Rico.
- Angeles, M. E., J. E. Gonzalez, D. J. Erickson III, and J. L. Hernández. 2007. Predictions of change in the Caribbean region using global general circulation models. *International Journal of Climatology* 27:555-569.
- Ashby, S. A., M. A. Taylor, and A. A. Chen. 2005. Statistical models for predicting Caribbean rainfall. *Theoretical and Applied Climatology* 82:65-80.
- Atkinson, M. and P. Cuet. 2008. Possible effects of ocean acidification on coral reef biogeochemistry: topics for research. *Marine Ecology Progress Series* 373.
- Australia. 2009. Climate Change Risks to Australia's Coast: A First Pass National Assessment. Page 169 in D. o. C. C. Australian Government, editor. Commonwealth of Australia.
- Bengtsson, L., M. Botzet, and M. Esch. 1997. Numerical simulations of intense tropical storms. Pages 67-90 *Hurricanes*. Springer-Verlag.
- Bengtsson, L., K. I. Hodges, M. Esch, N. Keenlyside, L. Kornblueh, J.-J. Luo, and T. Yamagata. 2007. How may tropical cyclones change in a warmer climate? . *Tellus* 59A:539-561.
- Biasutti, M., A. H. Sobel, S. J. Camargo, and T. T. Creyts. 2012. Projected changes in the physical climate of the Gulf Coast and Caribbean. *Climatic Change* 112:819-845.
- Bindoff, N. L., J. Willebrand, V. Artale, J. Cazenave, S. Gregory, S. Gulev, K. Hanawa, L. Quéré, S. Levitus, Y. Nojiri, C. K. Shum, L. D. Talley, and A. Unnikrishnan. 2007. Observations: Oceanic climate change and sea level Pages 385-432 in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. *Climate Change 2007: The Physical Science Basis*. Cambridge University Press, Cambridge.
- Brillinger, D., J. Curry, R. Jacobsen, E. Muller, R. Muller, S. Perlmutter, R. Rohde, A. Rosenfeld, C. Wickham, J. Wurtele. 2012. Berkeley Earth Surface Temperature Analysis. [online] www.BerkeleyEarth.org
- Bueno, R., C. Herzfeld, E. A. Stanton, and F. Ackerman. 2008. The Caribbean and Climate Change: The Costs of Inaction.
- Bush, D. M. 1995. *Living with the Puerto Rico Shore*. Duke University Press, Durham, NC.
- Campbell, J. D., M. A. Taylor, T. S. Stephenson, R. A. Watson, and F. S. Whyte. 2010a. Future climate of the Caribbean from a regional climate model. *International Journal of Climatology*:13.
- Campbell, J. D., M. A. Taylor, T. S. Stephenson, R. A. Watson, and F. S. Whyte. 2010b. Future climate of the Caribbean from a regional climate model. *International Journal of Climatology*:13.
- Cayan, D., P. Bromirski, K. Hayhoe, M. Tyree, M. Dettinger, and R. Flick. 2006. Projecting Future Sea Level. Page 64 in C. C. C. Center, C. E. Commission, and P. I. E. R. Program, editors.
- CCSP, editor. 2008. Weather and climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands: A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Department of Commerce, NOAA's National Climatic Data Center, Washington, DC.
- Chen, A. A., A. Roy, J. McTavish, M. Taylor, and L. Marx. 1997. Using SST Anomalies to Predict Flood and Drought Conditions for the Caribbean. Center for Ocean-Land Atmosphere Studies
- Chen, A. A. and M. A. Taylor. 2002. Investigating the link between early season Caribbean rainfall and the El Niño +1 year. *International Journal of Climatology* 22:87-106.

- Christensen, J., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C. G. Menendez, J. Raisanen, A. Rinke, A. Sarr, and P. Whetton. 2007. Regional Climate Projections. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, editors. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY USA.
- Daly, C., E. H. Helmer, and M. Quiñones. 2003. Mapping the Climate of Puerto Rico, Vieques and Culebra. *International Journal of Climatology* 23:1359-1381.
- Diaz, H. F. and R. S. Pulwarty. 1997. An Overview. Page 292 in H. F. Diaz and R. S. Pulwarty, editors. *Hurricanes: Climate and Socioeconomic Impacts*. Springer-Verlag, New York.
- Dickson, R. 1978. Weather and circulation of February 1978: Record or near-record cold east of the continental divide with a major blizzard in the northeast. *Monthly Weather Review* 106.
- Donnelly, J. P. and J. D. Woodruff. 2007. Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon. *Nature* 447:465-468.
- Duchon, C. E. 1986. Temperature trends at San Juan, Puerto Rico. *Bulletin of the American Meteorological Society* 67:1370-1377.
- Elsner, J. B., J. P. Kossin, and T. H. Jagger. 2008. The increasing intensity of the strongest tropical cyclones. *Nature* 455:92-95.
- Elsner, J. B., K. B. Liu, and B. Kocher. 2000. Spatial variations in major U.S. Hurricane activity: Statistics and a physical mechanism. *Journal of Climate* 13:2293-2305.
- Emanuel, K., R. Sundararajan, and J. Williams. 2008. Hurricanes and Global Warming: Results from Downscaling IPCC AR4 Simulations. *Bulletin of the American Meteorological Society* 89:347-367.
- Emanuel, K. A. 1997. Climate variations and hurricane activity: Some theoretical considerations. Pages 55-65 in H. F. Diaz and R. S. Pulwarty, editors. *Hurricanes, Climate and Socioeconomic Impacts*. Springer Verlag, Heidelberg.
- Emanuel, K. A. 1999. Thermodynamic control of hurricane intensity. *Nature* 401:665-669.
- Enfield, D. and E. Alfaro. 1999. The dependence of Caribbean rainfall on the interaction of the tropical Atlantic and Pacific Oceans. *Journal of Climate* 12:93-103.
- FEMA. 2012. Seven months later, disaster aid surpasses \$83.9 million. Press Release. Federal Emergency Management Agency, Online: www.fema.gov.
- Fitzgerald, D. M., S. van Heteren, and T. Montello. 1994. Shoreline processes and damage resulting from the Halloween Eve Storm of 1991 along the North and South shores of Massachusetts Bay, USA. *Journal of Coastal Research* 10:113-132.
- Frederick, K. and P. Gleick. 1999. Water and Global climate change: Potential impacts on U.S. Water Resources. Pew Center Global Climate Change.
- Gable, F. J., M. M. Affs, J. H. Gentile, and D. G. Aubrey. 1990. Global climate and coastal impacts in the Caribbean region. *Environmental Conservation* 17:51-60.
- Giannini, A., M. A. Cane, and Y. Kushnir. 2001. Interdecadal changes in the ENSO teleconnection to the Caribbean region and North Atlantic Oscillation. *Journal of Climate* 14.
- Giannini, A., Y. Kushnir, and M. Cane. 2000. Interannual Variability of Caribbean Rainfall, ENSO, and the Atlantic Ocean. *Journal of Climate* 13.
- Girvetz, E. H., C. Zganjar, G. T. Raber, E. P. Maurer, P. Kareiva, and J. J. Lawler. 2009. Applied Climate-Change Analysis: The Climate Wizard Tool. *PLoS ONE* 4:e8320.
- Gonzalez, J. E. and D. E. Comarazamy. 2009. Climate Impacts of LCLU Changes on a Tropical Coastal Region Under a Changing Climate. 2nd International Conference on Countermeasures to Urban Heat Islands. Environmental Energy Technologies Department, E.O. Lawrence Berkeley National Laboratory, Berkeley, CA.
- Gray, W. M. 1984. Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb Quasi-Biennial

Oscillation influences. *Mon. Wea. Rev.* 112:1649-1668.

- Gray, W. M., J. D. Sheaffer, and C. W. Landsea. 1997. Climate trends associated with multidecadal variability of Atlantic hurricane activity Page 1997 in H. F. Diaz and R. S. Pulwarty, editors. *Hurricanes: Climate and Socioeconomic Impacts*. Springer-Verlag, New York.
- Grinsted, A., J. C. Moore, and S. Jevrejeva. 2010. Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics* 34:461-472.
- Guinotte, J. M. and V. J. Fabry. 2008. Ocean acidification and its potential effects on marine ecosystems. *Annals of the New York Academy of Sciences* 1134:320-342.
- Guinotte, J. M., J. Orr, S. Cairns, A. Freiwald, L. Morgan, and R. George. 2006. Will human-induced changes in seawater chemistry alter the distribution of deep-sea scleractinian corals? *Front Ecol Environ* 4:141-146.
- Hawkins and Sutton. 2007. The potential to narrow uncertainty in regional climate predictions. *BAMS* 90.
- Hawkins and Sutton. 2011. The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics* 37.
- Hedges, S. B. 1996. Historical biogeography of West Indian vertebrates. *Annual Review of Ecology and Systematics* 27:163-196.
- Henderson-Sellers, A., H. Zhang, G. Berz, K. Emanuel, W. Gray, C. Landsea, G. Holland, J. Lighthill, S.-L. Shieh, P. Webster, and K. McGuffie. 1998. *Tropical Cyclones and Global Climate Change: A Post-IPCC Assessment*. Bulletin of the American Meteorological Society.
- Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* 50:839-866.
- Hoyos, C.D., P. A. Agudelo, P. J. Webster, and J. A. Curry. 2006. Deconvolution of the Factors Contributing to the Increase in Global Hurricane Intensity *Science* 7 April 2006: 312 (5770), 94-97. Published online 16 March 2006 [DOI:10.1126/science.1123560]
- IPCC. 2001. *Climate Change 2001: The Scientific Basis*. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson (eds). Cambridge University Press, Cambridge, UK, and New York, USA, 2001. No. of pages: 881.
- IPCC, 2007: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.
- Jevrejeva, S., J. C. Moore, and A. Grinsted. 2010. How will sea level respond to changes in natural and anthropogenic forcings by 2100? *Geophysical Research Letters* 37:5.
- Jones, P.D., Kilsby, C.G., Harpham, C., Glenis, V., Buroton, A. 2009. *UK Climate Projections science report*. Projections of future daily climate for the UK from the Weather Generator. University of Newcastle, UK.
- Jury, M. R. 2009. A quasi-decadal cycle in Caribbean climate. *Journal of Geophysical Research* 114.
- Jury, M. R. 2011. Long-Term Variability and Trends in the Caribbean Sea. *International Journal of Oceanography* 2011:9.
- Jury, M. R. and I. Gouirand. 2011. Decadal climate variability of the eastern Caribbean. *Journal of Geophysical Research* 116.

- Jury, M. R., R. Rios-Berrios, and E. Garcia. 2011. Caribbean hurricanes: changes of intensity and track prediction. *Theoretical Applied Climatology* 107:297-311.
- Jury, M. R., A. Winter, and B. Malmgren. 2007. Sub-regional precipitation climate of the Caribbean and relationships with ENSO and NAO. *Journal of Geophysical Research* 112.
- Karl, T. R., J. M. Melillo, and T. C. Peterson. 2009. *Global Climate Change Impacts in the United States*. Cambridge University Press.
- Kleypas, J. A., R. A. Feely, V. J. Fabry, C. L. Langdon, C. L. Sabine, and L. L. Robbins. 2006a. Impacts of Increasing Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18-20 April 2005, St. Petersburg, FL.
- Kleypas, J. A., R. A. Feely, V. J. Fabry, O. Langdon, C. L. Sabine, and L. L. Robbins. 2006b. Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18-20 April 2005. NSF, NOAA, USGS, St. Petersburg, FL.
- Knutson, T. R., J. McBride, J. Chan, K. A. Emanuel, G. J. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi. 2010. Tropical Cyclones and Climate Change. *Nature Geoscience* 3:157-163.
- Knutson, T. R., R. E. Tuley, and Y. Kurihara. 1998. Simulated increase of hurricane intensities in a CO₂-warmed climate. *Science* 279:1018-1020.
- Knutson, T. R. and R. E. Tuleya. 1999. Increased hurricane intensities with CO₂-induced warming as simulated using the GFDL hurricane prediction system. *Climate Dynamics* 18:1109-1128.
- Kunkel, K. E., P. D. Bromirski, H. E. Brooks, T. Cavazos, A. V. Douglas, D. R. Easterling, K. A. Emanuel, P. Ya, G. Groisman, G. J. Holland, T. R. Knutson, J. P. Kossin, P. D. Komar, D. H. Levinson, and R. L. Smith. 2008. Observed changes in weather and climate extremes. Pages 35-80 in T. R. Karl, G. A. Meehl, C. D. Miller, S. J. Hassol, A. M. Waple, and M. L. Murray, editors. *Weather and Climate Extremes in a Changing Climate: Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands (Synthesis and Assessment Product 3.3)*. U.S. Climate Change Science Program, Washington, D.C.
- Landsea, C. W., G. D. Bell, W. M. Gray, and S. B. Goldberg. 1995. The extremely active 1995 Atlantic Hurricane season: Environmental conditions and verification of seasonal forecasts. *Monthly Weather Review* 126:1174-1193.
- Landsea, C. W., N. Nicholls, W. M. Gray, and L. A. Avila. 1996. Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geophysical Research Letters* 23:1697-1700.
- Landsea, C. W., R. A. Pielke Jr., A. M. Mestas-Nunez, and J. A. Knaff. 1999. Atlantic basin hurricanes; indices of climatic changes. *Climatic Change* 42:89-129.
- Law, K. 2011. The Impact of Ocean Heat Content on Rapid Intensification of Atlantic Hurricanes. Pp. 616 in A. Lupo, editor. *Hurricane Research - Climate, Dynamics, and Societal Impacts*. InTech.
- Lewsey, C., G. Cid, and E. Kruse. 2004. Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean. *Marine Policy* 28:393-409.
- López-Marrero, T. d. M. and N. Villanueva Colón. 2006. *Atlas Ambiental de Puerto Rico*. Editorial de la Universidad de Puerto Rico, San Juan, PR.
- Lugo, A. E., O. M. Ramos González, and C. Rodríguez Pedraza. 2011. The Río Piedras Watershed and Its Surrounding Environment. Page 46 in U. S. D. o. Agriculture and U. S. F. Service, editors. *U.S. Forest Service*.
- Malaizé, B., P. Bertran, P. Carbonel, D. Bonnissent, K. Charlier, D. Galop, D. Imbert, N. Serrand, C. Stouvenot, and C. Pujol. 2011. Hurricanes and climate in the Caribbean during the past 3700 years BP. *The Holocene* 21:1-14.
- Martis, A., G. J. Van Oldenborgh, and G. Burgers. 2002. Predicting rainfall in the Dutch Caribbean - More than El Niño? *International Journal of Climatology* 22:1219-1234.
- McSweeney, C., M. New, G. Lizcano, and X. Lu. 2010. The UNDP Climate Change Country Profiles: improving the accessibility of observed and projected climate information for studies of climate change in developing countries. *Bulletin of the American Meteorological Society* 91:157-166.

- Meehl, G. A. 2009. Decadal Prediction: Can it be skillful? American Meteorological Society.
- Meehl, G. A., W. M. Washington, W. D. Collins, J. M. Arblaster, A. Hu, L. E. Buja, W. G. Strand, and H. Teng. 2005. How Much More Global Warming and Sea Level Rise? *Science* 307:1769-1772.
- Mendez, P. 2010. Análisis de tendencias hidroclimáticas recientes y transformación del paisaje en la isla de Puerto Rico. doctoral dissertation. Universidad de Salamanca, Salamanca, España.
- Mimura, N., L. Nurse, R. McLean, J. Agard, L. Briguglio, and P. Lefale. 2007. Small islands. Pages 687-716 in M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, editors. *Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK.
- Mitrovica, J. X., N. Gomez, and P. Clark. 2009. The sea-level fingerprint of West Antarctic collapse. *Science* 323.
- Muhs, D. R. 2004. Timing and Duration of the Last Interglacial Period from U-Series Ages of Unaltered Reef Corals, Northern and Western Puerto Rico. in Geological Society of America Annual Meeting, Denver, Colorado.
- Murphy, D. J. R., M. Hall, C. Hall, G. Heisler, S. Stehman, and A.-M. Carlos. 2010. The relation between land cover and the urban heat island in northeastern Puerto Rico. *International Journal of Climatology* 31:1222-1239.
- National Weather Service. 2012. Hurricane Georges Preliminary Storm Report. Online: http://www.srh.noaa.gov/sju/?n=1998_georges [Access Date: 4 December 2012]
- Neelin, J. D., M. Munnich, H. Su, J. E. Meyerson, and C. E. Holloway. 2006a. Tropical drying trends in global warming models and observations. *PNAS* 108:6.
- Neelin, J. D., M. Munnich, H. Su, J. E. Meyerson, and C. E. Holloway. 2006b. Tropical drying trends in global warming models and observations. *Proceedings of the National Academy of Sciences* 103:6110-6115.
- NOAA. 2012. The Final Word. in D. Anderson, C. Woodhouse, C. Morrill, J. T. Overpeck, and R. S. Webb, editors. *A Paleo Perspective on Global Warming*. NOAA Paleoclimatology Program.
- Northeast Climate Impacts Assessment (NECIA). 2006. *Climate Change in the U.S. Northeast. A Report of the Northeast Climate Impacts Assessment*. Cambridge, Massachusetts: Union of Concerned Scientists.
- Nurse, L.A. & Sem, G., 2001. Small Island States. In McCarthy, J.J. (ed.), *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Cambridge University Press, pp. 843-75.
- Nyberg, J., B. Malmgren, A. Winter, M. R. Jury, H. Kilbourne, and T. Quinn. 2007. Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. *Nature* 447:698-701.
- Orr, J., V. Fabry, O. Aumont, L. Bopp, and S. Doney. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* 437:681-686.
- Pachauri, R. K., A. Reisinger, and C. W. Team. 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups 1, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.
- Palmer, M. D. and K. Haines. 2009. Estimating Oceanic Heat Content Change Using Isotherms. *Journal of Climate* 22:4953-4969.
- Pelling, M. and J. I. Uitto. 2001. Small island developing states: Natural disaster vulnerability and global change. *Environmental Hazards* 3:49-62.
- Peterson, T. C., M. A. Taylor, R. Demeritte, D. L. Duncombe, S. Burton, F. Thompson, A. Porter, M. Mercedes, E. Villegas, R. Semexant Fils, A. Klein Tank, A. Martis, R. Warner, A. Joyette, W. Mills, L. Alexander, and B. Gleason. 2002. Recent changes in climate extremes in the Caribbean region. *Journal of Geophysical Research* 107.
- Pfeffer, W. T., J. T. Harper, and S. O'Neel. 2008. Kinematic Constraints on Glacier Contributions to 21st-

Century Sea-Level Rise. *Science* 321:1340-1343.

Picó, R. 1969. *La nueva geografía de Puerto Rico*. Universidad de Puerto Rico, Editorial Universitaria, Rio Piedras, Puerto Rico.

Prentice, C. S. and P. Mann. 2005. Paleoseismic study of the South Lajas fault: First documentation of an onshore Holocene fault in Puerto Rico. Pages 215-222 in P. Mann, editor. *Active Tectonics and Seismic Hazards of Puerto Rico, the Virgin Islands, and Offshore Areas*. Geological Society of American Special Paper 385.

Rayner, N. A., et al. (2003), Global analyses of sea surface temperature, sea ice, and night marine air temperatures since the late nineteenth century, *J. Geophys. Res.*, 108, 4407, doi:10.1029/2002JD002670.

Reading, A. J. 1990. Caribbean tropical storm activity over the past four centuries. *International Journal of Climatology* 10:365-376.

Reynolds, R.W. 1988. A real-time global sea surface temperature analysis. *J. Climate* 1: 75-86.

Reynolds, R.W. and D.C. Marsico. 1993. An improved real-time global sea surface temperature analysis. *J. Climate* 6: 114-119.

Reynolds, R.W. and T.M. Smith. 1994. Improved global sea surface temperature analyses using optimum interpolation. *J. Climate* 7: 929-948.

Ruttimann, Jacqueline. 2006. Oceanography: Sick seas. *Nature*. doi:10.1038/442978a

Sallenger, A. H. J., K. S. Doran, and P. A. Howd. 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *nature climate change* 1597.

Santer, B. D., T. M. L. Wigley, P. J. Gleckler, C. Bonfils, M. F. Wehner, K. AchutaRao, T. Barnett, J. Boyle, w. Brüggemann, M. Fiorino, N. Gillett, J. E. Hansen, P. D. Jones, S. A. Klein, G. A. Meehl, S. Raper, R. W. Reynolds, K. E. Taylor, and W. M. Washington. 2006. Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions. *PNAS* 103

Saunders, M. A. and A. S. Lea. 2008. Large contribution of sea surface warming to recent increase in Atlantic hurricane activity. *Nature* 451:557-561.

Seibel, B. A. and V. J. Fabry. 2003. Marine biotic response to elevated carbon dioxide. *Advances in Applied Biodiversity Science* 4:59-67.

Shay, L. K. and J. K. Brewster. 2010. Oceanic Heat Content Variability in the Eastern Pacific Ocean for Hurricane Intensity Forecasting. *Monthly Weather Review* 138:2110-2131.

Simpson, M. C., D. Scott, M. New, R. Sim, D. Smith, M. Harrison, C. M. Eakin et al. 2009. An Overview of Modelling Climate Change Impacts in the Caribbean Region with contribution from the Pacific Islands. Barbados: United Nations Development Programme

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, KB Averyt, M. Tignor, HL Miller. 2007. Summary for Policymakers. Cambridge University Press: Cambridge, UK.

Snow, E. R. 1943. *Great storms and famous shipwrecks of the New England Coast*. Yankee Publishing, Boston, MA.

Spence, J. M., M. A. Taylor, and A. A. Chen. 2004a. The effect of concurrent sea-surface temperature anomalies in the tropical Pacific and Atlantic on Caribbean rainfall. *International Journal of Climatology* 24:1531-1541.

Spence, J. M., M. A. Taylor, and A. A. Chen. 2004b. The effect of concurrent sea-surface temperature anomalies in the tropical Pacific and Atlantic on Caribbean rainfall. *International Journal of Climatology* 24.

Stanton, E. A. and F. Ackerman. 2007. *Florida and Climate Change: The Costs of Inaction*. Tufts University.

Stephenson, T. S., A. A. Chen, and M. A. Taylor. 2007. Toward the development of prediction models for the primary Caribbean dry season. *Theoretical Applied Climatology*.

Stoner, A. M., K. Hayhoe, and D. J. Wuebbles. 2009. Assessing general circulation model simulations of atmospheric teleconnection patterns. *Journal of Climate* 22:4348-4372.

Strachan, J. 2012. Tropical cyclones in 2011. *Weather* 67:31-34.

- Tans, P. and R. Keeling. 2012. NOAA Earth System Research Laboratory's Global Monitoring Division: Trends in Atmospheric Carbon Dioxide. NOAA.
- Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2011a. An Overview of CMIP5 and the Experiment Design. Bulletin of the American Meteorological Society.
- Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2011b. A Summary of the CMIP5 Experimental Design.
- Taylor, M. and E. Alfaro. 2005. Climate of Central America and the Caribbean. Pages 183-189 in J. E. Oliver, editor. Encyclopedia of World Climatology. Springer, Netherlands.
- Taylor, M. A., D. B. Enfield, and A. A. Chen. 2002a. The influence of the tropical Atlantic vs. the tropical Pacific on Caribbean rainfall. Journal of Geophysical Research 107 (C9), 3127.
- Taylor, M. A., D. B. Enfield, and A. A. Chen. 2002b. The influence of tropical Atlantic vs. the tropical Pacific on Caribbean rainfall. Journal of Geophysical Research 107:3127.
- Thieler, R. E., R. W. Rodriguez, and E. A. Himmelsstoss. 2007. Historical Shoreline Changes at Rincón, Puerto Rico 1936-2006. U.S. Department of the Interior's U.S. Geological Survey.
- Trenberth, K. E. and D. J. Shea. 2006. Atlantic hurricanes and natural variability in 2005. Geophysical Research Letters 33:1-4.
- Turner, R. E. 2003. Coastal ecosystems of the Gulf of Mexico and Climate Change. Page 236 in Z. H. Ning, R. E. Turner, T. Doyle, and K. K. Abdollahi, editors. Integrated Assessment of the Climate Change Impacts on the Gulf Coast Region. Gulf Coast Climate Change Assessment Council (GCRCC) and Louisiana State University (LSU) Graphic Services, Baton Rouge, LA.
- Velazquez-Lozada, A., Gonzalez, J. E., and Winter, A., 2006. Urban heat island effect analysis in San Juan Puerto Rico. Atmospheric Environment 40, 1731-1741.
- Vermeer, M. and S. Rahmstorf. 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences 106:21527-21532.
- Wada, A. and N. Usui. 2007a. Importance of Tropical Cyclone Heat Potential for Tropical Cyclone Intensification in the Western North Pacific. Journal of Oceanography 63:427-447.
- Wada, A. and N. Usui. 2007b. Importance of tropical cyclone heat potential for tropical cyclone intensity and intensification in the Western North Pacific. Journal of Oceanography 63:427-447.
- Walker, L. R., D. J. Lodge, N. V. L. Brokaw, and R. B. Waide. 1991. Ecosystem, plant, and animal responses to hurricanes in the Caribbean. Biotropica 23:313-521.
- Walker, L. R., W. L. Silver, M. R. Willig, and J. K. Zimmerman. 1996. Long term responses of Caribbean ecosystems to disturbances. Biotropica 28:414-614.
- Wang, C. and D. Enfield. 2001. The tropical Western Hemisphere warm pool. Geophysical Research Letters 28:1635-1638.
- Wigley, T. 1999. The science of climate change Global and U.S. perspectives. Pew Center on Global Climate Change.
- Woodruff, J. D., J. P. Donnelly, and W. R. Geyers. 2008. Reconstructing relative flooding intensities responsible for hurricane-induced deposits from Laguna Playa Grande, Vieques, Puerto Rico. Geology 36:391-394.
- Woods, C. A. and F. E. Sergile. 2001. Biogeography of the West Indies: Patterns and Perspectives. CRC Press, Boca Raton, FL.
- Zebiak, S. E. 1989. Oceanic Heat Content Variability and El Niño Cycles. Journal of Physical Oceanography 19:475-486.

Working Group 2 Report: Ecology and Biodiversity

Editors:

Kasey R. Jacobs¹, Lisamarie Carrubba², and Ernesto L. Díaz¹

Contributing Authors (In Alphabetical Order):

Richard Appeldoorn³, Roy Armstrong³, Lisamarie Carrubba², Ricardo J. Colón-Rivera⁴, Jorge Corredor³, Yasmin Detrés³, Carlos Diez⁵, Fernando Gilbes³, Carmen González^{5,6}, William Gould⁷, Rosana Grafals-Soto³, Edwin A. Hernández-Delgado³, Nilda Jimenez⁵, Craig Lilyestrom⁵, Melissa Meléndez³, Chris Nytch³, Coralys Ortiz¹, Ernesto Otero-Morales³, Antares Ramos⁹, Neftali Rios-López³, Loretta Roberson³, Jorge E. Saliva⁸, Mayra Sanchez³, Clark Sherman³, Susan Silander⁸, Brenda Soler-Figueroa³, Ernesto Weil³

¹ Department of Natural and Environmental Resources - Coastal Zone Management Program

² National Oceanic and Atmospheric Administration – National Marine Fisheries Service

³ University of Puerto Rico

⁴ Texas A&M University

⁵ Puerto Rico Department of Natural and Environmental Resources

⁶ Jobos Bay National Estuarine Research Reserve

⁷ USDA Forest Service – International Institute of Tropical Forestry

⁸ U.S. Fish and Wildlife Service

⁹ National Oceanic and Atmospheric Administration – Office of Ocean and Coastal Resource Management

Acknowledgments:

Our special appreciation goes to PRCCC member Jorge E. Saliva, PhD, who sadly passed away soon after completion of the seabirds and shorebirds section and after presenting his exceptional work at our July PRCCC meeting. The climate and conservation community will profoundly miss Jorge. We also thank Jess K. Zimmerman of the Institute for Tropical Ecosystem Studies at the University of Puerto Rico – Rio Piedras and Maria Uriarte of the Department of Ecology, Evolution & Environmental Biology at Columbia University for their contributions to the forest section. Co-author Neftali Rios-López is especially grateful to Dr. Alberto Puente-Rolón for valuable discussion, information, and unpublished data of snakes and other reptiles on their most likely responses to expected climate changes. A special thanks to EPA, DNER, NOAA, USFWS, USGS, and IITF for sponsoring the November 2011 conference *Climate Change in the Caribbean: Puerto Rico and the U.S. Virgin Islands* where many key discussions occurred as well as the Puerto Rico Tourism Company, the Puerto Rico Conservation Trust and The Nature Conservancy for their support of conference activities and throughout the development of this report. We also thank the Social and Environmental Research Institute, the South Carolina Sea Grant Consortium, and the University of South Carolina for their development and training of the VCAPS diagrams and process that was used to facilitate WG 2 meeting discussions and the writing process. WG 2 would like to thank the Caribbean Natural Resources Institute as many of our initial discussions were guided by their climate change publications. Lastly, WG2 is grateful for the eight anonymous reviewers for their input and suggestions.

TABLE OF CONTENTS

INTRODUCTION.....	92
REPORT ORGANIZATION.....	93
BEACH ECOSYSTEMS	94
INTRODUCTION TO BEACH ECOSYSTEMS	94
STATUS OF BEACH ECOSYSTEMS IN PUERTO RICO	94
OUTCOMES AND CONSEQUENCES OF CLIMATE CHANGE TO PUERTO RICO'S BEACHES	98
SEA LEVEL RISE.....	98
INCREASING TEMPERATURE	99
INCREASING CARBON DIOXIDE	100
TROPICAL STORMS AND HURRICANES	100
RESEARCH AND INFORMATION NEEDS FOR BEACH ECOSYSTEMS.....	102
SUMMARY OF CLIMATE CHANGE IMPACTS ON PUERTO RICO'S BEACH SYSTEMS.....	102
WETLANDS.....	106
INTRODUCTION TO WETLANDS AND THEIR ECOSYSTEM SERVICES.....	106
STATUS OF WETLANDS WORLDWIDE, IN THE CARIBBEAN, AND IN PUERTO RICO.....	110
WORLDWIDE	110
CARIBBEAN WETLANDS	110
PUERTO RICO'S WETLANDS	110
OUTCOMES AND CONSEQUENCES OF CLIMATE CHANGE ON WETLAND ECOSYSTEMS.....	111
SEA LEVEL RISE.....	112
CHANGES IN SALINITY	113
INCREASED TEMPERATURE	113
INCREASED CARBON DIOXIDE	113
PRECIPITATION CHANGES.....	114
TROPICAL STORMS AND HURRICANES	114

ADAPTIVE CAPACITY OF WETLANDS.....	115
RESEARCH AND INFORMATION NEEDS.....	116
SUMMARY OF CLIMATE CHANGE IMPACTS ON PUERTO RICO'S WETLAND ECOSYSTEMS.....	116
COASTAL LAGOONS.....	122
INTRODUCTION TO COASTAL LAGOONS.....	122
STATUS AND THREATS OF COASTAL LAGOONS.....	122
OUTCOME AND CONSEQUENCES OF CLIMATE CHANGE TO PUERTO RICO'S	
COASTAL LAGOONS.....	123
SEA LEVEL RISE.....	123
PRECIPITATION CHANGES AND FRESHWATER INFLUX.....	123
INCREASED TEMPERATURE.....	124
TROPICAL STORMS AND HURRICANES.....	124
RESEARCH GAPS AND INFORMATION NEEDS.....	124
SUMMARY OF CLIMATE CHANGE IMPACTS ON PUERTO RICO'S COASTAL LAGOONS	126
SEABIRDS AND SHOREBIRDS	127
INTRODUCTION TO SEABIRDS AND SHOREBIRDS	127
SEABIRDS	128
SEABIRD SPECIES	129
SEABIRD NESTING HABITATS.....	129
SHOREBIRDS.....	131
SHOREBIRD SPECIES.....	132
SHOREBIRD NESTING HABITAT.....	132
OUTCOMES AND CONSEQUENCES OF CLIMATE CHANGE ON SEABIRDS AND SHOREBIRDS	133
SEA LEVEL RISE/SALT WATER INTRUSION	133
INCREASED PRECIPITATION	135
INCREASED FREQUENCY/SEVERITY OF STORMS	136
INCREASED IRRADIATION/INCREASED MEAN TEMPERATURES.....	136

OCEAN ACIDIFICATION	137
RESEARCH AND INFORMATION NEEDS FOR SEABIRDS AND SHOREBIRDS.....	138
SUMMARY OF CLIMATE CHANGE IMPACTS ON SEABIRDS AND SHOREBIRDS.....	139
FORESTS	142
INTRODUCTION TO PUERTO RICO'S FORESTS	142
OUTCOMES AND CONSEQUENCES OF CLIMATE CHANGE ON PUERTO RICO'S FORESTS	144
COASTAL AND MOIST LOWLAND FORESTS – INCLUDING FRESHWATER PTEROCARPUS SWAMPS, AND OTHER LOWLAND MOIST FORESTS AND WOODLANDS.....	144
SUBTROPICAL DRY FORESTS	147
KARST FORESTS	149
LOWER MONTANE FORESTS	150
AREAS OF GREATEST VULNERABILITY.....	153
SOCIETAL CONSEQUENCES.....	154
RESEARCH GAPS AND INFORMATION NEEDS FOR PUERTO RICO'S FORESTS.....	154
SUMMARY OF PUERTO RICO'S FORESTS AND CLIMATE CHANGE	155
AMPHIBIANS AND REPTILES.....	157
INTRODUCTION TO AMPHIBIANS AND REPTILES.....	157
AMPHIBIANS.....	157
REPTILES.....	157
THE HERPETOFAUNAL PROBLEM	158
THE CARIBBEAN HERPETOFAUNA AS A STUDY MODEL.....	160
CLIMATE CHANGE SCENARIO: CURRENT STATUS AND EXISTING VULNERABILITIES IN THE CARIB- BEAN AND PUERTO RICO.....	160
TEMPERATURE.....	160
PRECIPITATION	163
SEA-LEVEL RISE	164
TROPICAL STORMS AND HURRICANES.....	167

RESEARCH AND INFORMATION NEEDS.....	167
SUMMARY OF CLIMATE CHANGE OUTCOMES/CONSEQUENCES ON PUERTO RICO’S AMPHIBIANS AND REPTILES.....	168
INTRODUCTION TO MARINE SYSTEMS.....	170
CORAL REEFS	172
INTRODUCTION TO CORAL REEFS	172
SEWAGE POLLUTION	172
LAND USE AND LAND COVER CHANGE	172
MARINE-BASED SOURCES OF POLLUTION	173
FISHERIES	173
STORMS AND HURRICANES.....	173
UNSUSTAINABLE TOURISM	174
STATUS OF PUERTO RICO REEFS.....	174
OUTCOMES AND CONSEQUENCES OF CLIMATE CHANGE ON PUERTO RICO’S CORAL REEFS	176
SEA LEVEL RISE.....	176
INCREASING TEMPERATURE.....	177
INCREASED CARBON DIOXIDE	181
PRECIPITATION CHANGES.....	182
TROPICAL STORMS AND HURRICANES	183
INCREASED DUST FROM ARID REGIONS	184
RESEARCH NEEDS AND INFORMATION GAPS.....	185
SUMMARY OF CORAL REEFS AND CLIMATE CHANGE.....	185
SUBMERGED AQUATIC VEGETATION - SEAGRASSES	188
INTRODUCTION TO SEAGRASSES	188
STATUS.....	190
OUTCOME AND CONSEQUENCES OF CLIMATE CHANGE TO PUERTO RICO’S SEAGRASSES	191
SEA LEVEL RISE (AND ALTERED CURRENTS/TIDAL REGIME)	191

CHANGES IN PRECIPITATION.....	192
INCREASED TEMPERATURE.....	192
INCREASED CARBON DIOXIDE AND OCEAN ACIDIFICATION.....	192
TROPICAL STORMS AND HURRICANES.....	193
OTHER IMPACTS OF GLOBAL CLIMATE CHANGE ON SEAGRASSES.....	193
RESEARCH GAPS AND INFORMATION NEEDS.....	194
SUMMARY OF CLIMATE CHANGE AND SEAGRASS BEDS.....	195
COASTAL AND PELAGIC FISH SPECIES	195
INTRODUCTION TO COASTAL FISHES	196
OUTCOMES AND CONSEQUENCES OF CLIMATE CHANGE ON COASTAL FISHES.....	198
INCREASING TEMPERATURE.....	198
INCREASING CARBON DIOXIDE	200
TROPICAL STORMS AND HURRICANES.....	201
OTHER CLIMATE CHANGE OUTCOMES FOR COASTAL FISHES.....	201
INTRODUCTION TO PELAGIC FISH SPECIES	201
OUTCOMES AND CONSEQUENCES OF CLIMATE CHANGE ON PELAGIC FISHES.....	203
TEMPERATURE.....	203
OCEAN ACIDIFICATION.....	203
RESEARCH GAPS AND INFORMATION NEEDS.....	204
SUMMARY OF THE OUTCOMES AND CONSEQUENCES OF CLIMATE CHANGE ON COASTAL AND PELAGIC FISHES.....	204
BIOLUMINESCENT BAYS	206
INTRODUCTION TO BIOLUMINESCENT BAYS	206
STATUS OF BIOLUMINESCENT BAYS.....	208
POTENTIAL OUTCOMES AND CONSEQUENCES OF CLIMATE CHANGE ON BIOLUMINESCENT BAYS.....	208
CHANGES IN PRECIPITATION AND STORMS	209

INCREASED TEMPERATURE.....	210
RESEARCH AND INFORMATION NEEDS.....	210
SUMMARY OF CLIMATE CHANGE IMPACTS ON BIOLUMINESCENT BAYS.....	211
MARINE MAMMALS.....	212
INTRODUCTION.....	212
REGIONAL MARINE MAMMALS STRESSORS.....	213
FISHERIES INTERACTIONS	213
POLLUTION AND MARINE MAMMALS HEALTH	213
HUNTING.....	213
VESSEL STRIKES.....	213
HABITAT DEGRADATION.....	213
NOISE POLLUTION	213
STATUS OF CARIBBEAN MARINE MAMMALS	214
PINNIPEDS.....	214
BALEEN WHALES.....	214
TOOTHED CETACEANS.....	214
OUTCOMES AND CONSEQUENCES OF CLIMATE CHANGE ON MARINE MAMMALS.....	215
POPULATION ABUNDANCE AND DISTRIBUTION.....	215
FOOD SUPPLY.....	216
DISEASES	216
CONTAMINANTS AND METABOLISM (WELLS, 2010)	216
KNOWLEDGE GAPS AND RESEARCH NEEDS.....	217
SUMMARY OF OUTCOME AND CONSEQUENCES OF CLIMATE CHANGE ON MARINE MAMMALS	217
INTERSECTING ISSUES	219
CONCLUSION	219
WORK CITED.....	221

INTRODUCTION

Puerto Rico is home to some of the world's most impressive natural and manmade wonders, such as 799 miles of coastline with over 300 beaches, vibrant coral reefs, pre-Columbian ceremonial parks and artifacts, the coquí (tiny tree frog endemic to the islands), historic sugar cane and coffee plantations, El Yunque rainforest (the only subtropical rainforest in the U.S. National Forest System), Mona Island that is home to more than 100 endangered species, and 51 natural protected areas that conserve wetlands, dry forests, rainforests, caves and caverns, groundwater, cays and islets, and critical habitats for many species of flora and fauna. All these features are why Puerto Rico has been affectionately given the name *la Isla del Encanto*, the Island of Enchantment. Without healthy ecological systems Puerto Rico would not be able to boast such wonders.

Biodiversity and ecosystems are already more stressed than at any comparable period of human history (Staudinger et al. 2012). Human activities globally and in Puerto Rico have caused and may continue to cause a loss in biodiversity and natural resources through unsustainable land-use; chemical, heavy metal and nutrient pollution of our soil and water; diversion of water; habitat fragmentation and degradation; selective exploitation of species; and the introduction of non-native species, disease and pests. The current rate of biodiversity loss is greater than the natural background rate of extinction. Furthermore, these losses directly impact societies around the world and locally as we are also losing the services the ecosystems and species provide, such as fresh air, clean water, reduction in pollution and contaminant concentrations, drinking water protection, urban heat reduction, natural protection against storm surges and hurricanes, prevention of landslides, recreation and tourism opportunities, cultural and historical preservation, and even mental and spiritual well-being. The U.S. Global Change Research Program found that as species ranges shifts new community assemblages can also substantially alter ecosystem structure and function and the distribution of ecosystem services. Changes in precipitation regimes and extreme events can cause ecosystem transitions, increase transport of nutrients and pollutants to downstream ecosystems,

and overwhelm the ability of natural systems to mitigate harm to people from extreme events (Staudinger et al. 2012).

Climate change is one of the most critical issues facing biodiversity and natural resource management in the world today. Land and ocean surface temperatures have warmed, the spatial and temporal patterns of precipitation have changed, sea level has risen, and we are experiencing more intense storms. These changes, particularly warmer regional temperatures, have affected the timing of reproduction in animals and plants and/or migration of animals, the length of the growing seasons, species distributions and population sizes, and the frequency of pest and disease outbreaks. Climate change is projected to affect all aspects of biodiversity; however, the projected changes have to take into account the effects from past, present, and future human activities. The effects of climate change, in terms of rising sea levels, increasing mean atmospheric and sea surface temperatures and changes in rainfall and weather patterns, are likely to be particularly severe for the ecological systems of the Caribbean islands and small island states. Small islands are variable in their marine, coastal and terrestrial biodiversity. Some are very rich. For example, coral reefs have the highest biodiversity of any marine ecosystem, with some 91,000 described species of reef taxa. And while terrestrial biodiversity is not as high as coral reefs of the Caribbean, endemism among terrestrial flora and fauna is particularly high in Puerto Rico. The International Union for the Conservation of Nature and Natural Resources (IUCN) ranks the countries with the highest percentage of endemic amphibians. Puerto Rico ranks 13th with 78.9%, above Chile, Papua New Guinea, the United States, Mexico, Brazil, India and China (IUCN 2012). Areas of high endemism should pay extra special attention to climate changes as already globally there is increasing evidence of population declines and localized extinctions that can be directly attributed to climate change (Staudinger et al. 2012).

Working Group 2: Ecology and Biodiversity of the Puerto Rico Climate Change Council (WG2 PRCCC) was tasked with assessing how Puerto Rico's ecosystems and species may be affected by climate

change. The goal of this report is not to detail every potential outcome of climate change, but rather this project was a first attempt at identifying Puerto Rico’s most knowledgeable researchers and practitioners in the field, collecting the best available scientific knowledge, coming to agreement on key drivers of ecosystem changes and ways Puerto Rico’s ecology and biodiversity may be altered, and identifying research gaps and information needs. The underlying vulnerabilities of ecosystems determine the adaptive capacity of Puerto Rico’s flora and fauna, and therefore the current status and threats to each of the systems assessed were considered a priority throughout the work of the PRCCC.

REPORT ORGANIZATION

The members of Working Group 2: Ecology and Biodiversity are all highly respected in their fields of biology, ecology, oceanography, natural resource management, fisheries management, hydrology, geochemistry, forestry, and geology locally and abroad. The reviewers of this report were local experts from Puerto Rico, from the continental United States, and from overseas such as other Caribbean islands and the United Kingdom. Through a number of small sub-working group meetings, large working groups meetings, full PRCCC meetings, and a conference in San Juan, *Climate Change in the Caribbean 2011: Puerto Rico and the U.S. Virgin Islands*, WG2 members meet in-person to discuss the report compilation, data analyses, key concepts; peer-reviewed published studies, and gray literature. Subgroups of the PRCCC WG2 also meet to discuss targeted ecosystems such as coral reefs and forests. However, the majority of report writing and discussions occurred via email and PRCCC Research Library correspondences (a shared electronic research library). Additional correspondences occurred via the PRCCC email listserv (the PR-CC-L). We also consulted with and established the basis for discussions with other climate scientists and ecologists from other Caribbean islands the United States.

The Working Group 2 report is organized by the ecosystems and species the working group members determined were important for this

first attempt at a climate change vulnerability assessment for Puerto Rico’s natural resources (Table 1). In each section of the report, the current status and threats or non-climate change stressors (termed “underlying vulnerabilities” in this report) are discussed as well as the potential ways certain climate parameters (air and sea surface temperature, precipitation, extreme events, storms and hurricanes, sea level rise, and ocean acidification) may affect that particularly ecosystem or species assessed. (For more detailed information on the observed and projected changes for each of the climate parameters read the PRCCC Working Group 1 chapter.) The information compiled here is from literature review using a variety of databases as well as through the networks of our PRCCC members and from efforts to reach out to other Caribbean scientists and experts. As such some relevant studies may not have been received. The Working Group members and the PRCCC as a whole recognize that the information contained in this report is the best available knowledge as of July 2012 and will need to be continuously edited and expanded over the years as new and improved information becomes available. Working Group 2 also identified research and information needs to guide future studies and initiatives for natural resource management, conservation and ecosystem-based adaptation.

Working Group 2: Ecology and Biodiversity Sectors Assessed

- Beach Ecosystems
- Forests
- Wetlands
- Coral Reefs
- Submerged Aquatic Vegetation (Seagrasses)
- Coastal Lagoons
- Bioluminescent Bays
- Cays and Islets
- Amphibians and Reptiles
- Sea Turtles
- Marine Mammals
- Sea birds and Shore Birds
- Coastal Fish Species
- Pelagic Fish Species

Table 1 Sectors assessed by Working Group 2 in report

BEACH ECOSYSTEMS

Introduction to Beach Ecosystems

A beach is a zone of loose material extending from the low water mark to a point landward where either the topography abruptly changes or transitional (from coastal to terrestrial) vegetation first appears (Cambers 1998). A wider definition of a *beach* includes the nearshore zone extending to a water depth of about 12 m where the waves are no longer able to move sediment on the bottom ((CANARI) 2008). A beach may consist of sediment ranging in size from clay to boulders. Beaches are very dynamic systems changing size, shape and even material composition from one day to another. A *dune* is an accumulation of windblown sand forming a mound landward of the beach and usually parallel to the shoreline. Coastal sand dunes provide extensive protection to many of the world's shorelines as they are important habitat for plants and animals, including rare and endangered species, as well as serve as natural barriers between coastal winds and waves and the human built environment of homes, roads, and buildings. The interaction of dunes with the adjacent beach and nearshore provides the essential basis of a stable shoreline, through the regular exchange of nutrients and minerals (Carter 1991). A *cliff* or *bluff* is a high, steep bank at the water's edge composed primarily of rock. Beach and dune systems should be seen as distinct but at the same time interacting through flows and impacts of organic and inorganic materials, such as, seeds and animals, sediment, salt spray and ground water flow.

Status of Beach Ecosystems in Puerto Rico

Globally it has been shown that 70% of the world's sandy beaches are eroding (Bird 1985, 1987). *Shoreline retreat* or beach migration is the more accurate scientific term, but *beach erosion* is the common term used by beachfront property owners. In the United States, approximately 86% of U.S. East Coast barrier beaches (excluding evolving spit areas) have experienced erosion during the past 100 years (Galgano et al. 2004). Widespread erosion is also well documented in

California (Moore et al. 1999) and in the Gulf of Mexico (Morton and McKenna 1999). This trend is repeated in the Caribbean. Based on regular monitoring at 200 sites in nine eastern Caribbean territories over the period 1985-1995, 70% of the measured beaches were eroding and 30% were stable or accreting (Cambers 1997). Average erosion rates varied between 0.27 and 1.06 meters per year (0.9 to 3.5 feet per year), with islands impacted by hurricanes showing the highest rates. Specific beaches retreated inland by as much as 18 meters (59.1 feet) during Hurricane Luis in 1995. Beach erosion is not a dominant process if there is a balance between the sediment input and the sediment output in the system under study. Seasonal changes over a period of several years followed by significant erosion during a particular storm event and slow but steady beach accretion after the storm, characterize systems with a balanced sediment input and output (i.e. sediment budget). The erosion in the insular Caribbean is attributed to anthropogenic factors, e.g. sand mining, and poorly planned coastal development and man-made structures (i.e., sea defenses); and to natural causes, such as winter swells and hurricanes. Anthropogenic or natural factors induce beach migration to reach a new equilibrium state sometimes resulting in net

“Beaches are nature’s shock absorbers – they protect the coastline from the relentless power of the surf, and they protect themselves from destruction during storms. The countless grains of sand on the visible beach – and its offshore extension – are a mobile belt of cushioning. When waves strike the coast, the billions of sand grains on the full width of the beach move and roll past each other. Sometimes huge volumes of beach sand are moved either seaward or landward. A beach may change its shape drastically during a storm in the process of absorbing and dissipating the tremendous energy of the waves”.

from Living with the Puerto Rico Shore

erosion, where the output of sediment is greater than the input, or total system disruption or loss. Tropical storms and hurricanes appear to be the dominant factor influencing the erosion, with beaches failing to return to their pre-hurricane levels. Indeed between 1995 and 1999, a period of severe hurricane activity for the islands of the northeastern Caribbean, it appeared that these numerous high-energy events introduced a certain vulnerability to the beach systems making recovery slower and less sustained (Cambers 2005). This loss of physical habitat has serious implications for the dependent flora and fauna.

The beaches of Puerto Rico are coastal resources of great importance. Including Vieques, Culebra, and other islets and cays, there are approximately 799 miles (1,285.86 km) of coasts, of which 129.2 miles (208 km) are beaches. In fact, Puerto Rico has over 300 beaches. The extension of the coast line is divided into 231 beaches in 42 of the 44 coastal municipalities. Of these, 97 have been classified as accessible or swimmable beaches by DNER (CPN 2002). There are three dominant groups of minerals, characteristic of Puerto Rico's beaches: quartz sands with feldspar; volcanic rock; serpentine and mineral group; and sands from calcium carbonate. Beaches in Puerto Rico are assets of public domain, or public trust lands, with minor exceptions. This is a legacy from Roman and medieval law which was transferred to Puerto Rico by the Spanish government as part of its port system and has remained despite the changes in sovereignty. Extraction of sand from the beaches for construction purposes once caused severe damage for a long period of time. The problem of extraction without proper authorization still persists, but the problem is more focused on river mouths rather than beaches, although some illegal dune extraction has occurred in recent years. Erosion has drastically reduced the width of some beaches and furthermore, water contamination interferes with the recreational use of some beaches.

Dune retreat and disappearance has also been widely documented throughout the Caribbean islands, including Puerto Rico. Extensive black sand dunes, 6 meter (18 feet) high, in St. Vincent and the Grenadines, were mined at Diamond

Bay in the 1980s, leaving a flat coastal lowland devoid of vegetation and vulnerable to flooding (Cambers 1998, 2005). Cliff retreat and changes in rocky shores are less well documented, although associated with the widespread beach erosion there appears to be an increase in the exposure of beachrock ledges (Cambers 1998). Dunes provide an important barrier against the onslaught of waves during weather events along Puerto Rico's North Coast (Puerto Rico Coastal Zone Management Program 2009). In Puerto Rico, dunes (or in some cases, dune remnants) can be found in the municipalities of Isabela, Quebradillas, Camuy, Arecibo, Barceloneta, Loíza, and Carolina. Of these places, the largest concentration of sand can be found in Isabela, followed by Carolina and Loíza. However, the height and size of these dunes may be insufficient for protection of life and property in the long term. Due to the massive extraction of sand, very few dunes remain. The extraction of sand during the 1960s and 1970s for the construction industry has eliminated large expanses of protective dunes. The practice of beach extraction has been banned. At *Tres Palmitas* beach in Loíza and the coast along Isabela beach erosion has resulted in saltwater intrusion. It is estimated that approximately 2.5 million cubic meters (m³) of sand have been extracted from dunes to the west of *Punta Jacinto* in Isabela, equivalent to the size of the Great Pyramid of Giza in Egypt. With the destruction of the dunes, the potential for shoreline damage due to storm surges has increased, although the magnitude of that potential is still unknown. The present-day conditions of some of the dunes are inadequate since their height, width, and stability offer neither security nor protection to life or property located in the coastal zone (Martínez et al. 1983, as cited by Valeiras 2007). Furthermore, the destruction of the dunes has contributed to coastal erosion as they form a reservoir of sand that replenishes the when beach levels are high and releases to supply sand to eroded beaches during storms (Coates et al. 2000). Additionally, the use of all-terrain vehicles along the beach has had negative consequences on the sand dunes and other coastal resources, such as wetlands and salt flats. These vehicles destroy dunes and rip out vegetation affecting dune equilibrium (Puerto Rico Coastal Zone Management Program 2009).

Bush et al. (1995) reported that hard rock shorelines off Guajataca on the North Coast and in parts of Old San Juan have retreat rates close to zero, while the retreat can be several meters in a single storm on sandy beaches such as El Tuque, the bluffs near Arroyo or Playita Machete on the south coast, or the beaches in the tourist areas of Condado and Isla Verde (Bush et al. 1995). More recently, in 2010 Dr. Maritza Barreto conducted a geomorphic assessment at selected beaches in Puerto Rico sponsored by the Puerto Rico Coastal Zone Management Program (Barreto 2010). The sites included: Playa Puerto Nuevo at Vega Baja, Playa Piñones at Loiza, Playa Fortuna at Luquillo, Playa Humacao at Humacao, Playa Salinas at Salinas and Playa Maní at Mayaguez (figure 1). This study integrated an evaluation of historical subaerial beach, beach profile and width changes studies. Historical subaerial beach changes were evaluated using vertical aerial photos from 1936 to 2010 (long-temporal scale study). Beach profile and width were measured using field techniques during August, September, October, November, and December 2010 (short temporal scale study). Data collections were done during normal conditions and after occurrences of storm systems (both tropical and extratropical). Historical beach changes showed loss of sand in all study sites during the 2007 period. Major beach changes were observed at Playa Fortuna, Luquillo and Playa Humacao. Major loss of sand was measured in Playa Fortuna (figure 2). Minor beach changes were identified in Playa Piñones, Playa Salinas, and Playa El Maní. The short temporal scale beach assessment indicated elevation and width suffered changes in all beaches included in the study. The final results of the study showed that geomorphic indicators (*i.e.*, eolianites, beach rock, coral reef, sand deposits, rocky shorelines) found in beach systems act as barriers that protect the beach plain from erosion processes. Furthermore, man-made structures and activities such as docks, housing, and deforestation affect sediment sources and transport that are important sediment inputs feeding beach systems and preventing erosion.

Construction of breakwaters or jetties for shore protection, navigational purposes or marinas has had a significant impact in Puerto Rico.

A widely recognized example of a man-made structure creating severe erosion/accretion problems in Puerto Rico is the breakwater in Aguadilla. Additionally, as a result of past and current shoreline management practices, coastal development, erosion, and the already observed sea level rise (see PRCCC WG1 report), the coastline around portions of Puerto Rico is retreating about one meter per year (1.0 m/yr), according to a USGS report. The authors considered sequences of past aerial photos to assess erosion and accretion (Thieler et al. 2007). See figure 3 for an example from Rinon. Other publications have come to the same conclusion as the USGS report that most of Puerto Rico's shoreline is eroding (Bush et al. 2009; Morelock 1978, 1984; Thieler and Danforth 1993, 1994b; Bush et al. 1995; Thieler et al. 1995; Morelock and Barreto 2003). However, not all sections of all beaches in Puerto Rico are eroding. Some are stable or are accreting as they transition to new configurations and profile equilibriums as a result of beach migration; for example, Luquillo Beach, the beach between Punta Vacía Talega (the headland west of the city of Loíza) and the Loíza River mouth (just west of the city of Loíza) (Bush et al. 2009). In *America's Most Vulnerable Coastal Communities* the Geological Society of America's authors list seven areas of anthropogenic actions that contribute to Puerto Rico's overall shoreline hazard vulnerability: (1) failure to take shoreline erosion into account; (2) constructing seawalls and revetments at the back of beaches; (3) insufficient construction setback from the shore; (4) other shoreline engineering structures like gabions (wire mesh baskets filled with cobbles or crushed rock); (5) sand mining; (6) inconsistent or uncontrolled shoreline stabilization; and (7) unrealistic cost-benefit considerations (Bush et al. 2009). These underlying vulnerabilities to Puerto Rico's beach systems are expected to worsen due to sea level rise, increasing temperature, increasing carbon dioxide, and increasing intensity of tropical storms.



Figure 1 Beach study sites (source: Barreto 2010)



Figure 2 Extreme subaerial beach loss at Playa Fortuna (December 2010) (source: Barreto 2010)

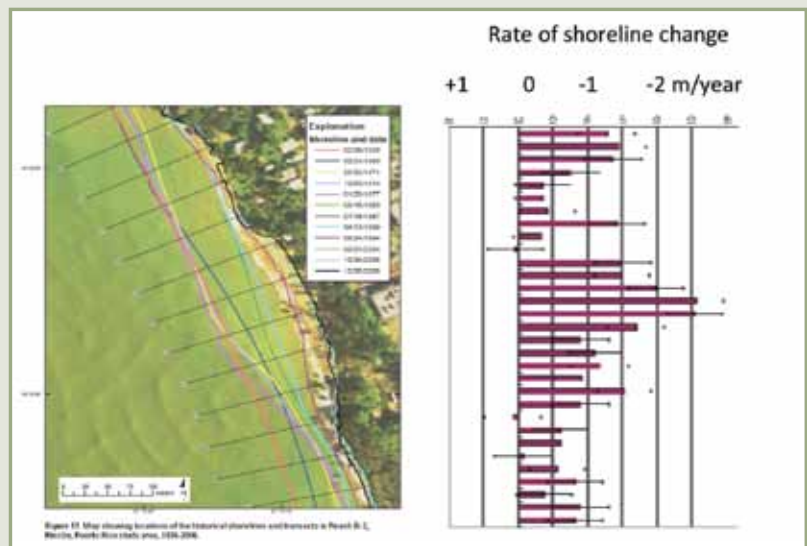


Figure 3 Coast lines every 10 year near Rincon, PR, with matching coastal recession graph.

Outcomes and Consequences of Climate Change to Puerto Rico's Beaches

Sea Level Rise

Sea level rise is one causative factor for dominant beach erosion (*i.e.*, inland migration) and was recognized as occurring long before the global attention from climate change discussions (Bruun 1962). The Bruun Rule (Bruun 1962), a descriptive rule of thumb, predicts that as sea level rises, sand is eroded from the upper beach and deposited on the offshore bottom so as to maintain a stable beach profile. This results in beach retreat so that for every 1 cm (0.4 in) of sea level rise, the beach retreats inland 1 meter (3.3 ft), figure 4, (note: this is a very rough approximation that applies to wide beaches with a slope of 1:100 where sediment transport is not altered by bedrock, buildings, seawalls or other obstructions, and does not include the presence of dunes as a sediment source).

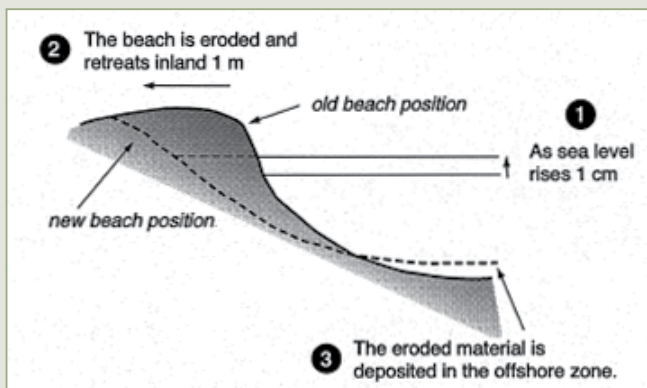


Figure 4 Beach retreat due to sea level rise (Cambers 1997)

However, such erosion may not take place regularly, but may come sporadically during storms (Williams et al. 1999). Thus, as the rate of sea level increases, the rate of beach erosion will increase. Where beaches cannot retreat inland because of other infrastructure or geological features, the rate of beach disappearance will increase. This will have implications for related systems such as dunes, coastal forests and emergent coastal wetlands. And due to the interconnectedness of these systems, impacts to the

beaches, impact other coastal ecosystems, which in turn impacts the beaches again. The concept that dunes are eroded during storms to replenish beach levels has been known since the mid-nineteenth century (Carter 1998). Sometimes the beach-dune exchange system is so well-balanced that storm losses equal interstorm gains, and the net shoreline movement is zero (Psuty 1990). With sea level rise and the diminishment of coastal sand dunes this beach replenishment after storms ecosystem service will be lost and beaches will experience greater shoreline retreat. (For other possible impacts to sand dunes from sea level rise see Christiansen et al. 1985; Christiansen and Bowman 1986; Boorman et al. 1989; Meulen 1990; Carter 1991).

There are many ecological and societal consequences of sea level rise and increased shoreline retreat. In addition to the devastating effects on the local and foreign tourism industry in Puerto Rico and on the ability of the coasts to protect life and property (see WG3 report), decreased beach area will reduce the availability of habitat for beach fauna and flora. A study by Fish *et al.* (2005) showed that a 0.5 m (1.6 ft) rise in sea level in the Caribbean would cause a decrease in turtle nesting habitat by up to 35% (Fish et al. 2005) (see sea turtle sections of this report for more information). The impacts go beyond marine fauna. For instance, certain species of land crabs, such as, *Gecarecinus lateralis* (black land crab) and *Cardisoma guanhumi* (blue land crab), found in Dominica and Puerto Rico, depend on being able to reach the sea to wash their eggs from their legs. This ability may be limited to decreased beach area, an increase in protective sea walls (as already causing problems for these crabs in Dominica), and rising sea levels. The estuarine areas these crabs inhabit will attempt to migrate inland as the seas rise and their required space may conflict with the coastal development that currently exists around Puerto Rico's coasts. This "coastal squeezing" may negatively affect the survival of land crabs. Additionally, ghost crabs or *Ocypode quadrata* inhabit Puerto Rico's beach systems and will also be affected by sea level rise. Some have stated that the decline in undeveloped beachfront habitat and alterations to

the upper intertidal zone by coastal development may represent the greatest threat to the ghost crab (first to stranded oil on beaches from oil tanker traffic which may cause a reduction in the breeding rate and increased mortality at molting) (Gao and Xu 2002, SCDNR and NOAA 2000).

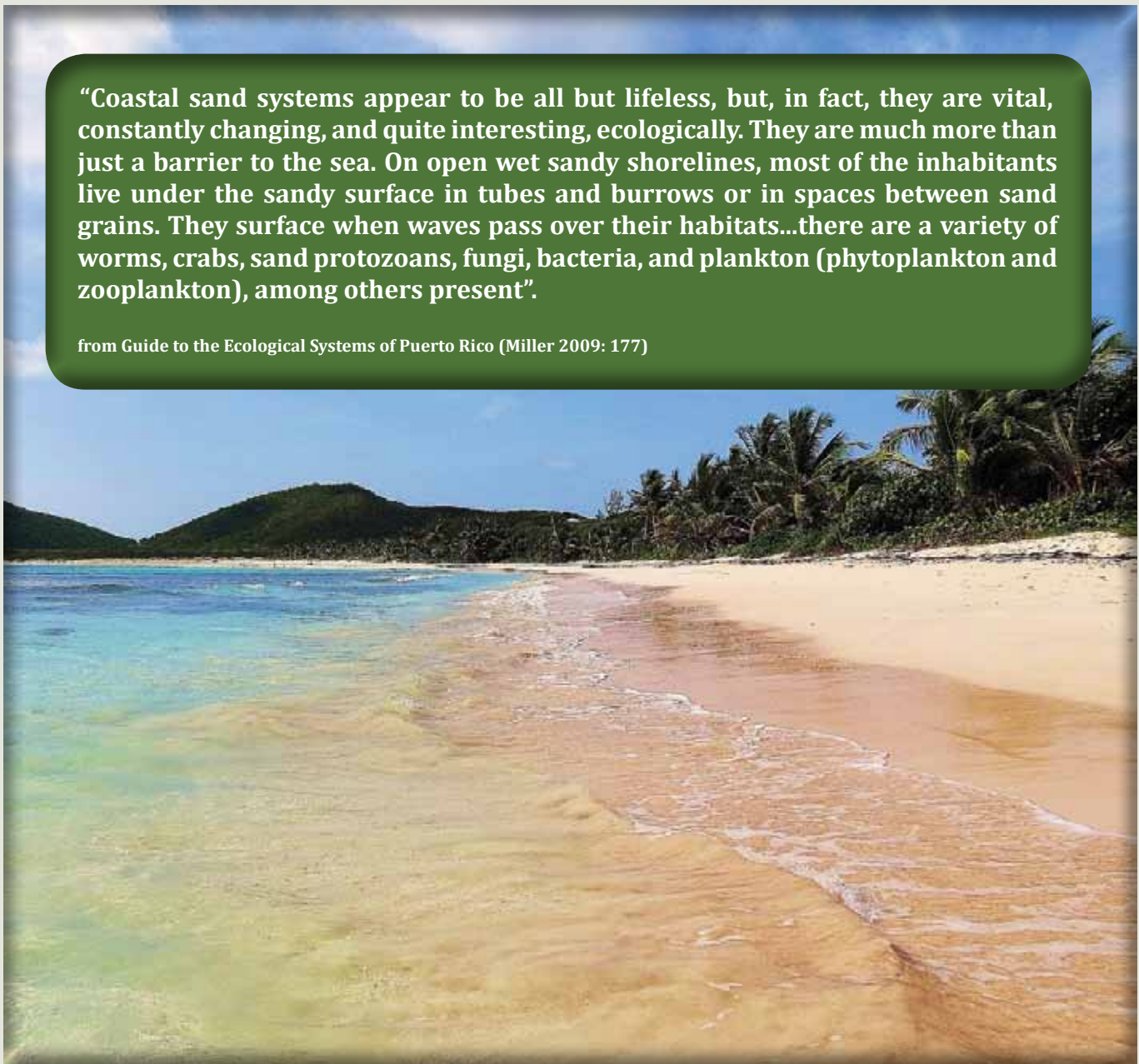
Increasing Temperature

The affects of increasing temperatures on beach ecosystems are mostly related to flora and fauna and less to do with beach stability. Perhaps the most well-known affect from climate change on

beach fauna are how increasing sand temperature of beaches influences the sex ratio of turtle hatchlings. To learn more about the outcomes and consequences of this see the sea turtle section of this report. Less well-known are the affects on smaller fauna of beaches. A simulation model study (Svenssoon et al. 2006) showed that increased sea surface temperature caused faunal community shift and heightened the possibility of invasive species among species of barnacles. Mollusks, particularly the earlier life stages, are particularly vulnerable to changes in UV radiation, pH, and water temperature (Przeslawski et al. 2005).

“Coastal sand systems appear to be all but lifeless, but, in fact, they are vital, constantly changing, and quite interesting, ecologically. They are much more than just a barrier to the sea. On open wet sandy shorelines, most of the inhabitants live under the sandy surface in tubes and burrows or in spaces between sand grains. They surface when waves pass over their habitats...there are a variety of worms, crabs, sand protozoans, fungi, bacteria, and plankton (phytoplankton and zooplankton), among others present”.

from Guide to the Ecological Systems of Puerto Rico (Miller 2009: 177)



Increasing Carbon Dioxide

The great diversity of beach types around Puerto Rico reflects the fact that there are numerous sources of sand. Sand grains may be fragments of weathered rock or the skeletal remains of marine organisms. Basically, sand comes from one of four sources: riverbeds; erosion of the nearby cliffs, bluffs, and dunes; transport onto the beach via longshore currents; or landward transport of material from offshore (Bush et al. 1995). Many Puerto Rico beaches are composed of coralline sand derived from coral reefs and other marine organisms. As the oceans become more acidic, calcium carbonate exposed to sea water may dissolve, thereby reducing the supply of sand to the beaches. Similarly, the beachrock ledges that form protective barriers near the low water mark on many of the region's beaches consist of calcium carbonate cementing sand grains together – a process also likely to be impacted by ocean acidification.

The doubling of atmospheric carbon dioxide will also have a direct effect on the growth rate of plants, including dune plants and other beach vegetation, through the enhanced accumulation of carbohydrates during photosynthesis. In an enriched carbon dioxide environment, photosynthesis rates may increase up to 100% (Pearch and Bjorkman 1983). However, there are important metabolic differences between species and therefore some plants respond more readily to rises in carbon dioxide than others. In the case of dune vegetation, there are several things to consider for carbon dioxide-enhancement: 1) the metabolic response of the plants; 2) the community response, including competitive plant strategies; 3) the reaction of species to changing physical conditions including increased sand supply to the foredunes and, perhaps, changes in precipitation and groundwater (Carter 1991). The major dune forming plants in Puerto Rico and

the Caribbean are C3 plants, such as *Sporobolus virginicus*, *Spartina patens*, *Ipomoea pes-caprae*, *Canavalia maritima* (these last two are creepers) and it is expected that, if other factors remain unchanged, that dune grasses will grow more rapidly as global climate change proceeds. That is of course if the dune vegetation can adapt to other climate change-induced ecological adjustments like burial from sediment accumulation, progressive destabilization of dune systems from sea level rise, increasing drought due to enhanced levels of evapotranspiration and more competition for limited nutrients, etc. (Carter 1991). It is unknown how well the vegetation will respond to such changes in Puerto Rico, and predictions are difficult to perform. There is a need for scientific evaluation and assessment of Puerto Rico's coastal vegetation and their responses to climate change.

Tropical Storms and Hurricanes

Puerto Rico was largely spared by major hurricanes during its decades of industrialization after World War II. In 1995 Bush et al. wrote: "Wind, waves, storm surge, and overwash are all most severe during hurricanes, but the majority of today's coastal residents and property owners have never experienced the full force of a hurricane. The relatively hurricane-free period from the 1960s until the 1989 brush with Hugo led to an apathetic disregard of the hurricane menace and increased development in high-hazard zones" (Bush et al. 1995: 28). However, in the last two decades the island faced damaging storms. Hurricane Hugo (a Category 3 storm) passed over the northeast corner of PR and caused an estimated \$1 billion in damages; Hurricane Georges (Category 2) crossed the island in 1998, leaving behind 12 dead and total damages amounting to \$2.3 billion (CIER 2007).

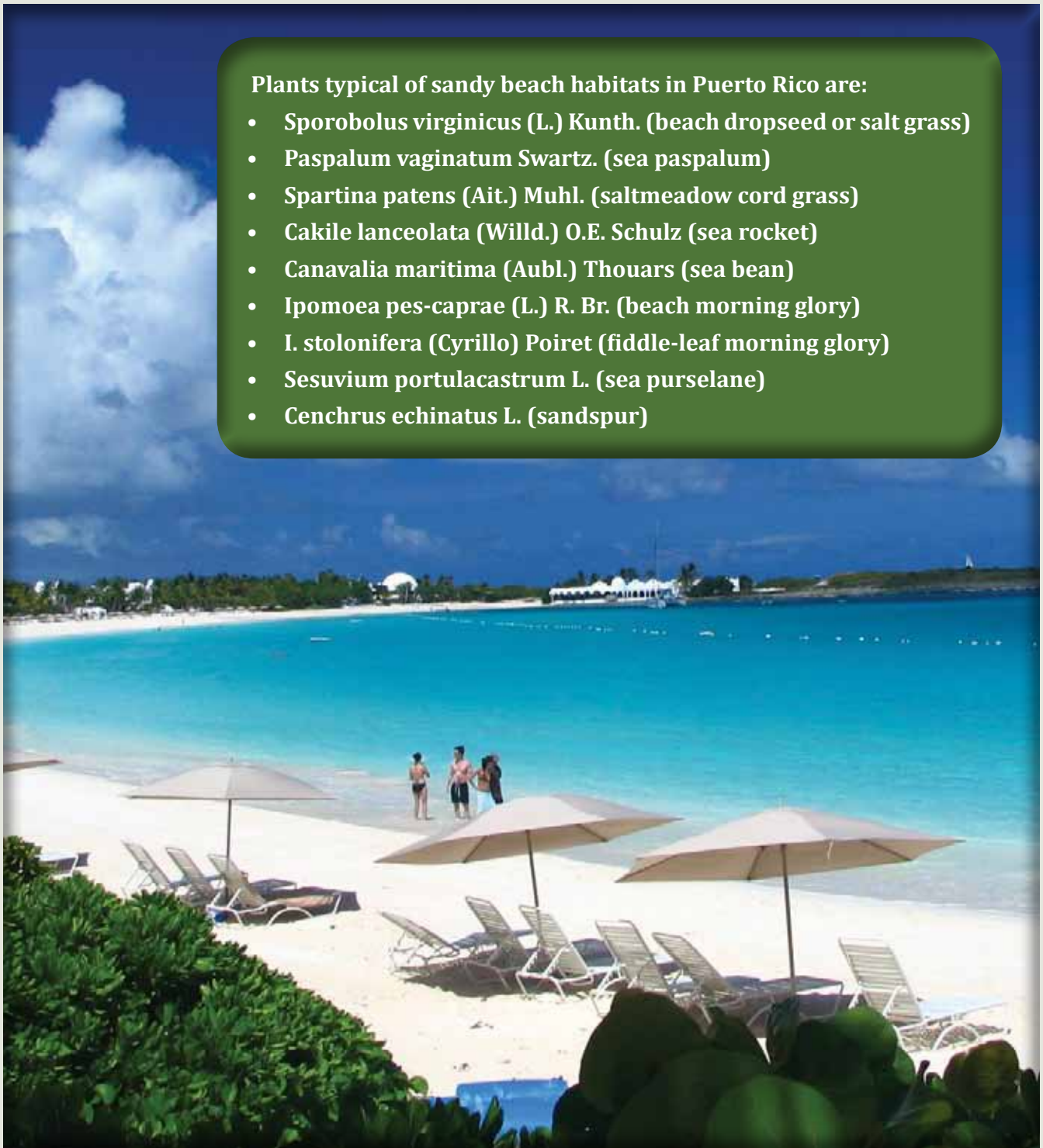
The climate projections for Puerto Rico are that these occurrences will increase in intensity, but

not necessarily frequency (see Working Group 1's findings). As these events become more intense, the rate of beach erosion is likely to increase (Cambers 1996). Whether beaches recover after storms by replenishing their sand supply depends on the conditions of each beach system: (1) the existence and stability of dune systems; (2) the

presence and proximity of coastal development and other man-made structures like sea walls and other hard shoreline structures; (3) the presence and health of naturally protective features such as coral reefs, seagrasses, mangroves, eolianites, and beach rock.

Plants typical of sandy beach habitats in Puerto Rico are:

- *Sporobolus virginicus* (L.) Kunth. (beach dropseed or salt grass)
- *Paspalum vaginatum* Swartz. (sea paspalum)
- *Spartina patens* (Ait.) Muhl. (saltmeadow cord grass)
- *Cakile lanceolata* (Willd.) O.E. Schulz (sea rocket)
- *Canavalia maritima* (Aubl.) Thouars (sea bean)
- *Ipomoea pes-caprae* (L.) R. Br. (beach morning glory)
- *I. stolonifera* (Cyrillo) Poir. (fiddle-leaf morning glory)
- *Sesuvium portulacastrum* L. (sea purselane)
- *Cenchrus echinatus* L. (sandspur)



Research and Information Needs for Beach Ecosystems

1. *Inundation Mapping.* Accurate mapping of sea level rise inundation, as well as storm surge combined with sea level rise inundation is greatly needed for Puerto Rico. At the time of this report Puerto Rico is lacking an official vertical datum (VD) for the islands. This means that accurate elevation data is simply not possible to obtain. LIDAR data, a high resolution data set, exists; however, without an accurate VD the results of an inundation analysis will not be suitable for coastal management. Without an official VD coastal areas cannot be adequately assessed for management purposes. Three studies exist for Puerto Rico to assess sea level rise on coastal areas using the North American Vertical Datum (*i.e.*, Ciudadanos del Karso 2010; Weiss et al. 2011; Capella 2010). They are an excellent first step for visualizations but more accuracy is required for scientific modelling and management decisions for beach ecosystems.
2. *Coastal Vegetation Responses.* More studies are needed on possible responses of coastal vegetation to climate change stressors. In particular, how will they respond to increased carbon dioxide in the atmosphere, sea level rise and associated saltwater intrusion, ecosystem migration, etc.
3. *Coastal dune geomorphology and response to sea level rise:* The morphology of the dune systems will be modified as the beach erodes, the source of sediment decreases and the energy of the waves reaches farther inland. The ability of the dune systems to migrate inland will mainly depend on two factors: the availability of inland space for the dune to migrate, which is greatly affected by the presence of permanent structures landward of the dune, and the availability of beach sediment to be transported by the wind and deposited landward of the beach. Each site will be different based on these factors

and management alternatives need to be developed based on site characteristics. An assessment of current dune morphology should be conducted to evaluate the present condition of the dune systems in Puerto Rico and the factors that may affect the availability of sediment and dune migration process.

4. *Loss of Ecological Functions.* Studies on the consequences of losing ecological functions from birds and other wildlife as they migrate away for Puerto Rico's beaches. For example, impacts of seed dispersal of coastal vegetation.
5. *Beach and Dune Restoration.* Studies on best practices for beach and dune restoration for ecological functions as well as the protection of life and property.
6. *New Public perception studies:* New studies to assess the perception of the people that live and/or use the coastal spaces of Puerto Rico should be conducted. Knowing the way people think and perceive the coast can facilitate the development of management alternatives that consider the priorities and knowledge of local communities, and the creation of education programs intended to inform the public about the importance of coastal processes. Having an educated community may facilitate the implementation and maintenance of management practices.

Summary of Climate Change Impacts on Puerto Rico's Beach Systems

Globally it has been shown that 70% of the world's sandy beaches are eroding, and dune retreat and disappearance is widespread throughout the Caribbean islands, including Puerto Rico. The beaches of Puerto Rico are coastal resources of great importance. Including Vieques, Culebra, and other islets and cays, there are approximately 799 miles (1,285.86 km) of coasts, of which 129.2 miles (208 km) are beaches. In fact, Puerto Rico has over 300 beaches. Beach erosion is not a dominant process if there is a balance between the sediment input and the sediment output in the system under study. Seasonal changes over a period of several

years followed by significant erosion during a particular storm event and slow but steady beach accretion after the storm, characterize systems with a balanced sediment input and output (i.e. sediment budget). The erosion in the insular Caribbean is attributed to anthropogenic factors, e.g. sand mining, and poorly planned coastal development and man-made structures (*i.e.*, sea defenses); and to natural causes, such as winter swells and hurricanes. Anthropogenic or natural factors induce beach migration to reach a new equilibrium state sometimes resulting in net erosion, where the output of sediment is greater than the input, or total system disruption or loss. Tropical storms and hurricanes appear to be the dominant factor influencing the erosion, with beaches failing to return to their pre-hurricane levels.

Sea level rise is another causative factor for dominant beach erosion (*i.e.*, inland migration) and was recognized as occurring long before the global attention from climate change discussions. For many beach systems, as the rate of sea level increases, the rate of beach erosion will increase. Where beaches cannot retreat inland because of other infrastructure or geological features, the rate of beach disappearance will increase. This will have implications for related systems such as dunes, coastal forests and emergent coastal wetlands. And due to the inter-connectedness of these systems, impacts to the beaches, impact

other coastal ecosystems, which in turn impacts the beaches again. Also, as storm events become more intense, the rate of beach erosion is likely to increase. Whether beaches recover after storms by replenishing their sand supply depends on the conditions of each beach system.

There are many ecological and societal consequences of sea level rise, increased intensity of storm events, and increased shoreline retreat. In addition to the devastating effects on the local and foreign tourism industry in Puerto Rico and on the ability of the coasts to protect life and property (see WG3 report), decreased beach area will reduce the availability of habitat for beach fauna and flora, such as sea turtles and crabs. Additionally, changes in temperature and carbon dioxide fertilization will affect beach and dune vegetation affecting flora and fauna as well as potentially disrupting the sand equilibrium of beaches. It is unknown how well the vegetation will respond to such changes in Puerto Rico, and predictions are difficult to perform. There is a need for scientific evaluation and assessment of Puerto Rico's coastal vegetation and their responses to climate change, as well as accurate inundation mapping and studies on the consequences of losing ecological functions of birds and other wildlife as they migrate away from Puerto Rico's beaches.



Box 1: Puerto Rico's Sea Turtles in a Changing World

Of the seven living species of sea turtles (Family Chelonioidae and Dermochelidae) found in all the world's oceans, three are known to nest in Puerto Rico: green turtle (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*), and leatherback (*Dermochelys coriacea*). Leatherbacks are only found during the nesting season, while hawksbills and greens are found in several life stages near our coasts. Juvenile loggerhead turtles (*Caretta caretta*) have been sighted now and again¹ and two stranding reports of olive ridley turtles (*Lepidochelys olivacea*).

Status of Puerto Rico's Sea Turtles

Turtle populations have been declining. Consequently, all species of sea turtles have been classified as threatened to various degrees. While the green and loggerhead turtles are considered to be "Endangered", the hawksbill and the leatherback turtles are classified as "Critically Endangered". These terms are used by the International Union for the Conservation of Nature (IUCN) to classify species which have exhibited population declines of more than 50% and more than 80%, respectively, throughout their global ranges over the course of three generations, which for most species of sea turtle is about 100 years.

The following summarizes issues affecting sea turtles²:

- Exploitation and use at the national level; for example, a number of countries in the region have moratoriums protecting sea turtle populations while some countries continue traditional sea turtle fishing practices;
- Illegal international trade; despite the fact that trade of this species is regulated by the Convention on International Trade of Endangered Species;
- Predation of eggs by domestic animals;
- Loss of nesting habitat (due to erosion caused by storms, sea level rise or sand mining activities);
- Loss of foraging areas (e.g. coral reefs and seagrass beds);
- Diseases, which appear to be increasing in occurrence.

In Puerto Rico, all species are protected by national and federal laws. Efforts to assess the conservation status of sea turtles in Puerto Rico began in 1984, when the first long-term survey was conducted to assess the nesting trends of hawksbill sea turtles in Mona Island. Since then, several collaborators and institutions such as federal agencies, Puerto Rico's government, NGOs and universities have been involved in the recovery and protection of Puerto Rico's sea turtles.



The main nesting beaches for hawksbill sea turtles are located at Mona Island Natural Reserve with approximately 1600 nests in 2010, representing the second most important rookery for this species in the insular Caribbean, and in the municipalities of Humacao, Maunabo, Patillas, Ponce (Caja de Muertos), Vieques and Culebra. Hawksbill nesting has increased not only on Mona Island, but also at other sites of mainland Puerto Rico and on Vieques.



The major nesting beaches for leatherback sea turtles in Puerto Rico are located at the north-east of the main island, in the municipalities of Fajardo, Luquillo, Maunabo, Vieques, and Culebra (Fig. 3). Approximately 300-1,700 nests of this species are laid each year. Leatherback nesting numbers have been increasing in the past seasons, except for Culebra Island, where leatherback nesting activities have been decreasing during the past 7 years (Figure 4).



There are very few reports for green sea turtle nesting activities in Puerto Rico, where the highest nesting numbers for this species had been reported for Vieques Island, with 400 nests in 2010. Additionally, there is only one official report for a loggerhead nest in Puerto Rico at Culebrita (a cay near Culebra Island) in the early 1980's. Although, there have been reports of possible loggerheads nesting at Vieques (but not confirmed).

¹ 3 sightings of juveniles were found in unhealthy states. The potential in Puerto Rico exists for Loggerheads but no established presence to-date.

² Bräutigam and Eckert (2006) provide detailed information on individual species, along with general trends and management issues.

Outcomes and Consequences of Climate Change for Puerto Rico's Sea Turtles

In 2005, the IUCN Marine Turtle Specialist Group identified climate change as one of five key hazards to sea turtles worldwide, making the issue a high priority for further study³.

Sea Level Rise

Research was conducted to predict the impact of sea level rise on Caribbean Sea turtle nesting habitat.³ The researchers concluded that nesting habitat lost from expected sea level rise would have serious implications for sea turtle populations in the region. Sea level rise is also expected to affect foraging grounds, such as seagrass beds, coral reefs and the open ocean.⁴ Further, climate change is expected to result in more frequent and more intense storms, which in turn, would compound the impacts of sea level rise, furthering eroding and altering the topography of beaches. The increase in tidal height may also flood eggs from underneath. If the sand is saturated by storm-driven waves or subsurface flooding and does not drain adequately, the embryos will drown⁴.

Increasing Temperature

In marine turtles, sex is determined by temperature in the middle third of incubation with female offspring produced at higher temperatures and males at lower temperatures within a thermal tolerance range of 25–35°C⁵. A mixture of sexes is produced within the threshold range of temperatures with 50% of either sex at a 'pivotal temperature'.⁶ A Caribbean sea turtle study found that measurements in both the sand and the clutches laid by hawksbill turtles at Pasture Bay, Antigua, show that for important parts of the nesting season temperatures are already above the level producing 50% of each sex (pivotal level); and it was estimated that fewer males were produced in 2003 than in the previous years.⁷ On Mona Island, Puerto Rico, several studies have indicated a slight increase in sand temperatures and, therefore, hawksbill nest temperatures as well.⁸ Long term studies at Mona Island to assess pivotal temperatures and hatchling sex ratios⁹, as well as beach profiles and sand and nest temperature for the main leatherback nesting beaches at Culebra Island are being conducted. Species such as the hawksbill turtle, which nest under the vegetation and in tropical beaches, may not be as affected as other species such as leatherback, green and loggerhead turtles which nests are laid exposed in the beach. In general, it is not clear precisely how great the effects of climate change on sea turtle reproduction will be. Comprehensive long-term data sets are needed to fully research the matter; and until then, how sea turtles will respond to climatic change remains a matter of speculation.

The long distance movement of marine turtles is one of the wonders of the natural world, with recapture techniques showing how some species move thousands of kilometers across the ocean.¹⁰ Research suggests that migration routes are strongly influenced by two factors: sea surface temperature and chlorophyll concentrations.¹¹ As such climate change has the potential to impact migratory patterns of sea turtles.

Temperature increases can affect severity of infection¹² and may also increase outbreaks of disease in sea turtles. Moreover, many disease outbreaks peak during El Niño events, suggesting a significant climatic influence on the interactions among hosts, pathogens, and the environment. Unusually warm or cold sea surface temperatures can displace food sources, reduce host defenses and alter the growth of disease pathogens.

Other climate change outcomes for Puerto Rico's sea turtles

Intense rains and flooding (extreme weather events) can provide pulses of nutrients, chemical pollutants and pathogens, all of which can promote disease outbreaks, in addition to the increasing temperatures. As listed in other sections of this report, sea turtle feeding grounds may be affected by climate change since green turtles and hawksbill turtles depend on sea grass beds and coral reefs ecosystems for food.

³ Fish et al. (2005)

⁴ SWOT Report (2006)

⁵ Ackerman (1997)

⁶ Mrosovsky (1988)

⁷ Glen and Mrosovsky (2004)

⁸ Barrientos et al. (in press)

⁹ Mrosovsky et al. (2009)

¹⁰ Meylan (1995)

¹¹ Thomas and Dabo (2005)

¹² Haines and Kleese (1976)

Introduction to Wetlands and their Ecosystem Services

Since 1970, the U.S. Army Corps of Engineers (Corps) and the U.S. Environmental Protection Agency (EPA) have defined Wetlands for regulatory purposes (Section 404 of the Clean Water Act) as "...areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas." The Ramsar Convention on Wetlands and Waterfowl (1971, as amended) defines wetlands as areas that "...include a wide variety of habitats such as marshes, peatlands, floodplains, rivers and lakes, and coastal areas such as saltmarshes, mangroves, and seagrass beds, but also coral reefs and other marine areas no deeper than six metres at low tide, as well as human-made wetlands such as waste-water treatment ponds and reservoirs." Among the most widely accepted definitions is that of Cowardin et al. (1979), adopted by the U.S. Fish and Wildlife Service, "Land where an excess of water is the dominant factor determining the nature of soil development and the types of animals and plant communities living at the soil surface. It spans a continuum of environments where terrestrial and aquatic systems intergrade." These definitions comprise three main aspects - water, soil, and organisms - which are accepted by wetland scientists as the basis for recognizing and describing wetland environments. The three basic components of wetlands are summarized below (Schot 1999, Charman 2002):

WETLANDS

1. **Ground water** -- Ground water (water table or zone of saturation) is at the surface or within the soil root zone during all or part of the growing season.
2. **Hydric soils** -- Soils are characterized by frequent, prolonged saturation and low oxygen

content, which lead to anaerobic chemical environments where reduced iron is present.

3. **Specialized vegetation** -- Plants adapted for growing in standing water or saturated soils.

Water quality is not specified--salinity varies from fresh, to brackish, to marine, to hypersaline. Acidity may span the entire range of naturally occurring pH values. Depth of standing water in pools and hollows is usually too deep to walk through but too shallow to swim in. However, tidal flats are flooded daily, and many wetlands experience deeper floods from time to time. Emergent vegetation ranges from heavily forested swamps to nearly bare playas and mudflats.

In Puerto Rico, the most widely used classification system is Cowardin 1979. This system was developed by the U.S. Fish and Wildlife Service and establishes two basic types: coastal (tidal or estuarine wetlands) and inland (also known as non-tidal, freshwater, or palustrine wetlands). Working Group 2 members of the PRCCC recommended evaluating potential affects of climate variability and change for coastal or tidally influenced wetlands as well as those riverine, palustrine wetlands (non-tidal) which due to their geographic location may be impacted by air or water temperature increase, increase in salinity, increase in sedimentation due to runoff, as well as increase in salinity due to sea level rise and increased coastal inundations. This section is the first attempt to do so.

Eight basic wetland types are recognized in Puerto Rico based on studies completed by the U.S. Army Corps of Engineers (U.S. Army Engineer Waterways Experiment Station 1978) but only seven are relatively common:

1. **Saltwater aquatic** -- Plants dominate in this type of wetland and may be floating or anchored to the bottom by roots. This type of wetland is permanently flooded by salt or brackish water. Seagrass beds are an

example of this type of wetland (but, due to their importance, seagrasses are discussed in a separate section). Other examples are submerged flats covered by macroalgae or mudflats.

2. **Saltwater flats** – Wetlands with a vegetative cover of 25% or less. These wetlands are flooded by saltwater during high tide. Salt flats that are found in many coastal areas, often associated with mangrove forests, are an example of this type of wetland.
3. **Saltwater marsh** – Wetlands with 25% or more vegetative cover of which less than 40% of the plants are trees or shrubs. These wetlands are regularly or occasionally flooded with salt or brackish water. This type of wetland is very common in the U.S. but not in Puerto Rico. Wetlands of this type that are found in Puerto Rico are dominated by ferns or succulent plants and are located behind mangrove forests.
4. **Saltwater swamps** – Wetlands with more than 40% cover of trees and shrubs. These wetlands are flooded occasionally or regularly by salt or brackish water. The most well-known example in Puerto Rico is the mangrove forest.
5. **Freshwater aquatic** – The dominant vegetation in this type of wetland is floating or anchored to the bottom by roots. These areas are permanently or almost always flooded. These wetlands are associated with creeks and rivers, lakes and ponds, and channels and reservoirs.
6. **Freshwater marsh** – Plants cover more than 25% of the area within this type of wetland and trees and shrubs cover less than 40% of the area. These wetlands are flooded occasionally or regularly. An example of a shallow freshwater marsh is a marsh dominated by species of grass adapted to wet conditions like juncos. Another example is a deep marsh where the most common species is cattails

and water lilies or other floating species are found in deeper areas of the marsh.

7. **Freshwater swamp** – Trees or shrubs cover more than 40% of the area within these wetlands. These wetlands are flooded by freshwater occasionally or regularly. In addition to the trees that grow in these areas, many epiphytes (plants that grow attached to other plants for stability) and vines grow in freshwater swamps. It is likely that this type of wetland was more common in the coastal zone of Puerto Rico in the past but the conversion of lands for agricultural use, the cutting of trees for wood, and fires set by people to clear land have caused a drastic decrease in the size of these wetlands.

Emergent coastal wetlands are wetlands that emerge above sea level and are influenced by astronomical tides. They include tidal freshwater marshes, salt marshes, mangrove swamps, and tidal flats. Tidal freshwater marshes are found upstream of estuaries where the tide still influences water level, but the water is predominantly fresh. Brackish and salt marshes are found closer to the coast and are subjected to periodic flooding by the sea. Mangroves represent a large variety of plant families that have genetic adaptations which enable them to colonize saline coastal environments (Field 1995). Tidal flats are depositional formations found near estuaries and in front of mangroves.

Emergent coastal wetlands, specifically mangroves, provide many important ecosystem services, such as sequestering carbon and mitigating against possible disasters. Coastal wetlands and marine ecosystems hold vast stores of carbon. Occupying only 2% of seabed area, vegetated wetlands represent 50% of carbon transfer from oceans to sediments. This carbon may remain stored in buried sediments for millennia. Loss of coastal wetlands and marine ecosystems such as peatlands, forested tidal wetlands, tidal freshwater wetlands, salt marshes, mangroves, and seagrass beds lead to decreased carbon sequestration and can also

lead to emissions of large amounts of CO₂ directly to the atmosphere. Mangroves are important carbon sinks, and sequester approximately 25.5 million tons of carbon every year. They also provide more than 10% of essential dissolved organic carbon that is supplied to the global ocean from land (Spalding 1997).

Carbon sequestration can be defined as the capture and secure storage of carbon that would otherwise be emitted to or remain in the atmosphere, or to prevent, carbon emissions produced by human activities from reaching the atmosphere, by capturing and diverting them to secure storage. It is through this process that agriculture and forestry practices remove CO₂ from the atmosphere (Melkania et al. 2007). Wetlands are a major sink of carbon dioxide. Wetlands' low decomposition rates associated to

capacity, better soil structure, improved soil quality and nutrient cycling, and reduced soil erosion (Derner and Schuman 2007). Figure 5 provides a list of other ecosystem services provided in Puerto Rico by wetland ecosystems, such as contaminant retention from land-based sources of pollution, servicing as nursery areas for recreationally and commercially-important fish species, tourism value, and cultural and mental well-being from aesthetically pleasing viewsheds.

Mangroves are wetland systems that have particularly tremendous social and ecological value. The annual economic value of mangroves, estimated by the cost of the products and services they provide, has been estimated to be \$200,000 - \$900,000 per hectare (Wells et al. 2006). The majority of the human population in the world is concentrated in coastal areas which

are more vulnerable to natural disasters such as floods, wind generated waves, tsunamis, and storm surges (Ramesh and Ramachandran 1999). Although mangrove ecosystems provide various services, the most important service provided by mangroves is the protection against coastal disasters and tsunamis (Rabindra Osti et al. 2009).

Generally, it is thought that mangroves prevent coastal erosion, and act as a barrier against typhoons, cyclones, hurricanes, and tsunamis, helping to minimize damage done to life and property (Upadhyay 2002; Dahdouh-

Guebas 2006; Pearce 1996; Mazda, Y et al. 1997), although the use of coastal vegetation as a "bioshield" against extreme events like large storm surges and tsunami is still under investigation in the scientific literature (Feagin et al. 2009). Mangrove tree species that inhabit lower tidal zones can block or buffer wave action with their stems, which can measure 30 meters high and several meters in circumference

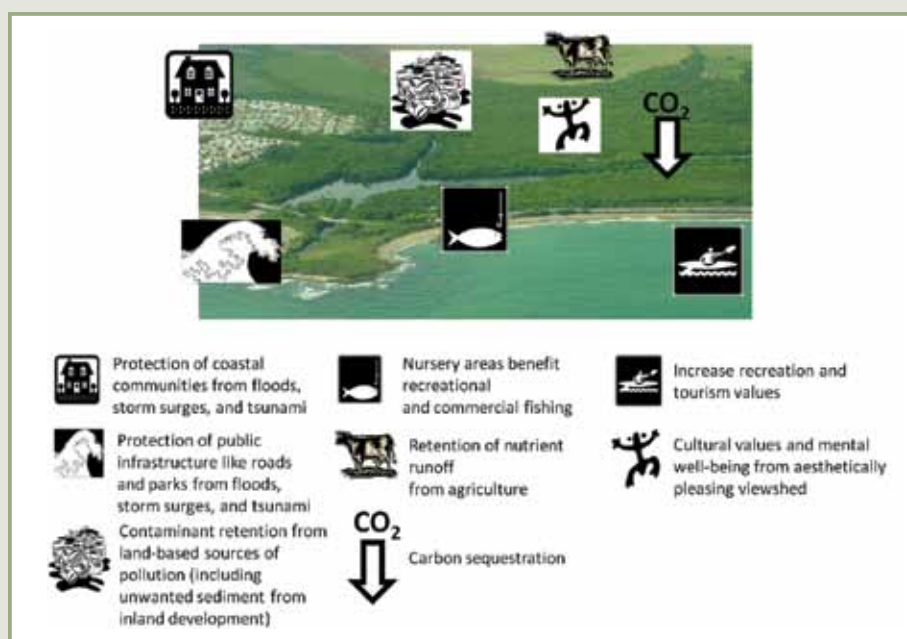


Figure 5 Ecosystem Services of Wetlands in Puerto Rico

anaerobic soils "slow down" the increasing rates of carbon dioxide emissions in Earth's atmosphere. Increased carbon dioxide levels globally also results in higher primary productivity in most, if not all, wetlands. This "CO₂-fertilization" effect could enhance the standing stock of carbon in the ecosystem (Mitra et al. 2005). Carbon sequestration also provides associated ecosystem co-benefits such as increased soil water holding

(Dahdough-Guebas 2006). Mangroves defend the land from wind and trap sediment in their roots, maintaining a shallow slope on the seabed that absorbs the energy of tidal surges (Pearce 1999).

Mangroves protect the coast against waves, currents and storms and from coastal erosion. They are like live sea walls, and more efficient than concrete wall structures (Kathiresan, 2000). Some of the mangrove species, such as *Rhizophora* (or the red mangrove) act as a physical barrier against tidal and ocean influences and shields the coast by means of their large above-ground aerial root systems and standing crop (Dahdough-Guebas et al. 2005). It is also found that these mangrove species seem to act as a protective force towards this natural calamity (McCoy et al. 1996).

In India and the Phillipines, villagers tell how they have been protected from tsunamis, cyclones and other natural disasters in locations where mangroves are intact, but suffer where mangroves have been converted to shrimp farms or were lost due to human activities (Dahdough-Guebas et al. 2005; Walters 2004). In Viet Nam mangroves have been observed to limit damage from tsunamis and cyclone waves and have led to large savings on the costs of maintaining sea dykes (Asian Wetland Symposium 2006). Remains of rows of mangroves planted by Maoris can still be seen in New Zealand to stabilize the coast indicating that mangroves helped in coastal protection (Vannucci, 1997).

Wave energy of tsunamis may be reduced by 75% if the waves pass through 200 meters of mangrove (Massal et al. 1999). It has also been found that 1.5 km belt of mangrove may be able to reduce entirely a wave one meter high (Mazda et al. 1997). It has been reported in literature that mangroves even protected villages and reduced death toll during floods and cyclones (Das and Vincent 2008). The benefits of mangroves for shoreline protection and storm damage control have been estimated to

run into tens of thousands of dollars per km² in Sri Lanka and Malaysia. Studies carried out in Viet Nam show that the value over time of mangroves in protecting against extreme weather events lies around US\$55,000 per km² (IUCN 2006).

It has been reported in the literature that mangroves reduce cyclone impact by dissipating wave energy and decreasing the impact caused due to cyclone (Badola and Hussain 2005; Fosberg 1971). Das and Bellamy (2007) also concluded that mangroves played an effective role in providing protection against cyclones. In one study by Narayan et al (2010) it was concluded that the mangroves have a definite positive effect on the ports in terms of wave attenuation. From studies done world wide it has been concluded that cyclone impacts have been greatly lessened and losses in life and property damage would have been avoided if healthy mangrove forests had been conserved along coastlines (ASEAN 2009).

Other ecological and socioeconomic values of mangrove ecosystems are well known and increasingly recognized. Well-protected mangroves provide valuable life support services such as fisheries nurseries and habitat, coastal protection, or water quality services yielded. Mangroves also play a vital role in the interconnected nature of coral reefs, mangroves, forests, and sea grasses, which provide joint benefits to human populations. In turn, these economic benefits accrue to local, national and global populations. The economic costs of mangrove ecosystem loss and degradation is expected to be felt the hardest by the economically disadvantaged coastal communities, specifically due to their limited options for alternative livelihoods and coping capacity against hazard events.

Status of Wetlands Worldwide, in the Caribbean, and in Puerto Rico

Worldwide

Between 1980 and 2005, 35,000 km² of mangroves were cleared and drained; about 20% of the total area of mangroves was lost (Spalding et al. 2010). Coastal wetlands are under direct and increasing threat from land use changes pressures (Coleman et al. 2008), from indirect impacts of upstream disruption to sediment supply, and from development pressures and rising sea level at the coast. Altered sediment supply exacerbate sea level rise, with local rates commonly twice, and in some locations as much as 10 times global rates (Syvitski et al. 2009). Large areas of coastal wetlands worldwide have been drained and converted to other uses. Seagrass beds have declined by 29% since the 19th century, and the rate of loss is estimated to have increased by an order of magnitude in the past 40 years (Waycott et al. 2009). Salt marshes and freshwater tidal marshes have lost more than 50% of their historical global coverage, with the current rate of loss estimated at 1-2% per year (Secretariat of the Convention on Biological Diversity 2010).

Caribbean Wetlands

Emergent coastal wetlands, particularly mangrove forests are widespread and an important resource in the insular Caribbean (Spalding et al. 1997). Despite the attempts to protect them by implementing coastal management and planning programs and declaring them Wetlands of International Importance or Ramsar sites, there is still a net loss of mangroves and salt marshes in the insular Caribbean (Bacon 2000). Of the 195 wetland sites investigated by Bacon in 1991, some 47% showed evidence of serious resource degradation resulting from human impact and all sites showed some damage (Bacon 1991; 1995). A range of impacts were identified with the most important being:

- Landfill and solid waste dumping;

- Vegetation clearing, particularly unregulated cutting for timber or charcoal production;
- Reclamation for agriculture, including some fish pond construction;
- Hydrological alteration, particularly by roadways or flood diversion schemes;
- Pollution by factory and domestic effluent.

Puerto Rico's Wetlands

Lugo and Cintron (1975) classified the Puerto Rican mangroves into two groups based on climate and other criteria. The northern-coast mangroves are subject to high wave energy, high precipitation, and river runoff. The southern-coast mangroves are subject to low wave energy regime, low precipitation and low river runoff, if any. Basin and riverine mangroves predominate in the northern-coast type mangroves, while fringe mangroves predominate in the southern-coast type mangroves. All types are subtropical (*sensu* Holdridge), and subject to the same temperature regime. According to the 1989 National Inventory of Mangroves for Puerto Rico (Torres Rodriguez 1994), there are 97 "mangrove sites", or places where mangrove ecosystems occur around the island; these sites typically contain various fragments of mangrove forest. Mangroves cover about 1,900 ha in northeastern Puerto Rico and account for 22% of all of the island's mangrove forests. The largest remaining areas are found east of the Rio Espíritu Santo, in the Las Cabezas Reserve, in the Ceiba Forest, and at Roosevelt Roads. These mangroves are typically characterized as: *Rhizophora mangle* dominated stands on coastal and estuarine fringes; *Avicennia germinans* and *Laguncularia racemosa* in basins as pure or mixed stands; or *Conocarpus erectus* and the shrub *Suriana maritima* in mixed stands. Species richness is very low. Mangrove forest structure is strongly affected by salinity, nutrient availability, and storm disturbance. Typical mixed mangrove *Laguncularia racemosa*-*Avicennia germinans* associations growing at the Las Cabezas Reserve and Roosevelt Roads areas had canopy heights of 12 m, stem densities (stems ≥

10 cm) of 344 stems ha⁻¹, and relatively low basal area (15 m² ha⁻¹) and aboveground biomass (57 t ha⁻¹) (Gould et al. 2006).

Mangrove forests have gone through a period of decline and partial recovery related to human activities such as altered hydrology for agricultural practices, urbanization, and the implementation of conservation activities (Martinuzzi et al. 2009). Martinuzzi et al. (2008) used historical information and long-term landscape analyses to relate land use changes over the last 200 years. The population density of Puerto Rico has undergone dramatic increases in the last 200 years from about 50 people/km² to more than 400 people/km². Four distinct eras of mangrove change were visible over this time period. During the agricultural era (1800-1940) the area of mangroves declined 45%. As the economy changed to industrial in the late 1940s, the area of mangroves increased due to reduced land use pressure on these wetlands. However, with urban expansion between 1960s and 1970s, another decline was evident. Public concern for mangrove conservation resulted in the legal protection of all the mangroves in 1972, and since then their area has expanded. Between 1977 and 2002 the mangrove coverage in Puerto Rico increased by 12% from 7,443 hectares to 8,323 hectares. This study also found that past human activity altered the original proportion of mangrove species. The area of mangroves increased in rural and urban/rural sites, but not in urban ones. In urban sites the mangroves decreased by 2%. The number and size of mangrove-forest fragments were impacted by land use, and urban areas had fewer and smaller fragments than vegetated areas. Fifty five percent (55%) of today's mangroves are located in rural sites, thirty eight percent (38%) in urban/rural sites, and seven percent (7%) in urban sites. In addition, fifty nine percent (59%) are located in protected sites, or within reserves, twenty six percent (26%) are in partially protected sites, or sites that are partially included within reserves and fifteen percent (15%) are in non-protected sites, or outside of reserves.

Outcomes and Consequences of Climate Change on Wetland Ecosystems

Climate modeling studies generally estimate that that global temperature will rise a few degrees in the next century (see Working Group 1 report). Such warming is likely to raise sea level by expanding ocean water, and melting glaciers and portions of the Greenland Ice Sheet (Titus and Narayanan 1995). Warmer polar ocean temperatures could also melt portions of the Ross and other Antarctic ice shelves, which might increase the rate at which Antarctic ice streams convey ice into the oceans (Titus and Narayanan 1995). The dynamics and evolution of wetlands along the coasts is strongly influenced by the gradual rise of sea level that has occurred during the last half of the Holocene period and continues to the present. Rising sea level drives wetland evolution by changing the hydrology, hydrodynamics, and sediment dynamics of the coastal zone (Nuttall *et al.* 1997). When wetland elevation is low relative to sea level, frequent inundation by tides enhances the supply of suspended sediment and nutrients to the wetland. This stimulates accretion by sedimentation. As well, the enhanced nutrient supply supports abundant growth of vegetation, and this contributes to accretion through the production of roots and rhizomes and by trapping suspended sediment for incorporation into new wetland sediment. If the elevation of the wetland increases relative to sea level, tidal inundation becomes less frequent; accretion slows; and the rate at which wetland elevation increases is reduced (Nuttall et al. 1997).

Our current understanding of how wetlands will respond to sea level rise is the prediction that they will either migrate landward or be lost, according to the Brinson *et al.* (1995) model of coastal habitat migration. According to Titus and Narayanan (1995), there is a 10 percent chance that climate change will contribute 30 centimeters (cm) by the year 2050, 65 cm by the year 2100, and two (2) meters (m) by the year 2200.

Global climate change is expected to exacerbate the loss and degradation of mangrove forests and the loss or decline of their species, and to harm the human populations dependent on their services (Millennium Ecosystem Assessment, 2005). Coastal wetlands in Small Island Developing States are especially vulnerable to impacts from relative sea level rise since they have a limited capacity to adapt, including limited space to accommodate landward migration of mangroves and other coastal ecosystems. After surveying over 200 coastal wetland sites in the insular Caribbean, Bacon (1994) suggests that responses to sea level rise would be quite variable since there is a wide range of wetland types and geomorphic settings in the region.

Sea Level Rise

Salt water and tides combine to create an environment in which most plants, except salt-tolerant species (halophytes), cannot survive. Mangrove swamps, dominated by halophytic shrubs or trees, are common in warm climates such as southern Florida and Puerto Rico. Tidal freshwater wetlands form in upstream coastal areas where the influence of salt water ends. Under natural conditions, coastal wetlands adjust to rising seas and changes in local storm patterns, but climate changes and human activities that alter natural conditions disrupt wetland hydrology, biogeochemical cycling, and other processes that sustain wetlands (Morris et al., 2002). The potential effects from rising sea levels on mangroves are:

- Probable loss of total mangrove areas due to erosion of the seaward margin of the mangroves and loss of protective lagoon bars and sea barriers;
- Relocation and migration of mangroves inland, rather than overall loss. This landward migration can be obstructed if the landward margin of the mangrove area is steep or if there are seawalls and other developments (coastal squeeze), thereby reducing the areas of coastal ecosystems;

- Change in mangrove forest structure. Landward replacement of black mangrove (*Avicennia*) by red mangrove (*Rhizophora*) and possible increased growth and productivity of the mangrove areas from carbon dioxide fertilization;
- Increase in mangrove area and changes to associated wetland community types and distribution. Saline intrusion into inland freshwater wetlands and rejuvenation of salinas and scrub mangrove sites.

Mangrove forests in the Insular Caribbean are of four main functional types (Lugo & Snedaker, 1974) based on edaphic and hydrologic conditions: riverine, fringe, basin and scrub. Bacon (1994) stressed the importance of site-specific analysis and recommended that more attention be paid to site physiography, hydrology and ecology in predicting responses of tropical coastal wetlands to sea level rise. For instance, among the most at-risk wetland ecosystems are mangroves, but the good news is that not all coastlines with mangrove forests are projected to experience negative impacts to sea level rise. Mangrove ecosystems on low relief islands and those deprived of sediment are especially vulnerable. In contrast, mangroves with ample sediment supplies and/or room to move inland are likely to survive projected rates of sea-level rise (McLeod and Salm 2006:6). If the sedimentation rate keeps pace with local rising sea level, mangrove forests could remain largely unaffected (Snedaker, 1993; Ellison, 1996). Mangroves have demonstrated different tolerances to changes in sea level, salinity, and storms (McLeod and Salm 2006:6). However, their ability to migrate landward or seaward is also determined by local conditions, such as infrastructure (e.g., roads, agricultural fields, dikes, urbanization, seawalls, and shipping channels) and topography (e.g., steep slopes). If inland migration or growth cannot occur fast enough to account for the rise in sea level, then mangroves will become progressively smaller with each successive generation and may perish (UNEP 1994).

Changes in Salinity

Increases in salinity can be due to sea level rise, groundwater depletion owing to reduced freshwater flux, ground water extraction, or reduced rainfall. This can result in reduced seedling survival and growth, and decreased photosynthetic capacity (Ball & Farquhar, 1984). Loss of freshwater wetlands with saline intrusion is documented in Florida (Ross *et al.*, 1994). More information on changes in salinity and wetlands is provided in the section on precipitation changes and wetlands.

Increased Temperature

Temperature affects the growth, survival, reproduction, and distribution of plants and animals. Through its effects on basic metabolic processes such as respiration, photosynthesis, budburst, egg laying, and food availability, an increase in temperature could, in theory, alter biological diversity at every level in the food web. As air and water temperature increase, species ranges will likely expand toward environments that are presently cooler (IPCC 2007a; Parmesan and Yohe 2003). If dispersal capabilities are limited or suitable habitat is not available, local extirpations and extinctions are likely to occur (Thomas *et al.* 2004). Increased temperatures in terrestrial habitats will reduce streamflow and alter water quality into deltas, estuaries and in coastal regions, causing addition change and/or degradation of coastal ecosystems. However, mangroves are not expected to be adversely impacted by the projected increases in sea surface temperature (Field 1995 as cited in McLeod and Salm 2006). Most mangroves produce maximal shoot density with mean air temperature rises to 25° C and stop producing leaves when the mean air temperature drops below 15° C (Hutchings and Saenger 1987). At temperatures above 25° C, some species show a declining leaf formation rate (Saenger and Moverly 1985). Temperatures above 35° C have led to thermal stress affecting mangrove root structures and establishment of mangrove seedlings (UNESCO 1992; Banus, 1983). At leaf temperatures of 38.0 - 40.0° C, almost no photosynthesis occurs (Clough *et al.* 1982;

Andrews *et al.* 1984 as cited in McLeod and Salm 2006). Combined with higher atmospheric carbon dioxide levels, increased temperature is expected to increase mangrove productivity, by increasing growth and litter production and expansion of the geographical range of some species (Ellison, 1996 as cited in McLeod and Salm 2006). Some scientists have suggested that mangroves will move poleward with increasing air temperatures (UNEP 1994; Field 1995; Ellison 2005). Although it is possible that some species of mangrove will migrate to higher latitudes where such range extension is limited by temperature, Woodroffe and Grindrod (1991) and Snedaker (1995) suggest that extreme cold events are more likely to limit mangrove expansion into higher latitudes.

Increased Carbon Dioxide

Plants respond to higher carbon dioxide concentrations (CO₂) with increases in net photosynthesis and water use efficiency, leading to greater productivity. This “CO₂-fertilization” effect could affect the standing stock of carbon in the ecosystem. Some plants are more responsive to increases in CO₂—these are called C3 species. C4 species are less responsive to CO₂ because they are already quite efficient at capturing CO₂. Because of species differences in sensitivity to CO₂, the composition of a wetland is one factor that will determine whether increases in CO₂ will have an effect or not. One simple prediction is that C3 species will increase in abundance relative to C4 species in a mixed community as CO₂ increases. Mangrove stands would remain under this scenario due to lack of competition.

Increased levels of CO₂ are expected to enhance photosynthesis and mangrove growth rates (UNEP 1994). For example, increased levels of CO₂ significantly increased photosynthesis and the average growth rates in two Australian mangrove species, *Rhizophora stylosa* and *Rhizophora apiculata*, but only when grown at lower salinity levels (Ball *et al.* 1997). Additionally, it is expected that there will be an increase in productivity in mangroves and more efficient water use due to reduced stomatal conductance (Warrick *et al.*, 1987).

Precipitation Changes

Changes in precipitation and run-off patterns appear likely as climate change intensifies, but the uncertainties are large. Changes in freshwater runoff patterns can affect coastal and estuarine biota through several pathways. If freshwater flows to the coast decrease or the timing of freshwater runoff to estuaries changes, the salinity of coastal wetlands and estuaries is likely to increase. The distribution of coastal biota is closely linked with salinity of water and soils. Few studies have documented the interactions between runoff, salinity, and species distribution. Earlier and faster snowmelt in temperate and polar regions due to increasing global temperatures signify changes in freshwater and nutrient delivery to the coast from meltwater-dominated watersheds. Changes in the timing of freshwater runoff to estuaries could affect the productivity of many estuarine and marine fishery species (Nicholls et al. 2007). Changes in runoff can also affect sediment delivery, which has important implications for coral reef ecosystems. Freshwater inflows into estuaries influence water residence time, vertical stratification, salinity, control of phytoplankton growth rates, and the flushing of contaminants in estuaries. In estuaries with very short water residence times, phytoplankton are generally flushed from the system as fast as they can grow, reducing the estuary's susceptibility to eutrophication and harmful algal blooms. Wetland response to climate change depends on local interactions between sediment and organic matter accumulation, hydrology, subsurface processes, and storm events (Reed, 1995; Cahoon et al. 1995). Over the past several decades, water management systems (*i.e.*, Valle de Lajas- Laguna de Guánica and Caño Tiburones), urban sprawl and the increased frequency and intensity of storms have altered the timing and amount of sediment delivered to wetlands.

Changes in rainfall patterns caused by climate change may have a profound effect on both the growth of mangroves and their areal extent (Field 1995; Snedaker 1995). It is known that during long-term droughts some mangrove forests contract while salt flats expand (Cintron

et al. 1978). Decreased precipitation results in a decrease in mangrove productivity, growth, and seedling survival, and may change species composition favoring more salt tolerant species (Ellison 2000, 2004). Decreased precipitation and increased evaporation is also likely to result in a decrease in mangrove area, decrease in diversity, and projected loss of the landward zone to unvegetated hypersaline flats and a decline in growth rates (Ellison 1996; Snedaker 1995).

On the other hand, increasing precipitation may allow for a greater accumulation of sediment and organic matter from runoff resulting in an increased elevation of mangroves (which in turn might help the mangroves adapt to sea level rise). Greater amounts of rainfall could increase mangrove area, diversity of mangrove zones, and mangrove growth rates in some species (Field 1995). Increased precipitation may also allow mangroves to migrate and outcompete saltmarsh vegetation (Harty 2004). Increased rainfall should result in reduced salinity and exposure to sulphates and an increase in the delivery of terrigenous nutrients. The extent of mangrove areas can be expected to increase with increased rainfall, with colonization of previously unvegetated areas at the landward fringe. The diversity of mangrove zones and growth rates should increase (Ellison 1996).

Tropical Storms and Hurricanes

Large storm impacts have resulted in mass mortality in 10 Caribbean mangrove forests in the last 50 years (Jimenez et al. 1985; Armentano et al. 1995). Studies in Anguilla before and after Hurricane Luis in 1995 showed that the mortality rate of the mangroves varied between 68 and 99% as a result of the category 4 hurricane (Bythell et al. 1996). Cahoon et al. (2003) demonstrated that mass mangrove mortality in Honduras caused by a hurricane led to peat collapse which slowed recovery rates following the disturbance. Model projections of South Florida mangroves suggest that an increase in hurricane intensity over the next century is likely to result in a decrease in the average height of mangroves (Ning et al. 2003). Major storms can also lead to a change

in community structure based on a differential response to damage from the storm. Roth (1997) suggests that species proportions may shift because they have different rates of regeneration. Projected increases in the frequency of high water events (Church et al. 2001, 2004) could affect mangrove health and composition due to changes in salinity, recruitment, inundation, and changes in the wetland sediment budget (Gilman et al. 2006). Storm surges can also flood mangroves and, when combined with sea-level rise, lead to mangrove damage or mortality. As previously mentioned however, depending on the speed of change mangrove systems may be able to cope with increasing sea levels and storm surges by migrating inland. Flooding, caused by increased precipitation, storms, or relative sea-level rise may result in decreased productivity, photosynthesis, and survival (Ellison 2000). Inundation of lenticels in the aerial roots can cause the oxygen concentrations in the mangrove to decrease, resulting in death (Ellison 2004). Inundation is also projected to decrease the ability of mangrove leaves to conduct water and to photosynthesize (Naidoo 1983).

Adaptive Capacity of Wetlands

The ability of wetlands to migrate inland to areas of decreasing tidal inundation along undeveloped shores is one way coastal wetlands can persist in spite of rising seas (Ross et al. 2000). However, in many areas coastal development just above the extreme high tide line has limited or eliminated opportunities for wetland migration, a phenomenon that has been labeled “coastal squeeze” (Twilley 1997). The maximum rate that wetlands can migrate into available inland areas is unknown relative to projected changes in sea level over the next century. Nonetheless, the vulnerability of coastal resources and infrastructure to sea-level rise can be expected to increase as both human development and climate change progress (Twilley et al. 2001). Assessing mangrove vulnerability to climate change, and in

particular sea level rise, needs to be done at the local level since vulnerability is site-specific. To build resilience into mangrove conservation plans, managers need to identify and protect mangroves that more likely to survive sea level rise. Table 2 provides an assessment of mangrove vulnerability to sea level rise based on environmental conditions. To assess the adaptive capacity of Puerto Rico’s mangroves site assessments would need to be conducted using the environmental conditions presented in the table, such as whether there is sufficient sediment and freshwater sources, and whether the mangroves are being “squeezed” between coastal development and sea level and therefore unable to migrate inland.

Vulnerability	Local Conditions	Explanation
Most Vulnerable	Low relief islands	- low rates of sediment and peat accretion, particularly vulnerable to sea-level rise because they are subject to drought and wave erosion - expected to experience increased flooding, inundation and salinization of soils and freshwater (Shea et al. 2001).
	Lack of rivers	- lack of sediment and freshwater
	Carbonate settings	- often associated with atolls and islands, where landward migration to escape sea-level rise may not be possible - sediments are mostly locally derived
	Areas subsiding due to tectonic movements, groundwater extraction, or underground mining	- will experience higher sea-level rise and inundation
	Micro-tidal sediment starved environments (small Caribbean islands) (Ellison 1993)	- lack of sediment will lead to decreased geographic distribution and species diversity of mangroves (Houghton et al. 2001)
	Mangroves blocked by coastal development or steep topography	- unable to move inland when sea level rises
Least Vulnerable	Mangroves in deep sediment on high islands	- structurally stronger than mangroves in shallow sediment on low islands (Gillison 1980) and less vulnerable to storm surges than low islands (UNEP 1994) - high islands will be better adapted to survive predicted climate changes due to their larger surface areas, freshwater availability, better soils, and more diverse resources (Shea et al. 2001).
	Riverine mangroves	- receive large amounts of sediment from other areas (Woodroffe and Grindrod 1991) - most productive mangrove habitats due to high nutrient concentrations associated with sediment trapping (Ewel et al. 1998).
	Macro-tidal sediment rich environments (mangroves in northern Australia)	- access to sediment and strong tidal currents to redistribute sediment (Woodroffe and Grindrod 1991)
	Mangroves with room to move landward (backed by low-lying areas, salt flats, undeveloped areas)	- have the opportunity to expand inland when sea level rises
	Mangroves in remote areas	- have limited anthropogenic stresses and not blocked by coastal communities from moving landward
	Mangroves surrounded by flourishing dense mangrove forests	- have steady supply of propagules and seeds

Table 2 an assessment of mangrove vulnerability to sea level rise based on environmental conditions. Courtesy of McLeod, Elizabeth and Salm, Rodney V. (2006). *Managing Mangroves for Resilience to Climate Change*, IUCN, Gland, Switzerland.

Research and Information Needs

1. Accurate Sea Level Rise mapping
2. Annual monitoring of wetland condition:
 - a. Monitoring changes in salinity and hydrology. To determine the salinity and hydrology in mangrove systems, a network of piezometer clusters can be installed at the site for continuous and manual measurements of salinity and water level (Drexler and Ewel 2001).
 - b. Measuring and monitoring changes in elevation. Annual measurements of the soil elevation deficit (elevation change minus sea-level rise) will help determine mangrove ecosystem vulnerability to sea-level rise (Cahoon and Lynch 1997). Current rates of sedimentation can be measured using artificial soil marker horizon plots. Marker horizons measure vertical accretion which incorporates both sediment deposition and sediment erosion. Marker horizons are often used with Surface Elevation Tables (SETs). SETs are used to monitor mangrove vertical accretion and subsidence and provide highly accurate and precise measurements (+/- 1.4 mm total error) of sediment elevation relative to sea-level rise (Cahoon et al. 2002a). To determine how changes in sea-level rise will affect a particular area, it is important to understand the factors influencing surface elevation, such as sedimentation rate, groundwater flow, and biological productivity (Rogers 2004; Whelan et al. 2005). Elevation changes are influenced by both surface and subsurface processes within the soil profile. Surface processes include sediment deposition and sediment erosion, and subsurface processes include root growth, decomposition, porewater flux, and compaction (Cahoon et al. 2002c).
3. Determining mangrove and other wetland vegetation response to historical sea-level rise. Pollen and radiocarbon analyses have been used to document environmental and mangrove dynamics during the Holocene (Wooller et al. 2004; Yulianto et al. 2004; and Versteegh et al. 2004). In a study in Belize, scientists extracted a 10 meter long mangrove peat core. They extracted and radiocarbon dated fragments of mangroves leaves preserved in the core (Wooller et al. 2004). The core provided an 8600 14C year record of mangrove ecosystem changes. Pollen data from the core was used to determine changes in the floral composition of mangroves forests through the Holocene and indicated significant environmental changes such as disturbance from hurricanes or fluctuations in sea level. Changes in stand structure, which is related to changes in salinity, nutrient status, and sea level, were determined by analyzing variations in the stable carbon and nitrogen isotopes in the fossilized mangrove leaves. Historic sediment accumulation rates can also be calculated from 210Pb ("Lead-210") profiles in vibracores (Walsh and Nittrouer 2004). 210Pb is a naturally occurring radioactive isotope of lead that is used to date sediments.
4. Establishment of sentinel sites and a long-term wetland monitoring network (NOAA has a wetlands/CCSLR monitoring program)
5. Assessments of non-mangrove wetland systems in the near future are needed to better understand how climate changes may affect all wetland systems.

Summary of Climate Change Impacts on Puerto Rico's Wetland Ecosystems

Seven basic wetland types are relatively common in Puerto Rico: (1) saltwater aquatic; (2) saltwater flats; (3) saltwater marsh; (4) saltwater swamps (the most well-known example in Puerto Rico is the mangrove forest); (5) freshwater aquatic; (6) freshwater marsh; (7) freshwater swamp. Coastal wetlands provide many important

ecosystem services, such as sequestering carbon, mitigating against possible disasters, assisting with prevention of coastal erosion, contaminant retention from land-based sources of pollution, serving as nursery areas for recreationally and commercially-important fish species, local and foreign tourism, and cultural and mental well-being from aesthetically pleasing viewsheds.

Worldwide, coastal wetlands are under direct and increasing threat from land use changes pressures, from indirect impacts of upstream disruption to sediment supply, and from development pressures and rising sea level at the coast. Large areas of coastal wetlands worldwide have been drained and converted to other uses. Salt marshes and freshwater tidal marshes have lost more than 50% of their historical global coverage, with the current rate of loss estimated at 1-2% per year.

Mangroves are wetland systems that have particularly tremendous social and ecological value. In Puerto Rico, mangroves cover about 1,900 ha in northeastern Puerto Rico and account for 22% of all of the island's mangrove forests. The largest remaining areas are found east of the Rio Espíritu Santo, in the Las Cabezas Reserve, in the Ceiba Forest, and at Roosevelt Roads. These mangroves are typically characterized as: *Rhizophora mangle* dominated stands on coastal and estuarine fringes; *Avicennia germinans* and *Laguncularia racemosa* in basins as pure or mixed stands; or *Conocarpus erectus* and the shrub *Suriana maritima* in mixed stands. Species richness is very low. Mangrove forest structure is strongly affected by salinity, nutrient availability, and storm disturbance. Mangrove forests have gone through a period of decline and partial recovery related to human activities such as altered hydrology for agricultural practices, urbanization, and the implementation of conservation activities.

The negative outcomes and consequences of climate change on wetland system, specifically mangroves, are expected to be primarily due to sea level rise. When wetland elevation is low relative to sea level, frequent inundation by tides enhances the supply of suspended sediment and nutrients to the wetland. This stimulates accretion

by sedimentation. As well, the enhanced nutrient supply supports abundant growth of vegetation, and this contributes to accretion through the production of roots and rhizomes and by trapping suspended sediment for incorporation into new wetland sediment. If the elevation of the wetland increases relative to sea level, tidal inundation becomes less frequent; accretion slows; and the rate at which wetland elevation increases is reduced. Our current understanding of how wetlands will respond to sea level rise is the prediction that they will either migrate landward or be lost. Globally, climate change is expected to exacerbate the loss and degradation of mangrove forests and the loss or decline of their species, and to affect the human populations dependent on their services. Coastal wetlands in islands are especially vulnerable to impacts from relative sea level rise since they have a limited capacity to adapt, including limited space to accommodate landward migration of mangroves and other coastal ecosystems. The potential effects from rising sea levels on mangroves are:

- Probable loss of total mangrove areas due to erosion of the seaward margin of the mangroves and loss of protective lagoon bars and sea barriers;
- Relocation and migration of mangroves inland, rather than overall loss. This landward migration can be obstructed if the landward margin of the mangrove area is steep or if there are seawalls and other developments (coastal squeeze), thereby reducing the areas of coastal ecosystems;
- Change in mangrove forest structure. Landward replacement of black mangrove (*Avicennia*) by red mangrove (*Rhizophora*) and possible increased growth and productivity of the mangrove areas from carbon dioxide fertilization;
- Increase in mangrove area and changes to associated wetland community types and distribution. Saline intrusion into inland freshwater wetlands and rejuvenation of saline and scrub mangrove sites.

For wetlands in general, increases in salinity due to changes in sea level, precipitation, and groundwater supplies can result in reduced seedling survival and growth, and decreased photosynthetic capacity. Temperature affects the growth, survival, reproduction, and distribution of plants and animals. As air and water temperature increase, species ranges will likely expand toward environments that are presently cooler. If dispersal capabilities are limited or suitable habitat is not available, local extirpations and extinctions are likely to occur. Increased temperatures in terrestrial habitats will reduce stream flow and alter water quality into deltas, estuaries and in coastal regions, causing addition change and/or degradation of coastal ecosystems. However, mangroves are not expected to be adversely impacted by the projected increases in sea surface temperature, but rather extreme cold events in higher latitudes are more likely to limit mangrove expansion. Assessing mangrove vulnerability to climate change, and in particular sea level rise, needs to be done at the local level since vulnerability is site-specific.

Changes in rainfall patterns caused by climate change may have a profound effect on both the growth of mangroves and their areal extent. It is known that during long-term droughts some mangrove forests contract while salt flats expand. Decreased precipitation results in a decrease

in mangrove productivity, growth, and seedling survival, and may change species composition favoring more salt tolerant species. On the other hand, increasing precipitation may allow for a greater accumulation of sediment and organic matter from runoff resulting in an increased elevation of mangroves (which in turn might help the mangroves adapt to sea level rise). Greater amounts of rainfall could increase mangrove area, diversity of mangrove zones, and mangrove growth rates in some species. Increased precipitation may also allow mangroves to migrate and outcompete saltmarsh vegetation. More studies are required to better understand how precipitation may change in Puerto Rico and the corresponding changes in wetland systems.

From this brief literature review, it is found that wetlands provide critical ecosystem services to Puerto Rico, such as water quality, coastal protection from waves and storms, fisheries production and tourism. These ecosystem services are at risk from climate change. Puerto Rico agencies and organizations should continue monitoring at local level, research, conservation and restoration programs should be undertaken and whenever possible damages to wetland habitats should be avoided. Every effort should be taken by the government and private sector to conserve and restore wetland ecosystems.



Box 2: Humacao Natural Reserve Case Study: Saltwater intrusion into freshwater wetland ecosystems

By Ricardo J. Colón-Rivera

The Humacao Natural Reserve (HNR) is located on the east coast of Puerto Rico and is composed mainly of wetland ecosystems. During the 1920's, extensive areas of wetlands were drained and extensive networks of levees were constructed for the establishment of sugar cane plantations.¹ By 1979, the fields were abandoned and the drainage pumps unattended when Hurricane David and Tropical Storm Frederick struck Puerto Rico in August of that year. These storms filled the abandoned fields back with water and the six coastal lagoons of the HNR were formed. In the year 2000, the U.S. Army Corps of Engineers (ACOE) began the construction of a channel that would divert excess runoff in the lagoons to the ocean during big rain events, with the purpose of protecting the adjacent community of Punta Santiago from frequent floods. Shortly after the finalization of the project, a big rainfall event opened the mouth of the Antón Ruiz river allowing the ocean to connect with the lagoons through the newly constructed channel causing an increase in the overall salinity of the system. Saltwater intrusion events now occur on a regular basis and are usually preceded by large amounts of rainfall.

Ten years after the final stages of construction of the ACOE channel, the saltwater intrusion caused by the hydrological alteration to the lagoons has caused at least four major ecological changes. Each of these events represent a unique research opportunity and serve as an interesting window to the long term effects of sea level rise (and saltwater intrusion) into the freshwater coastal ecosystems of Puerto Rico and similar ecosystems in the tropics. Hence, the HNR lagoon system serves as a natural laboratory to explore the consequences of altered hydrology and saltwater intrusion expected for the coastal freshwater ecosystems of Puerto Rico in the context of sea level rise.

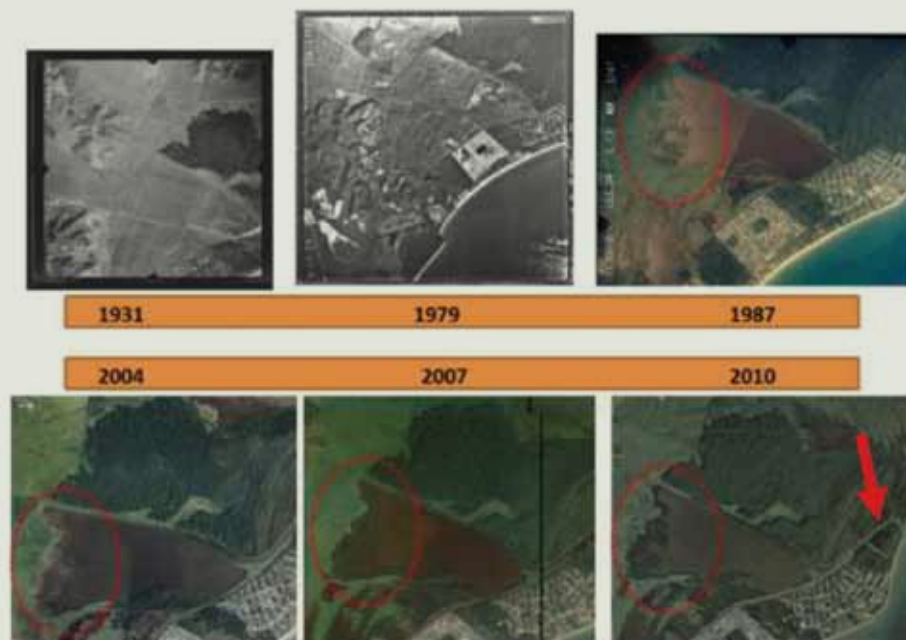


Figure 2.1. Historical progression of the Humacao Natural Reserve lagoon vegetation. The area in these images corresponds to the Mandri 2 and Mandri 3 lagoons, directly connected to the drainage channel (marked by the red arrow). The dark green area to the north east of the images corresponds to the *Pterocarpus* forest of the HNR. In the 1931 image, we can observe the patterns formed by the sugar cane plantations, a common feature of the Puerto Rico's coastal plains during this time. By the time the second image was taken in January of 1979, these plantations were already abandoned and some accumulation of water is visible in the fields. During August of that same year, Hurricane David and Tropical Storm Frederick caused flooding that overtopped the levees and created the HNR lagoon system. After the early 2000's, changes in the hydrological and salinity regimes of the lagoons caused the loss of the herbaceous vegetation creating mudflats (evident in the 2004 image) that allowed the subsequent colonization by red mangrove (2007 and 2010 images, areas highlighted in the dashed red circle). Images courtesy of the DNER, figure prepared by the author for this report.

¹(Ferrer Montañó et al., 2005)

The main observable changes in the Humacao Nature Reserve from saltwater intrusion are:

1. *A shift in the main species of fish present in the lagoons*

The most complete study of the Humacao Natural Reserve's fisheries, conducted before the completion of the drainage channel and the subsequent saltwater intrusion events (during 2000-2001), Ferrer-Montañó et al. (2005) identified the Redbreast and Mozambique Tilapia (*Tilapia rendalli* and *Oreochromis mossambicus*, respectively) as the most harvested species in the Humacao Natural Reserve lagoons. They identified that ~95% of the subsistence anglers (24% of the sample) were local residents that fished almost daily to supplement their diets. These anglers preferred live bait as it attracted more tilapia. Due to the increased salinity in the HNR lagoons most of the tilapias are restricted to the Santa Teresa lagoon², the farthest from the channel and the least saline.³ In the rest of the lagoons, tilapia species have been replaced mostly by the striped mojarra (*Eugerres plumieri*) and other saltwater tolerant species that were less abundant in the reserve. Some questions remain unanswered: How did the fish composition in the HNR change after the saltwater intrusion and how did the local anglers adapt to this species change? Does the striped mojarra fill their dietary needs or did they lose a reliable source of fish protein? Of course, other aspects of this event include the effects on fish biodiversity and local food webs.

2. *Change of vegetation species composition cover in the lagoons edges*

Before the saltwater intrusion events, most of the edges of the lagoons were covered by freshwater marshes composed mainly of southern cattail (*Typha domingensis*) and other herbaceous species. This was one of the most important aspects of the HNR, since freshwater wetlands are less common in Puerto Rico than mangroves forests. During this past decade, most of the *T. domingensis* cover was lost and eventually replaced by mangroves (mostly white mangroves, with red mangroves more common in higher salinity sites, such as the one featured in figure 2.1). The freshwater tree *Pterocarpus officinalis* used to be common near the areas close to the mouth of the Antón Ruiz river, close to the ACOE channel. Increased salinities have killed these trees in some areas that are now being colonized by mangroves as well (figure 2.2).



Figure 2. Dead *Pterocarpus* trees (standing) and an understory dominated by red mangrove on sites that suffered saltwater intrusion. Photo by R.J. Colón

3. *Absence of migratory bird species associated to freshwater marsh vegetation*

One of the most evident examples of the effects of saltwater intrusion into the coastal wetlands of the HNR is the dramatic reduction of nesting sites of the Caribbean coot (*Fulica caribaea*), as evidenced by biological surveys conducted before and after the construction of the drainage channel. The Caribbean coot is a migratory bird species that is considered uncommon in the Caribbean and benefited greatly from the HNR freshwater ecosystems. HNR biologists counted approximately 200 nests on surveys prior to the year 2000, as opposed to the 20 nests counted on the last survey in 2009.⁴ To the reserve biologists this is not surprising, given that this species nests on marsh vegetation in shallow water. Due to increased salinity, most of these wetlands have been replaced by mangroves along the edges of the HNR lagoons giving the Caribbean coot no place to nest. Further research is needed to study the effects on this and other bird species, as well as important food sources like submerged aquatic vegetation in the lagoons.

²Manuel Córabet, *Reserve Manager*, pers. comm. Feb. 21, 2012

³Ferrer (2007)

⁴Manuel Córabet, *Reserve Manager*, pers. comm. Feb. 21, 2012

4. Bioluminescence in the HNR lagoons

Bioluminescence displays in the water are an occasional feature of marine ecosystems. In the tropics, there are several bioluminescent dinoflagellates, although coastal lagoons with constant recurrence of bioluminescence are less common and usually dominated by *Pyrodinium bahamense* (figure 2.3). Bioluminescent lagoons or Bio-bays, are important tourist attractions with the capacity of generating important revenue for local entrepreneurs. These Bio-bays are characterized by shallow entrances, narrow channel connections to the ocean and high salinities (see section on Bioluminescent Bays for more information). In the HNR lagoon system, these conditions are met depending on certain seasonal and environmental factors like rainfall and tidal influence. After the construction of the drainage channel, high salinities and dry conditions have increased the recurrence of bioluminescence events in the HNR lagoons, something that has been observed by local managers and other stakeholders. These events are an interesting indicator of the alteration to the lagoons hydrological and geomorphological features and deserve further research. During the remaining years of the 21st Century, sea level rise is expected to increase the input of saltwater into the HNR and alter the tidal aspects of its hydrological processes. Will bioluminescence become a common feature of the HNR or will it be just be part of the transitory state? What can we learn from these lagoons that can be applied to other coastal lagoons in Puerto Rico?

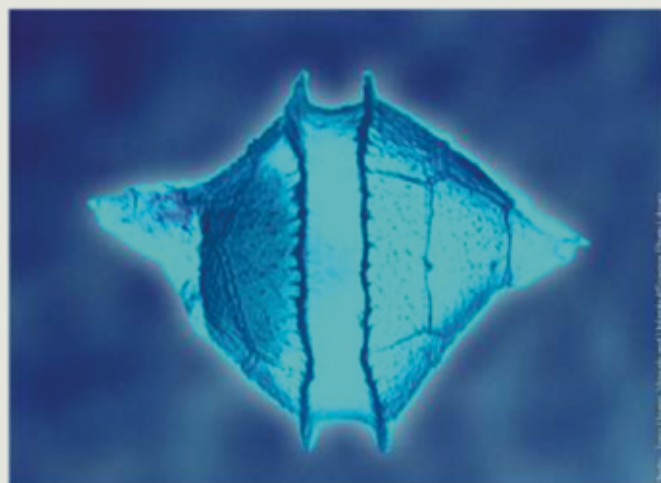


Figure 2.3. A bioluminescent Dinoflagellate (*Pyrodinium bahamense*) now found in the Humacao Nature Reserve due to saltwater intrusion. SEM X2600

Conclusion

The events discussed are just the most evident aspects of a decade's worth of ecological changes caused by man-made hydrological alteration on the coastal wetlands of the Humacao Natural Reserve. There are many more aspects that will not be as apparent and that are equally as interesting: (a) effects on the diversity of other vertebrate and invertebrate species; (b) biogeochemical process such as carbon allocation and nutrient cycling; and (c) given the close relation of the Punta Santiago community with the HNR, the socio-ecological implications of all these changes. In this light, the Humacao Natural Reserve serves us as natural laboratory that can help us understand complex aspects of social-ecological system response to long-term events like climate change.

Acknowledgements

Special thanks to HNR manager Manuel Córbet, biologist Luis Encarnación, and the rest of the Humacao Natural Reserve personnel. Information cited as personal communication was obtained during a recorded interview with Mr. Córbet and Mr. Encarnación on February 21st, 2012 in the HNR headquarters.

Cited literature

- Ferrer Montaña, O. J., Dibble, E. D., Jackson, D. C., & Rundle, K. R. (2005). Angling assessment of the fisheries of Humacao Natural Reserve lagoon system, Puerto Rico. *Fisheries Research*, 76(1), 81–90. doi:10.1016/j.fishres.2005.05.010
- Ferrer, O. J. (2007). Temporal and spatial environmental structure of the Humacao Natural Reserve lagoon system, Puerto Rico. *Ciencia*, 15(2), 193–204.

COASTAL LAGOONS

Introduction to Coastal Lagoons

Coastal lagoons are shallow water bodies separated from the sea by sand bars or other dry land. These berms may break during storms allowing exchange between the lagoons and the coast, or exchange may occur through channels from the lagoon to the sea. Some coastal lagoons receive freshwater input directly from rivers and streams while others only receive freshwater from stormwater flows during rain events. Coastal lagoons are often associated with wetland systems in the coastal zone ranging from fresh to brackish wetlands. The difference in the amount of fresh and saltwater influx leads to differences in the salinities of coastal lagoons. This also affects the amount and type of flora and fauna present in coastal lagoons. Mangroves are the dominant vegetation around coastal lagoons. Lagoons with a direct connection to the sea provide habitat for seabirds and fish, including species of commercial and recreational importance. In the Virgin Islands, research has shown that coastal lagoons gradually formed in sheltered bays or inlets that were originally open to the sea (Thomas and Devine 2005). The areas were gradually separated from the sea as coral reefs grew across the mouth of the bay forming a berm that was then colonized by mangroves (Thomas and Devine 2005). A similar process probably formed many of the coastal lagoons in Puerto Rico. Researchers have found remnants of coral reefs in the Joyuda Lagoon in Cabo Rojo (E. Otero, pers. comm.), which supports the theory that the area was once a coastal embayment with coral reefs.

In Puerto Rico, there are marine lagoons, which have a free interchange with the sea and a substantial part of their volume flows with the tides; hypersaline lagoons, which are found in areas with little rainfall and high evaporation and have little freshwater input and little connection to the sea; and brackish lagoons, which are semi-closed and are connected to drainages where seawater is diluted by the freshwater input (Vivaldi and Paniagua 1986). Marine lagoons typically have sandy bottoms and clear waters

and are colonized by seagrass and macroalgae and contain populations of coral reef species. Hypersaline lagoons are often relatively devoid of vegetation and fauna due to the elevated salinities. Brackish lagoons are often colonized by estuarine species that can tolerate changes in dissolved oxygen and temperature (Vivaldi and Paniagua 1986). Perhaps the best known coastal lagoons in Puerto Rico are within the San Juan Bay Estuary System, which contains the Condado Lagoon, San José Lagoon, Torrecillas Lagoon, and the Piñones Lagoon. The lagoon system in this area is also the largest mangrove forest system on the island and provides habitat for a variety of wildlife including birds, fish, reptiles, mollusks, and crustaceans (Ventosa-Febles et al. 2005). Both marine and brackish lagoons in Puerto Rico often provide nursery habitat for species that are important in the coral reef ecosystem, as well as species that spend at least a portion of their time in estuarine environments, such as native shrimp species.

Status and Threats To Coastal Lagoons

The greatest threat to coastal lagoons is development. The influx of stormwater and sediment-laden runoff from upland development into coastal lagoons results in contamination of the waters in the lagoons, as well as changes in patterns of salinity and sedimentation of the lagoons, which can result in the eventual filling of these areas. In the U.S. Virgin Islands, core samples collected from salt ponds that have become dry land have shown that terrestrial sediments from uplands led to the filling of these areas over time (Thomas and Devine 2005). Development along the shorelines of lagoons alters water quality, as well as eliminates habitat for birds and other organisms that are important in the food web. The construction of marine facilities in lagoons also affects water quality through the introduction of marine debris into the water column, as well as accidental spills of petroleum products and other contaminants (such as cleaning agents) and the resuspension of sediments or accidental groundings due to the shallow nature of coastal lagoons. Dredging of lagoons to support marine

activities also affects water quality and can alter flow patterns, which affects the organisms living in the lagoons that are adapted to natural conditions within the lagoons.

Other threats to coastal lagoons include discharges of untreated stormwater and wastewater. Untreated stormwater from roads and other developed areas often contain petroleum products and other contaminants. In addition, the use of coastal lagoons as stormwater ponds alters their natural function and patterns of fresh and saltwater exchange, thus affecting the flora and fauna of the lagoons (Vivaldi and Paniagua Valverde 1986). The discharge of wastewater can lead to significant decreases in dissolved oxygen in the water column due to the increase in production by bacteria, algae, and other organisms associated with the influx of nutrients. If the dissolved oxygen levels in the water column become too reduced, fish kills can result.

Outcome and Consequences of Climate Change to Puerto Rico's Coastal Lagoons

Potential threats to coastal lagoons from climate change may come from rising sea level, changing tidal regime, changes in freshwater influx and associated changes in water quality (including salinity, nutrients, and sediment), and changes in the distribution and intensity of extreme event).

Sea Level Rise

Rising sea level will have a greater affect on low-lying, shallow-gradient coastal lagoons and other ecosystems because these typically respond to sea level rise by migrating landward along undeveloped shorelines with gentle slopes (Anthony et al. 2009). However, if sea level rise accelerates, landward migration might not be fast enough to prevent inundation and developed coastlines will make migration impossible, thereby increasing the vulnerability of coastal structures to inundation and storm damage (Anthony et al. 2009). Landward migration of lagoon barriers will also lead to steep and

narrower barriers and increased exchange with the sea, which will also increase the lagoon berm's vulnerability to breaching and increase flushing rates (Zimmerman 1981, Anthony et al. 2009). If breaching of the barrier increases, then the salinity in the lagoon will change and the species' composition in the lagoon may be altered.

Additionally, coastal lagoons may be more susceptible to point and non-point sources of pollution as sea levels rise. Specific to sewage treatment plants, if the plants are not able to discharge properly via gravity with higher water levels, depending on the location of nearby treatment plants, seawater may enter combined sewer systems or overwhelm the system allowing for direct discharge of sewage and other pollutants into the lagoons.

Precipitation Changes and Freshwater Influx

Alterations in the frequency, magnitude, and timing of rain events could result in changes in salinity and dissolved oxygen patterns in coastal lagoons due to changes in freshwater influx (Anthony et al. 2009). In areas where precipitation is expected to increase or where storms become more intense, increased runoff will lead to increased transport of nutrients and sediment to coastal lagoons and decreases in salinity (Day et al. 2008, Anthony et al. 2009). Increases in nutrient levels in coastal lagoons could result in increases in eutrophication. Studies in the Mar Menor Lagoon in Southeast Spain have shown that the main primary producer, which is a macroalgal species, has such a high biomass that it has increased the resistance of the lagoon to eutrophication due to its ability to uptake high nutrient levels from the water column that are then retained in bottom sediments (Lloret and Marín-Guirao 2008). However, if climate change projections prove true, the productivity of the algae will eventually decline and eutrophication of the lagoon will occur (Lloret et al. 2008).

Additionally, many management plans for coastal lagoons and estuaries have a high priority of controlling nonpoint sources of pollution. One such management plan is Jobos Bay National Estuarine Research Reserve's (JBNERR) on the south coast. Investigators of the USDA Agricultural Research Service detected a pesticide spike in water samples after a storm event, confirming a direct link from nonpoint source runoff from the watershed and

Warmer temperatures may increase toxicity of pollutants that already exist in Puerto Rico's coastal lagoons or result in higher solubility leading to higher concentrations of pollutants that newly enter the lagoons.

water quality in the Reserve (JBNERR 2010). Other types of nonpoint sources of pollution that management plans are concerned about are nutrient runoff that leads to eutrophication, chemical contamination that endangers wildlife and human health, and sediment influxes that smother coral reef and seagrass communities. Changes in precipitation patterns, specifically increases in heavy downpour events, will make this management priority more challenging as more watershed-based contaminants enter Puerto Rico's coastal waterbodies.

Increased Temperature

Changes in air temperatures influence the water temperature of slow-moving, shallow waters in coastal lagoons (Turner 2003). In addition, due to ocean temperature increases, lagoons with tidal connections to the sea will also be affected. Air temperatures increase more rapidly over land than the ocean as evidenced by a study in Narragansett Bay, Rhode Island that showed the rate of increase in the annual average surface water temperature over the past 5 years was approximately 4 times greater than that of the

ocean (Anthony et al. 2009). Water temperatures affect levels of dissolved oxygen (levels decrease as temperatures increase), as well as species' physiology (Anthony et al. 2009). Therefore, increases in water temperature in coastal lagoons and associated decreases in dissolved oxygen levels will lead to changes in benthic communities, as well as highly mobile species such as fish. Changes in community composition of coastal lagoons could promote invasive flora and fauna species. Shifts in the availability of food due to changes in water temperature and impacts on species growth and cyclical migrations will also affect animals such as migrating birds.

Additionally, warmer temperatures may increase toxicity of pollutants that already exist in Puerto Rico's coastal lagoons or result in higher solubility leading to higher concentrations of pollutants that newly enter the lagoons. Other water quality implications of increasing temperatures on coastal lagoons could be increased stratification, greater algal growth, and a greater quantity of parasites and bacteria.

Tropical Storms and Hurricanes

Coupled with rising sea level, even slight changes in the frequency, intensity, timing, and distribution of tropical storms and hurricanes are expected to result in substantial impacts to coastal wetlands (Michener et al. 1997), including coastal lagoons. Long-term changes in storm frequency, intensity, timing, and distribution could affect biotic functions such as community structure and productivity and physical processes such as nutrient cycling (Michener et al. 1997).

Research Gaps and Information Needs

Coastal lagoons in Puerto Rico have not been well-studied with the exception of some of the areas within the San Juan Bay Estuary System. Some studies of the Joyuda Lagoon were conducted in the 1980's by the Department of Marine Science of the University of Puerto Rico (J. López, pers. comm.) and DNER (Ventosa-Febles et al. 2005);

however, research is also needed to determine changes in the lagoon due to the high level of development occurring in the watershed that has resulted in the alteration of the creek that is one of the main freshwater sources to the lagoon and the alteration of wetlands and road construction that has altered the saltwater connection between the lagoon and the sea. Because characterizations of the flora and fauna of many of the lagoons around the island have not been done, it will be difficult to determine the extent of climate change impacts on these systems. Therefore, the following is needed:

- Research to characterize the physical and biological aspects of Puerto Rico's coastal lagoons should be completed as soon as possible.
- Permanent monitoring stations should be established in a representative sample of lagoons in order to track changes in the physical and biological characteristics and determine whether these are associated with climate change or human impacts.
- Better management of coastal lagoons is needed in order to reduce or eliminate human impacts so that the systems can adapt to changing conditions associated with climate change.

Predictions of climate change impacts on coastal wetlands require a better understanding of the linkages between terrestrial, wetland, atmospheric, oceanographic, and human

components of the ecosystem. Thus, the following is also needed:

1. A watershed scale approach that incorporates atmospheric and oceanographic data in modeling of scenarios to determine potential climate change impacts on coastal lagoons and potential shifts in lagoon composition and characteristics is necessary. Michener et al. (1997) presented two conceptual models of broad-scale comparative research for assessing ecological responses to climate change. One used a space-for-time substitution coupled with long-term studies to assess impacts of rising sea level and disturbance on coastal wetlands and the other used a moisture-continuum model to assess the effect of climate change and associated shifts in moisture regimes on wetland ecosystems (Michener et al. 1997). Similarly, (Bortone 2006) proposes the establishment of a sampling network with established sampling protocols to determine the important variables to monitor and a comprehensive plan to assess the environmental effects of hurricanes on coastal ecosystems. As part of this effort, Burtone (2006) recommends the mining of historical data to assess the role of hurricanes in shaping coastal ecosystems over time in order to better determine whether changes in storms due to climate change are different from processes that already occur in natural systems in response to hurricanes.



Summary of Climate Change effects on Puerto Rico's Coastal Lagoons

Coastal lagoons are shallow water bodies separated from the sea by sand bars or other dry land. Mangroves are the dominant vegetation around coastal lagoons. Lagoons with a direct connection to the sea provide habitat for seabirds and fish, including species of commercial and recreational importance. In Puerto Rico, there are marine lagoons and brackish lagoons. Perhaps the best known coastal lagoons in Puerto Rico are within the San Juan Bay Estuary System, which contains the Condado Lagoon, San José Lagoon, Torrecillas Lagoon, and the Piñones Lagoon. The lagoon system in this area is also the largest mangrove forest system on the island and provides habitat for a variety of wildlife including birds, fish, reptiles, mollusks, and crustaceans. Both marine and brackish lagoons in Puerto Rico often provide nursery habitat for species that are important in the coral reef ecosystem, as well as species that spend at least a portion of their time in estuarine environments, such as native shrimp species.

The greatest threat to coastal lagoons is development. The influx of stormwater and sediment-laden runoff from upland development into coastal lagoons results in contamination of the waters in the lagoons, as well as changes in patterns of salinity and sedimentation of the lagoons, which can result in the eventual filling of these areas. Other threats to coastal lagoons include discharges of untreated stormwater and wastewater. Untreated stormwater from roads and other developed areas often contain petroleum products and other contaminants.

Potential threats to coastal lagoons from climate change may come from rising sea level, changing tidal regime, changes in freshwater influx and associated changes in water quality (including salinity, nutrients, and sediment), and changes in the distribution and intensity of extreme

event). Rising sea level will have a greater effect on low-lying, shallow-gradient coastal lagoons and other ecosystems because these typically respond to sea level rise by migrating landward along undeveloped shorelines with gentle slopes. However, if sea level rise accelerates, landward migration might not be fast enough to prevent inundation and developed coastlines will make migration impossible, thereby increasing the vulnerability of coastal structures to inundation and storm damage. Landward migration of lagoon barriers will also lead to steep and narrower barriers and increased exchange with the sea, which will increase the lagoon berm's vulnerability to breaching and increase flushing rates. If breaching of the barrier increases, from gradual sea level rise or more acute events like storms, then the salinity in the lagoon will change and the species' composition in the lagoon may be altered.

Alterations in the frequency, magnitude, and timing of rain events could result in changes in salinity and dissolved oxygen patterns in coastal lagoons due to changes in freshwater influx. Increases in nutrient levels in coastal lagoons could result in increases in eutrophication. Changes in air temperatures influence the water temperature of slow-moving, shallow waters in coastal lagoons. In addition, due to ocean temperature increases lagoons with tidal connections to the sea will also be affected. Air temperatures increase more rapidly over land than the ocean. Water temperatures affect levels of dissolved oxygen (levels decrease as temperatures increase), as well as species' physiology. Therefore, increases in water temperature in coastal lagoons and associated decreases in dissolved oxygen levels will lead to changes in benthic communities, as well as highly mobile species such as fish. Changes in community composition of coastal lagoons could promote invasive flora and fauna species. Shifts in the availability of food due to changes in water temperature and impacts on species growth and cyclical migrations will also affect animals such as migrating birds. Additionally, warmer

temperatures may increase toxicity of pollutants that already exist in Puerto Rico's coastal lagoons or result in higher solubility leading to higher concentrations of pollutants that newly enter the lagoons.

Coastal lagoons in Puerto Rico have not been well-studied with some exceptions. Because characterizations of the flora and fauna of many of the lagoons around the island have not been done, it will be difficult to determine the extent of climate change impacts on these systems. Therefore, research to characterize the physical and biological aspects of Puerto Rico's coastal lagoons should be completed as soon as possible. Permanent monitoring stations should be established in a representative sample of lagoons in order to track changes in the physical and biological characteristics and determine whether these are associated with climate change or human impacts. Better management of coastal lagoons is also needed in order to reduce or eliminate human impacts so that the systems can adapt to changing conditions associated with climate change.

SEABIRDS AND SHOREBIRDS

Introduction to Seabirds and Shorebirds

Puerto Rico is the easternmost and smallest of the Greater Antilles, situated 1,600 km southeast of Florida, U.S.A., between the Caribbean Sea and the Atlantic Ocean (18° 15' N, and 66° 30' W), 110 km east of the Dominican Republic and about 37 km west of the U.S. Virgin Islands. Puerto Rico is roughly 8,960 km², with a maximum length from east to west (from Punta Puerca to Punta Higüero) of 180 km, and a maximum width from north to south (from Isabela to Punta Colón) of 65 km. Over 70% of Puerto Rico's terrain is mountainous, with a central mountain chain transecting the island from east to west, coastal lowlands on the north and south, and a karst region in the northwest consisting of rugged, limestone formations.

The main island of Puerto Rico is surrounded by many groups of small islands and cays, and the following ones harbor one or several species of seabirds and/or shorebirds: Northwest Cays (half a km off the north coast, between Quebradillas and Manatí); Cordillera Cays (about 2 km east of Las Cabezas de San Juan, between Fajardo and the Culebra Archipelago); Culebra Archipelago (about 17 km east of Fajardo); Vieques (about 14 km southeast of Naguabo); Cayos Fríos (about 2 km south of Ponce); Caja de Muertos (about 9.6 km south of Ponce); Cayo Guayanilla (about 5 km south of Guayanilla); Montalva Cays (20-300 m south of Guánica); Parguera Cays (3-6 km south of Lajas); Mona and Monito (about 80 km west of Cabo Rojo); Isla Ratones (about 500 m west of Cabo Rojo); and Desecheo (about 19 km west of Rincón) (figure 6).

Cliffs, mudflats, salt flats, inland artificial lakes, coastal saline ponds, and sand deposits on river mouths within the main island of Puerto Rico or close to its shore are also important roosting, foraging, staging, or breeding sites for seabirds and/or shorebirds, such as: Northwest Cliffs (between Aguadilla and Camuy); Cueva del Indio (Camuy); Isla del Frío (off Ponce); the mouth of the Añasco, Cibuco (Manatí), and Arecibo rivers; Lago La Plata (Toa Alta-Naranjito); Lago Carraízo (Trujillo Alto-Caguas); Laguna de Las Salinas (Ponce); La Jungla Salt Flats (Guánica); Cabo Rojo Salt Flats (Cabo Rojo); and Boquerón Natural Reserve (Cabo Rojo).

Deep ocean waters fringe Puerto Rico: the Mona Passage to the west, between Puerto Rico and the Dominican Republic (about 1,000 m deep), the Puerto Rico Trench lying 120 km to the north (about 8.5 km deep), and to the south the sea bottom descends to the 5 km Venezuelan Basin. Pelagic seabirds travel to these areas to feed on fish attracted to the deep, rich upwelling waters.

Seabirds

There exists no single definition of which groups, families, and species are seabirds; and most definitions are in some way arbitrary. Schreiber and Burger (2002) state that “The one common characteristic that all seabirds share is that they feed in saltwater; but, as seems to be true with any statement in biology, some do not.” For the purpose of this document, seabirds are defined as any bird species that spend most of their time in coastal waters or the open ocean. Most tropical seabirds in the West Indies, which include Puerto

concentration of complete regional populations in a few sites. Furthermore, populations are slow to recover from disturbance because of their low reproductive output (Schreiber and Lee 2000).

Croxall et al. (2012) analyzed a broader, but less sensitive, measure of overall seabird population trends is provided by the Red List Index (RLI, from Butchart et al. 2004, 2007), which measures trends in extinction risk and is virtually the only trend indicator currently available for seabirds on a worldwide and/or regional basis. The RLI is based on the movement of species through IUCN

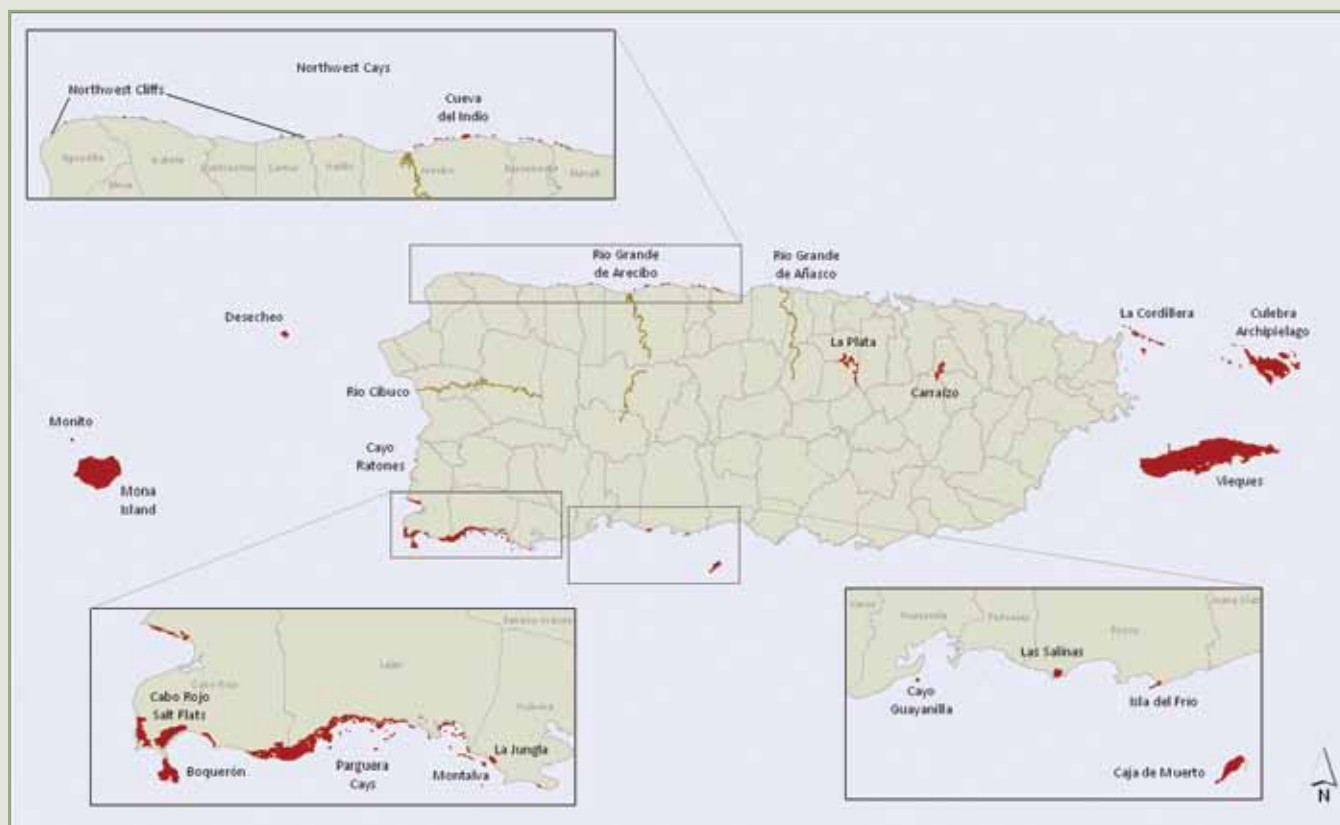


Figure 6 Cays, islets, cliffs, mudflats, salt flats, inland artificial lakes, coastal saline ponds, and river mouth areas of Puerto Rico known to harbor one or several species of seabirds and/or shorebirds

Rico, exist at moderate to relatively low densities; they normally feed at sea at great distances from the breeding colonies, and typically produce just one slow-growing chick per year (Schreiber and Lee 2000, Weimerskirch 2002). The combined result is that seabirds are more vulnerable to environmental stressors (*e.g.*, storms, predators, habitat modification, and man-made factors) on their breeding sites than most land birds, because of the protracted period of nest occupancy and the

Red List categories owing to genuine improvement or deterioration in status (*i.e.*, re-categorizations owing to improved knowledge or revised taxonomy are excluded). It shows that, over the last 20 years, seabirds have had a substantially poorer conservation status than non-seabirds and that they have deteriorated faster over this period (Croxall et al. 2012). Seabirds are more threatened than a number of other similarly speciose groups (*e.g.*, raptors, pigeons, gamebirds and waterbirds),

and are marginally more threatened than parrots. Among seabirds, pelagic species are more threatened and have deteriorated faster than coastal species (Croxall et al. 2012).

Seabird species

Sixteen species of seabirds breed in Puerto Rico and its adjacent islands. Five species are resident throughout the year: Brown Booby (*Sula leucogaster*), Red-footed Booby (*S. sula*), Masked Booby (*S. dactylatra*), Brown Pelican (*Pelecanus occidentalis*), and Magnificent Frigatebird (*Fregata magnificens*). Eleven species are migrants absent for part of each year: Audubon's Shearwater (*Puffinus lherminieri*), White-tailed Tropicbird (*Phaethon lepturus*), Red-billed Tropicbird (*P. aethereus*), Laughing Gull (*Larus atricilla*), Royal Tern (*Thalasseus maximus*), Sandwich Tern (*T. sandvicensis*), and Cayenne Tern (*T. eurygnatha*), Roseate Tern (*Sterna dougallii*), Least Tern (*Sternula antillarum*), Bridled Tern (*Onychoprion anaethetus*), Sooty Tern (*O. fuscatus*), and Brown Noddy (*Anous stolidus*) (Saliva 2009). Although Royal and Sandwich Terns are found throughout the year, apparently most of the individuals observed outside the breeding season are transient birds. Common Terns (*Sterna hirundo*) are regularly observed early in the summer, loafing at Roseate Tern breeding colonies, but they usually depart Puerto Rico by midsummer (Saliva, pers. obs.).

Other seabird species have been reported sporadically at seabird colonies or foraging in waters off Puerto Rico such as Gull-billed Tern (*Sterna nilotica*), Arctic Tern (*Sterna paradisaea*), Black Noddy (*Anous minutus*), Black Tern (*Chlidonias niger*), Parasitic Skua (*Stercorarius parasiticus*), Herald Petrel (*Pterodroma arminjoniana*), Greater Shearwater, (*Puffinus gravis*), Double-crested Cormorant (*Phalacrocorax auritus*), Wilson's Storm Petrel (*Oceanites oceanicus*), Leach's Storm Petrel (*Oceanodroma leucorhoa*), Sooty Shearwater (*Puffinus griseus*), and Manx Shearwater (*Puffinus puffinus*) (Gochfeld et al. 1988; Raffaele et al. 1998; Saliva, pers. obs.).

During their non-breeding season, the following migratory seabirds are regularly seen (*i.e.*, at least every other year) in Puerto Rico: Ring-billed Gull (*Larus delawarensis*), Lesser Black-backed Gull (*L. fuscus*), Herring Gull (*L. argentatus*), Great Black-backed Gull (*L. marinus*), Black-headed Gull (*L. ridibundus*), Franklin's Gull (*L. pipixcan*), and Forster's Tern (*Sterna forsteri*) (Raffaele et al 1998; Saliva pers. obs.). Others, such as Black-legged Kittiwake (*Rissa tridactyla*), Bonaparte's Gull (*L. philadelphia*), and Black Skimmer (*Rynchops niger*) are far less common (Saliva, pers. obs.).

Seabird nesting habitats

Tens of thousands of islands across the world are used by over 250 species of seabirds for nesting and roosting, sometimes in extremely high densities (Croxall et al. 1984). While seabirds primarily forage at sea, their daily or seasonal returns to islands result in the transport and concentration of substantial quantities of marine nutrients on land, and can cause significant physical and chemical alterations of island habitats (Anderson and Mulder 2011). Most seabirds nest either on cliffs or on, or beneath, the slopes or flat interiors of islands (Nelson 1979), and prefer to nest in offshore islands away from large land masses; particularly ground-nesting seabirds which are vulnerable to mammalian predators. Although a variety of habitats are found within the main island of Puerto Rico; ranging from wet montane forests to dry coastal scrub, mangrove lagoons, salt ponds, limestone and volcanic cliffs, salt flats, mud flats, and sandy beaches, only five species of seabirds nest within the main island of Puerto Rico: White-tailed Tropicbird, Brown Pelican, Least Tern (Saliva 2009), Noddy Tern, and Bridled Tern (Saliva, pers. obs.). There are no historical records of other seabird species nesting on the main island, even in coastal areas that appear suitable for nesting. During the non-breeding season, other migratory seabirds as described above use coastal areas around the main island as staging grounds; particularly the mouths of major rivers and coastal manmade structures such as concrete pilings, buoys, and jetties.

Rocky shores are beach rock formations resulting from cementing sand, shell fragments, and precipitation of calcium carbonate coming into the sea from drainage out of the karst region (Miller and Lugo 2009). Volcanic rocks and cays, which contain jagged depressions on the rock that provide nesting habitat for some seabird species, are small rocky coastal formations frequently over washed by heavy north swells. They range from a few meters (feet) above sea level to about six meters (20 feet) high. Vegetation is only found on the larger rocky cays (> half a hectare). A few of these are connected to the main island through a thin strip of volcanic material. The rocky cays that are used by seabirds, however, are usually separated from other land and access is difficult unless sea conditions allow climbing over the jagged edge (Saliva 2009). Three species of seabirds nest on this type of habitat: Roseate Tern, Noddy Tern, and Bridled Tern (Saliva 2009).

Cliffs are vertical or near-vertical coastal features composed of sedimentary rock, pillow lava, cemented sand, or limestone rock. The great advantages of island cliffs are safety from ground predators, and the provision of wind and air space, which greatly facilitates landing and departure (Nelson 1979). A cliff face offers several distinct types of nesting site; from broad, flat ledges to caves and crevices. Some cliffs may have a dry coastal scrub community present; some of which may exhibit extreme wind/salt shear and may only be a few centimeters tall (Miller and Lugo 2009). Although many cliff features are found around the coast of Puerto Rico, only the following have been reported as seabird cliff nesting areas: Aguadilla cliffs (Aguadilla), Mona and Monito islands (Mayagüez), Cabo Rojo lighthouse (Cabo Rojo), Caño Valdivieso (Ponce), Cayo Conejo (Vieques), Caja de Muerto (Ponce), and Cayo Morrillito (Ponce). In addition, in the Culebra archipelago seabirds nest on cliffs at Punta Soldado and the islets of East Geniquí, West Geniquí, Alcarraza, Yerba, and Lobito. White-tailed Tropicbirds, Red-billed Tropicbirds, Noddy Terns, and Bridled Terns use the cavities and caves on cliff faces; whereas

Noddy Terns use ledges that protrude from the cliff face, and Sooty Terns, Brown Boobies, Masked Boobies, and Laughing Gulls use flatter surfaces near the cliff edge (Saliva 2000).

Coralline cays are small, low-elevation, islands formed on the surface of coral reefs formed by the gradual deposit of sediment layers (primarily dead stony corals and sand) building up on the reef surfaces (Hopley 1981). These depositions occur on the windward or leeward areas of reef surfaces, and sometimes around an emergent outcrop of old reef. Cay sediments are largely composed of calcium carbonate produced by myriad plants (*e.g.*, *Halimeda*) and animals (*e.g.*, corals, mollusks, and foraminifera), and small amounts of silicate sediment are also contributed by sponges and other creatures (Folk and Robles 1964, Scoffin 1987, Yamano et al. 2000). Over time, soil and vegetation may develop on a cay surface, assisted by the deposition of seabird guano. There is much debate and concern over the future stability of cays in the face of growing human populations and pressures on reef ecosystems, and predicted climate changes and sea level rise (Kench and Cowell 2003; Hart 2003). Coralline cays in Puerto Rico are primarily found in the Reserva de La Cordillera east of Fajardo and its adjacent cays and along the southwest coastline from Ponce to Cabo Rojo. Scattered coralline cays may also be found off Vieques Island and Fajardo-Ceiba. Royal Terns, Sandwich Terns, Roseate Terns, Least Terns, Sooty Terns, and Bridled Terns nest on the ground in coralline cays (Saliva, pers. obs.).

Vegetation used by seabirds in Puerto Rico include the canopies of red mangrove (*Rhizophora mangle*), buttonwood (*Conocarpus erectus*), sea grape (*Coccoloba uvifera*), bay cedar (*Suriana maritima*), and wild banyantree (*Ficus citrifolia*); as well as shaded areas under grass clumps (*e.g.*, *Cyperus* spp.), shrubs (*e.g.*, *Croton*), and small/stunted trees (*e.g.*, *Bursera*). Vegetation used by seabirds may be located on mangrove islets, coralline cays, at the edge of cliffs, on cliff faces, or the top of rocky cays. Most of this vegetation

tends to be of short growth due to the constant wind force in coastal areas that limits their upward growth (Miller and Lugo 2009); with the exception of red mangrove. Brown Pelicans, Red-footed Boobies, Noddy Terns, and Frigatebirds construct flimsy nests on the canopy of such vegetation; whereas Sooty Terns, Bridled Terns, Roseate Terns, Laughing Gulls, Audubon's Shearwaters, Brown Boobies, and Masked Boobies nest on the ground near or under thick vegetation (Saliva and Burger 1989; Saliva, pers. obs.).

Salt flats are extensive level tracts coated with salt deposits left by evaporation of rising ground water or a temporary body of surface water. These salt flats or "salinas" are frequently positioned to the rear of coastal fringing mangrove swamps on the south coast of Puerto Rico, in areas that have access to sea water (Miller and Lugo 2009). The sea water then evaporates and produces high salt concentrations in the water and soils. The hypersaline environment cause reduced mobilization of nutrients and hyperosmotic conditions, both of which limit species richness (Copeland and Nixon 1974). Salt-tolerant plant species that can be present along the fringes of saline ponds include black mangrove (*Avicennia germinans*), glassworts (*Salicornia perennis* and *S. virginica*), saltwort (*Batis maritima*), and sea purselane (*Sesuvium portulacastrum*) (Miller and Lugo 2009). Species of blue-green and green algae tolerate hypersaline water conditions and are the major primary producers of salt flat systems (Tripp 1996). Aquatic organisms are usually limited to crustaceans and salt tolerant insects, all of which feed on algae and attain high abundances, in part, due to lack of competition and predation (Carpelan 1957, Gear 1992, Tripp 1996). Fish such as mullet (*Mugil cephalus*), mojarra (*Gerres subfasciatus*), and tilapia (*Oreochromis mossambicus*) will intrude into saline ponds during high tide or when large rain events flood the saline ponds (Saliva, pers. obs.). Brown Pelicans, Royal Terns, Sandwich Terns, Laughing Gulls, and several migratory non-breeding gull and tern species (*e.g.*, Forster's Tern,

Gull-billed Terns) take advantage of these flooding events to feed on small fish. The Least Tern is the only seabird recorded nesting along the shores of saline ponds and salt flats in Puerto Rico (Saliva, pers. obs.).

Shorebirds

The definition of "shorebird" is even more elusive than that of "seabird"; since it encompasses a wide group of birds, including "waders" and any bird species that is found near the edge of bodies of water at some point during their annual cycle (Hansen et al. 2004). However, for the purpose of this document, a shorebird is a bird species belonging to suborders Scolopaci (phalaropes and sandpipers) and Charadrii (plovers, avocets, stilts, and oystercatchers). Other waders such as egrets, herons, cranes, bitterns, ibises, and flamingoes are not considered shorebirds in this discussion (van Tuinen et al. 2004).

Shorebirds are among the world's greatest migrants; many species travel from the high Arctic regions to the southern limits of Australasia, Africa, and South America. Because of the huge distances travelled, virtually any of the migrant species is capable of turning up unexpectedly, even on the "wrong" continent (Hayman et al. 1986). Shorebirds show a high degree of site fidelity, returning to their breeding or wintering sites year after year; and they often show a remarkable return-rate to the vital "stepping-stone" wetlands on the migration route (Hayman et al. 1986). Many shorebirds will return to the same area of the same beach or estuary each year on migration (Saliva pers. obs.). Most shorebirds are highly gregarious and often occur in mixed species flocks; and several species remain in the region late enough to be seen in breeding plumage (Raffaele et al. 1998). At the Cabo Rojo Salt Flats, migratory species start to arrive in late July; with many individuals remaining through the winter, while others depart before December (Gear 1992).

Shorebird species

The sandpiper group is characterized by their long necks and legs, and thin pointed bills; and most of them wade in shallow waters or on wet flats where they probe in the mud for invertebrates (Raffaele et al. 1998). The most common species from this group found in Puerto Rico include Semipalmated sandpiper (*Calidris pusilla*), Western Sandpiper (*Calidris mauri*), Least Sandpiper (*Calidris minutilla*), Greater Yellowlegs (*Tringa melanoleuca*), Lesser Yellowlegs (*Tringa flavipes*), Solitary Sandpiper (*Tringa solitaria*), Willet (*Catoptrophorus semipalmatus*), Spotted Sandpiper (*Actitis macularia*), Ruddy Turnstones (*Arenaria interpres*), Sanderling (*Calidris alba*), Stilt Sandpiper (*Calidris himantopus*), Short-billed Dowitcher (*Limnodromus griseus*), and Common Snipe (*Gallinago gallinago*). Small sandpipers (primarily semipalmated and western sandpipers) comprise 60-70% of the shorebirds present on salt flats during autumn migration (Wunderle et al. 1989, Gear 1992).

Sandpipers such as Upland Sandpiper (*Bartramia longicauda*), Hudsonian Godwit (*Limosa haemastica*), Marbled Godwit (*Limosa fedoa*), Whimbrel (*Numenius phaeopus*), Red Knot (*Calidris canutus*), White-rumped Sandpiper (*Calidris fuscicollis*), Pectoral Sandpiper (*Calidris melanotos*), Dunlin (*Calidris alpina*), Buff-breasted Sandpiper (*Tryngites subruficollis*), Ruff (*Philomachus pugnax*); as well as phalaropes such as Wilson's Phalarope (*Phalaropus tricolor*) and Red-necked Phalarope (*Phalaropus lobatus*), are uncommon or vagrant in Puerto Rico (Raffaele et al. 1998).

Plovers are chunky birds with relatively shorter necks, bills, and legs than sandpipers; and a distinctive broadening at the bill tip which sandpipers lack (Raffaele et al. 1998). Plover species regularly found in Puerto Rico include Black-bellied Plover (*Pluvialis squatarola*), Snowy Plover (*Charadrius alexandrinus*), Wilson's Plover (*Charadrius wilsonia*), Semipalmated Plover (*Charadrius semipalmatus*), and Killdeer

(*Charadrius vociferus*). Piping Plover (*Charadrius melodus*) and American Golden Plover (*Pluvialis dominica*) are rare visitors to Puerto Rico.

Stilts and avocets are noisy, gregarious, mostly black-and-white wading birds with very long legs; with one species, the Black-necked Stilt (*Himantopus himantopus*), commonly found in Puerto Rico. The American Avocet (*Recurvirostra americana*) is vagrant and very rare in Puerto Rico (Raffaele et al. 1998).

Oystercatchers are very distinctive, fairly large shorebirds with large, brightly colored bills that are unusual in that they are laterally compressed (Raffaele et al. 1998). One species is found in Puerto Rico; the American Oystercatcher (*Haematopus palliatus*).

Shorebird nesting habitat

The lower reaches of Puerto Rico's rivers are estuaries where fresh and salt water mix, and saltwater can flow upstream in these rivers as far as several kilometers inland (Miller and Lugo 2009). Shorebirds use estuarine forested shrub swamps found along the coast; where there are tides, currents, and storm surges that expose the habitats to salty conditions as exemplified by the coastal forests dominated by red and black mangroves (Miller and Lugo 2009). Some shorebird species also use coralline cays as foraging, breeding, and roosting sites (Saliva, pers. obs.). Some species would also forage along sandy beaches or frequent hypersaline areas to utilize the abundant prey resources found there (Mahoney and Jehl 1985). The Cabo Rojo salt flats, part of the Caribbean Islands National Wildlife Refuge, have been identified as an important migratory staging area for at least 22 species of shorebirds that use these salt flats annually (USFWS 1993, Collazo et al. 1995). Findings indicate that this hypersaline lagoon system is the single most important converging point for migrating shorebirds on the island during autumn migration and winter (Gear 1992).

Most of the shorebird species that are found in Puerto Rico only use the available habitats as stopovers during their northward or southward migrations to re-fuel. Four shorebird species breed on the ground in salt flats: Black-necked Stilt, Killdeer, Wilson's Plover, and Snowy Plover (Gear 1992); but Killdeer would also nest in manmade, recently-mowed fields (Saliva, pers. obs.). American Oystercatchers and Wilson's Plovers regularly nest in offshore coralline cays southwest of Puerto Rico (Saliva, pers. obs.).

Outcomes and Consequences of Climate Change on Seabirds and Shorebirds

Effects of weather and climate on birds can be long term, occurring over hundreds of years, or as short as a passing rain storm (Schreiber 2002). The long-term effects of weather on birds undoubtedly have helped shape their particular demography and other life-history characteristics affecting the decision to nest each year, where and when to nest, annual nest success, chick growth rate, and adult survival (Schreiber 2002). Effects can be direct (*e.g.*, difficulty flying, thermal stress, flooding of nests, loss of eggs, extirpation of the species) or indirect (*e.g.*, destruction of nesting habitat, change in food distribution, decreased visibility of prey). Weather can affect the availability of food, cost of catching food, transportation cost of food, ability to find food, timing of the breeding season, number of birds that attempt to nest in a given season, clutch size, reproductive success, chick growth, thermoregulation, and adult survival (Schreiber 2002). At both high and low latitudes, unpredictable changes in food availability induced by environmental events cause changes in the onset of breeding and increased mortality of adults and chicks (Finney et al. 1999). When changes in local environmental conditions cause a decrease in the available food supply, adult birds often desert nests going elsewhere to find food (Schreiber 2002).

The following are climate change stressors affecting seabirds and shorebirds in Puerto Rico:

- a. Sea level rise/salt water intrusion
- b. Increased precipitation
- c. Increased frequency/severity of storms
- d. Increased irradiation/increased mean temperatures
- e. Ocean acidification

Sea level rise/salt water intrusion

Significant change in water level would impact prey availability and nesting habitat conditions for shorebirds. Gear (1992) found that the dominant abiotic factors likely to affect the macro-invertebrate community preyed upon by shorebirds at the Cabo Rojo Salt Flats are water level and salinity. Of the alternative explanations advanced to examine the distribution patterns among selected habitat units, it appears that changes in calidrid distribution were due to shifts in both densities and depth (*i.e.*, accessibility) of preferred prey in the eastern and middle lagoons versus the mud flat (alternative 3). Thus, marked changes in the distribution of calidrids among these habitats in 1990 may be explained on the basis of physical conditions and invertebrate food resources (Gear 1992). Gear (1992) documented the higher quality of deeper areas in 1991 in terms of prey abundance; where he found that prey densities were several orders of magnitude higher than in similar areas in shallower water. However, although prey abundance may be higher, deeper waters would exclude short-legged shorebirds from accessing prey; and water levels above 30 cm would exclude almost all shorebirds from using this habitat despite the abundance of prey. Indirect effects of the expected sea level rise on shorebirds include starvation during migration stopovers for re-fueling, displacement into less optimal habitat, potential increase in predation in less optimal habitat, and nest failure.

Nesting habitat would be affected by the expected sea level rise as low-lying islands, such as, the coralline offshore cays and coastal salt flats of southwestern Puerto Rico, may be the most affected by sea level rise of all coastal areas. Most of these islands are at, or less than two meters (about three feet), above sea level. Storm-driven swells and high tides frequently wash over the lowest sections of these cays, and deposit large chunks of coral that form a berm on the seaside of the cays. Species that use these cays prefer nesting in the low-lying sections, where some sand and small pieces of coral aggregate, rather than on the coral berm. Unfortunately, their preferred nesting areas are the ones most prone to coastal flooding and destruction from storm surge. Nests located in these areas are regularly abandoned after a strong storm washes over the eggs (Saliva, pers. obs.), and mortality of eggs in some years may include a large portion of a colony (Douglas 2000, Saliva, pers. obs.). Roseate Terns that lose their nests to storm surge may relay their nests elsewhere within or outside of the colony area; but re-nesters late in the breeding season usually have poor reproductive success (Douglas 2000, Saliva, pers. obs.). For example, a Roseate Tern colony of 207 pairs at Cayo Media Luna East in southwest Puerto Rico (presumably late nesters and re-nesters from a failed colony at Cayo Turrumote II) failed completely (Douglas 2000).

In some instances, entire low-lying coralline cays may disappear underwater. Such is the case of a small coralline/sand island off the south coast of Guayanilla, Puerto Rico; in an area called Arrecife Unitas. Arrecife Unitas is a shallow sand bank surrounded by extensive seagrass beds located at (17°57'51" N, 66°46'49" W) between Punta Verraco and Punta Gotay, Guayanilla. When the U.S. Fish and Wildlife Service began surveying tern nesting areas along the southwest coast of Puerto Rico in 1991, Arrecife Unitas was composed of submerged wetlands and an above-surface small area of less than 300 square meters of coralline sand; with an elevation of less than half a meter (Saliva pers. obs.). This small sand island became to be named "Cayo Guayanilla" and qualitative assessments were made of its development. Dr. Jorge Saliva and his FWS team observed a

group of Royal Terns loafing on the island, but no nesting activity in 1991. Their first record of seabird nesting activity at Cayo Guayanilla was in the summer of 1993, when about 110 pairs of Least Tern were observed nesting on the island; which had grown considerably to a little less than a quarter acre and had a small patch of vegetation (grass) on it. In subsequent years, more submerged areas surfaced that provided nesting habitat for Least Terns, Sandwich Terns, Roseate Terns, Wilson's Plovers, American Oystercatchers, and a Bahama Pintail (*Anas bahamensis*).

By 1995, another section of submerged wetland surfaced to form a small sand spit about 50 meters southeast of Cayo Guayanilla, and by the summer of 1996 the two sand pits had joined to form a horseshoe shape cay with an open pond in the middle and short vegetation on both spits. The cay maintained this horseshoe shape and acquired more sand and vegetation through the summer of 1999 (surprisingly, it did not appear to lose size or shape from the passing of Hurricane Georges in September 1998), but by the summer of 2000 the island had been split in half by a shallow canal near its center. In 2001, it was still split by a deeper canal and the north portion was smaller in size and with more vegetation than observed in 2000. By 2003, the southern portion of Cayo Guayanilla was submerged and the northern portion was about a third of the size observed in 2001, and in 2005 the entire island was underwater. It has continued to be underwater until the present (2012), although during aerial surveys at other times of the year (*e.g.*, December) we have seen a small accumulation of sand on the original northern portion of Cayo Guayanilla. Therefore, all shorebird and seabirds species that nested at Cayo Guayanilla were forced to look for nesting areas elsewhere or not breed at all. The disappearance of Cayo Guayanilla has resulted in the loss of the main Least Tern nesting area in Puerto Rico. We believe that Sandwich and Roseate Terns joined the nesting populations further west, whereas Least Terns shifted to nest at Punta Gotay in the mainland. However, we did not have individually banded/radio-tagged birds that we could follow to determine where the colonies moved. Any Least Terns that moved to Punta Gotay would have been exposed to potential

predation by rats, mongoose, cats, and dogs; as well as human trampling.

Increased precipitation

The value of the Cabo Rojo Salt Flats as a migratory stopover has been established by cumulative data collected since 1985. The continued use and value of this stopover is related to the availability and abundance of food resources (Gear 1992). Furthermore, variation in autumn rainfall, both within and between years, causes salinity changes and the seasonal flooding and desiccation of algal mats to occur unpredictably. This poses a sharp contrast to shorebird stopover areas in higher latitudes where high-amplitude tidal cycles result in more predictable patterns. Thus, invertebrate species richness at the Cabo Rojo Salt Flats is likely to have been truncated by both the magnitude and the unpredictable timing of environmental stresses (Gear 1992). The timing and predictability of invertebrate productivity is an important aspect of the traditional use of stopover areas by shorebirds. Intrinsic biological rhythms of invertebrates may be of critical importance to the seasonal predictability of these areas and their traditional use by shorebirds. Although the Cabo Rojo Salt Flats do not exhibit highly predictable bursts of invertebrate productivity, the site may still be relatively predictable in comparison to other tropical wetland sites in the Caribbean (Gear 1992).

Most seabirds and shorebirds are able to avoid some changes in precipitation by simply flying to a different area (Schreiber 2002). Species whose plumage is not water-resistant (Sooty Terns, Bridled Terns, and Frigatebirds) would stay airborne and continuously shake off excess water (Saliva, pers. obs.). Although there are few studies on the behavior of birds during extreme weather conditions at their breeding sites, probably because of human risk and difficulty in studying, some observations suggest that many adult seabirds such as Sooty Terns, Roseate Terns, Sandwich Terns, Laughing Gulls, Boobies, and Pelicans can withstand heavy rains while on the nest (Saliva, pers. obs.). They would crouch down over the eggs and remain motionless waiting for

the rain to pass. Species that nest at the edge of cliffs or on top of vegetation would be minimally affected by heavy precipitation, since excess water would percolate through the nest structure and into the ground. However, heavy rain that causes flooding of the nests would invariably result in nest abandonment in ground nesters such as Wilson's and Snowy Plovers, Killdeer, American Oystercatchers, and several seabird species. Increased/heavy precipitation may be fatal to White-tailed Tropicbirds, Red-billed Tropicbirds, and Audubon's Shearwaters that nest in borrows or under large rocks; due to flooding of the nests and collapse of burrows over eggs, young, or adults.

Increased precipitation may also affect shorebird and seabird species in Puerto Rico, by modifying nesting habitat conditions. Heavy rain is typically followed by increased abundance and thickness of vegetation cover in and around nesting areas. Changes in vegetation may make a colony site unsuitable for nesting, causing a decline in the number of birds in an area (Schreiber and Schreiber 1989). Bird species that require or prefer nesting in open areas such as Killdeer, Wilson's Plover, Black-necked Stilt, Snowy Plover, American Oystercatcher, Brown Booby, Masked Booby, Royal Tern, Sandwich Tern, and Least Tern may find their nesting habitat encroached by vegetation; thus, unsuitable for breeding. Other species such as Roseate Tern and Laughing Gull, which may nest either on bare ground or under/near vegetation, would probably adapt well to increased vegetation cover; moving to whichever appropriate site is available. Species that prefer some vegetation cover over or near their nests, such as the Sooty Tern, Bridled Tern, and Audubon's Shearwater may benefit from increased vegetation; if vegetation is not so dense to impede their movement in and out of the nest. However species such as the Magnificent Frigatebird, Brown Pelican, and Red-footed Booby, which nest on top of thick vegetation, would likely benefit from additional native vegetation cover.

Increased frequency/severity of storms

Flying to a different area may not be a suitable alternative for nesting seabirds and shorebirds during severe storms; especially when hatching approaches and the parents are reluctant to leave their nests unattended. Mortality may be particularly high if adult birds do not leave the colonies soon enough before a severe storm hits the area. Additionally, if storms are frequent and severe, species may not have sufficient time to successfully relay and raise young. Not much is known about the foraging behaviour of seabirds during severe storm events, but food may not be accessible to most seabird species during severe storms primarily because of mechanical constraints imposed by their foraging techniques (plunge diving) in high, gusty winds. Shorebirds, being less aerial than seabirds, may experience heavier mortality at their breeding areas during severe storms; directly from the impact of strong winds, and indirectly from impaired food acquisition for both adult and young birds.

Philopatric species (those that return to nest at the same site every year) may be the most affected by severe storms that destroy habitat and make it unsuitable for nesting in subsequent years. If nest loss occurs early enough in the breeding season, many species will relay their nests; but when it occurs late in the season, few to no birds relay, possibly due to insufficient time to complete the cycle or because of energy constraints, or both (Schreiber 2002). Species that depend on vegetation for nesting may find their nesting habitat temporarily modified (*e.g.*, heavy salt spray that withers vegetation), severely modified to the extent that is unsuitable for the species (*e.g.*, severe defoliation), or destroyed (*e.g.*, coastal shrubs uprooted). Although some species may make relatively fast adjustments to the loss or modification of vegetation (*e.g.*, Brown Pelicans and most tern/gull species), other species may take longer or totally abandon the area (*e.g.*, Magnificent Frigatebird and Red-footed Booby). After Hurricane Hugo in September of 1989, Brown Pelicans at Dutchcap Key in St. Thomas, U.S.

Virgin Islands nested on bare ground and the top of small bushes, after the canopy of tall trees such as *Bursera simaruba* and *Pisonia subcordata* was eliminated by the storm (Saliva, pers. obs.). Red-footed Boobies, on the other hand, did not nest on their usual *Ficus citrifolia* tree at the top of Cayo Geniquí in the Culebra archipelago, after the same hurricane defoliated that tree; and did not return to that cay until two years later when they nested on another, younger tree (Saliva, pers. obs.).

Severe storms are accompanied by heavy winds which could be fatal to species that nest on top of vegetation. Magnificent Frigatebirds, Brown Pelicans, and Red-footed Boobies construct feeble nests that are easily destroyed during strong winds. Eggs and young birds may fall from the nests, and perish from ground impact, predation, or starvation (Saliva, pers. obs.). Juveniles of these three species are clumsy and gangly, and can be knocked off from their nests or perching branches by strong winds, falling through the vegetation and becoming either fatally entangled or falling to the ground and starving to death from abandonment (Saliva, pers. obs.). Although Boobies and Pelicans may nest throughout the year, their peak nesting periods are during the winter months (November-February) or early spring (April-May). Nesting of these species outside of the rainy season may be an adaptation to avoid mortality of eggs and young birds during strong winds. However, if climate change results in changes in the seasonality and duration of storms, these species may experience significant mortality of eggs and young during severe storms.

Increased irradiation/increased mean temperatures

Irradiation and mean habitat temperatures affect the behaviour of shorebirds and seabirds, and may have profound effects on breeding outcomes. Seabirds use various behavioural methods to thermoregulate when overheated or chilled; from changing incubation postures in gulls and terns during hot days to huddling in groups during cold spells in penguins (Bartholomew and Dawson 1979, Saliva 1995).

Although seabird species that nest under thick vegetation may not normally experience heat extremes, unusual weather events may negatively affect, directly or indirectly, the behavior of adult and young birds. At temperatures above the effective evaporative cooling temperature, Sooty Terns will leave their nests unattended and fly off to the water to dip their chest/belly feathers to cool off; leaving their nests unattended and exposed to predators and heat stress during this time (Saliva 1995). Thus, increased temperatures brought about by climate change may alter adult nest attendance and indirectly contribute to nest failure, not only in species whose nests are directly exposed to solar radiation (*e.g.*, Roseate Tern, Sandwich Tern, Royal Tern, Least Tern), but also species that nest under shelter such as the Sooty Tern, Bridled Tern, and Laughing Gull. During prolonged, extreme temperature periods, the shelter provided by vegetation may prove ineffective in maintaining sufficiently cool temperatures on their nests to allow normal incubation and chick rearing.

The extent to which adult survival is affected by environmental variability is poorly known due to the lack of sufficient studies using marked birds (Weimerskirch 2002). However, environmental conditions affecting food supply, such as increasing ocean and water temperatures, may influence survival of long-lived species such as seabirds and shorebirds. A classic example is the relationship between climate (El Niño Southern Oscillation-ENSO), schooling fish, and seabirds (Guanay Cormorant- *Leucocarbo bougainvilli*, Peruvian Booby- *Sula variegata*, and Brown Pelican- *Pelecanus occidentalis*) off the coast of Perú. Warm temperatures brought about by ENSO cause fish to change their travelling paths; avoiding the waters near seabird colonies and causing mass seabird die offs. Through techniques in modeling of survival it has been possible to relate the survival of adult Emperor Penguins (*Aptenodytes forsteri*) to oceanographic anomalies related to the Antarctic Circumpolar Wave that produces warm events (Weimerskirch 2002). During the warm events that occur every 4 to 5 years, adult survival drops to low values; some

years to 0.75, whereas in other years survival is 0.92 to 0.97. However, although adult seabird survival may not be affected in some species because they can fly to follow food, young seabirds may be abandoned and starve to death when fish behavior is altered by climatic events. For some species like Roseate Tern and Least Tern, which depend on predatory fish such as species of tuna (*Thunnus* spp.), mackerel (*Scomberomorus* spp.), dolphinfish (*Coryphaena* spp.), and jacks (*Caranx* spp.) to drive schools of larval or small fish up near the water surface; absence of predatory fish may result in unavailability of prey fish, even though the prey fish may be present.

Ocean acidification

Ocean acidification reduces the ability of marine algae and free-swimming zooplankton to maintain protective shells, and thus the survival of larval marine species, including commercial fish and shellfish, is also reduced (NOAA 2008). This could have indirect profound consequences on seabirds that depend on larval fish for feeding young chicks. If larval fish are not available to seabirds because plankton stocks have dwindled due to ocean acidification, massive mortality of young seabirds may occur; reducing the ability of those seabird species to replenish the populations. Seabird species that forage on larger fish or that can switch prey items to larger fish may have a slight, albeit temporary, advantage while stocks of larger fish are available.

Long term, indirect impacts of ocean acidification include interference with the formation of coralline cays where several shorebird and seabird species nest, which may be hindered by the disappearance of reef-building calcareous corals and algae (Wootton et al. 2008). Therefore, seabird and shorebird species that depend on coralline cays would be forced to select less suitable nesting areas, or not reproduce at all.

Research and Information Needs for Seabirds and Shorebirds (not in order of importance)

1. Study the effects of water level and salinity fluctuation on *Dasyhelea* (midge flies), *Trichocorixa* (waterboatmen), and algae through controlled experiments. For example, the existing seasonal cycles of desiccation and flooding, as opposed to permanent flooding, may be critical to the maintenance of algal mats and insect productivity for shorebirds.
2. Establish a careful banding program for the long-term monitoring of populations and colony-site shifting, and conduct studies on the demography and dispersal rates of selected shorebird and seabird species using band-recapture techniques. Main target species should be Least Tern, Roseate Tern, Sandwich Tern, Royal Tern, and American Oystercatcher.
3. Establish feral mammal eradication programs on islands currently or potentially used by shorebirds and seabirds.
4. Conduct Least Tern habitat assessment and studies of breeding success at different colony sites. Least Terns nest in areas prone to flooding, sea level rise effects, and mammalian predators. Their numbers are very small and little is known about the status of their populations and breeding success.
5. Habitat restoration of seabird nesting areas at historical nesting locations in Cayo Matojo (Royal and Sandwich terns), Cayo Lobito (Royal and Sandwich terns), Cayo Geniquí West (Brown Booby), Peninsula Flamenco (Sooty Tern), and Cayo Yerba (Sooty Tern)- Culebra archipelago; through habitat manipulation (removal of invasive plants and encroaching dead vegetation) and the use of decoys to attract terns to the manipulated habitat.
6. Attracting Red-footed Boobies and “seeding” of their historical nesting areas in Desecheo Island and Cayo Geniquí; through vocalization playbacks, the use of decoys, and translocation of immature Red-footed Boobies from Mona or Monito Islands.
7. Colony assessment and habitat enhancement for Least Terns nesting in salt flat areas of Balneario de Boquerón and Refugio de Vida Silvestre de DRNA in Cabo Rojo; mud flats of La Jungla, Guánica; and Punta Gotay, Tallaboa, through the construction of elevated platforms, use of decoys, and vocalization playbacks.
8. Enhancement of Roseate Tern nesting habitat on coralline cays off Lajas and Guánica, PR; through the use of artificial, wooden nest structures (boxes) and Roseate/Sandwich Tern decoys.
9. Re-assessment of rat eradication at Cayo Don Luis (southwestern Puerto Rico) and determination of Brown Pelican re-occupancy and nest success after eradication. Brown Pelican breeding success has been very low on this island, possibly due primarily to rat predation. Rats were eradicated from this island in 2010, but we have not been able to follow up on potential rat re-invasion and Pelican nest success after eradication. This would serve as part of post-delisting monitoring that the Service has to conduct as part of the Brown Pelican delisting process.
10. Assessment of rat invasion at Sooty Tern, Noddy Tern, Brown Booby and Masked Booby nesting sites at several low-lying cays in the Reserva de La Cordillera, and manipulation (removal) of invasive plant species to enhance nesting habitat for these species.
11. Conduct habitat vulnerability assessments for low-lying cays that currently harbor shorebird and seabird species, and other such cays not currently occupied.
12. Conduct status surveys, habitat characterization, and breeding success studies of Snowy Plover and American Oystercatcher in Puerto Rico.

Summary of Climate Change effects on Seabirds and Shorebirds

Over the last twenty years, seabirds have had a substantially poorer conservation status than non-seabirds, and they have deteriorated faster over this period. Seabirds are more vulnerable to environmental stressors (*e.g.*, storms, predators, habitat modification, and man-made factors) on their breeding sites than most land birds, because of the protracted period of nest occupancy and the concentration of complete regional populations in a few sites. Furthermore, populations are slow to recover from disturbance because of their low reproductive output.

Cliffs, mudflats, salt flats, inland artificial lakes, coastal saline ponds, and sand deposits on river mouths within the main island of Puerto Rico or close to its shore are also important roosting, foraging, staging, or breeding sites for seabirds and/or shorebirds, such as: Northwest Cliffs (between Aguadilla and Camuy); Cueva del Indio (Camuy); Isla del Frío (off Ponce); the mouth of the Añasco, Cibuco (Manatí), and Arecibo rivers; Lago La Plata (Toa Alta-Naranjito); Lago Carraízo (Trujillo Alto-Caguas); Laguna de Las Salinas (Ponce); La Jungla Salt Flats (Guánica); Cabo Rojo Salt Flats (Cabo Rojo); and Boquerón Natural Reserve (Cabo Rojo).

The following climate stressors affect seabirds and shorebirds in Puerto Rico: (1) sea level rise and saltwater intrusion; (2) increasing precipitation; (3) increased severity of storms; (4) increased irradiation and mean temperatures; and (5) ocean acidification (figure 7). The expected sea level rise (see Working Group 1 report) have the indirect effects on seabirds and shorebirds of starvation during migration stopovers for re-fueling, displacement into less optimal habitat, potential increases in predation in less optimal habitat, and nest abandonment and mortality of eggs and

chicks. Such is the case of a small coralline/sane island off the south coast of Guayanilla; in an area called Arrecife Unidas. The U.S. Fish and Wildlife Service monitored the growth and eventual disappearance of this island in 1991. By 2004 the island was completely submerged. Five species of seabirds and shorebirds had to move elsewhere to breed, in some cases to mainland areas filled with predators.

Increased precipitation may modify nesting habitat conditions, availability and abundance of food resources, cause nest abandonment, or even death of young and adults. Increasingly more intense storms may destroy habitat and result in unsuitable nesting areas in subsequent years, and impaired food acquisition. Increasing irradiation and mean temperatures may alter adult nest attendance and prey fish behavior and indirectly contribute to nest failure. And lastly, ocean acidification could interfere with critical processes such as reef building, carbon sequestration via phytoplankton sedimentation, and consumer-resource interactions.

More research is needed to determine how and to what extent Puerto Rico's seabirds and shorebirds are vulnerable to climate changes. Colony assessments and habitat enhancement for Least Terns nesting in salt flat areas of Balneario de Boquerón and Refugio de Vida Silvestre de DRNA in Cabo Rojo; mud flats of La Jungla, Guánica; and Punta Gotay, Tallaboa, through the construction of elevated platforms, use of decoys, and vocalization playbacks should be conducted. Status surveys, habitat characterization, and breeding success studies of Snowy Plover and American Oystercatcher in Puerto Rico should also be a research priority. And habitat vulnerability assessments for low-lying cays that currently harbor shorebird and seabird species, and other such cays not currently occupied.

1. Increased precipitation may modify nesting habitat conditions, availability and abundance of food resources, cause nest abandonment, or even death of young and adults.

2. Increased severity of storms may destruct habitat and result in unsuitable nesting areas in subsequent years, and impaired food acquisition.

3. Increased irradiation and mean temperatures may alter adult nest attendance and prey fish behavior; indirectly contributing to nest failure.

4. Ocean acidification (declining pH) could interfere with critical processes such as reef building, carbon sequestration via phytoplankton sedimentation, and consumer-resource interactions.

5. Sea Level Rise Indirect effects of the expected sea level rise on seabirds and shorebirds include starvation during migration stopovers for re-fueling, displacement into less optimal habitat, potential increase in predation in less optimal habitat, and nest abandonment and mortality of eggs and chicks.



Figure 7 Figure 1 Summary of how five climate stressors could potentially affect Puerto Rico's Seabirds and Shorebirds

Box 3: Puerto Rico's Disappearing Cays and Islets

Photos Courtesy of Dr. Miguel Canals, DNER



(A) Aerial photos of the cays Mata Hueca in 1963 and (B) of the same area in 2007.

FORESTS

Introduction to Puerto Rico's Forests

Forest composition and structure are strongly tied to climate – at large scales as climate governs seasonality, temperatures, and precipitation – and at local scales where climate interacts with topography, elevation, and soils to affect site characteristics. In this section we first provide an overview of the type and extent of the dominant forests in Puerto Rico, and identify the major stressors related to climate change that are likely to affect those forested systems. We then treat each forest type in more detail and discuss the potential outcomes and consequences of specific climate stressors on the biological communities of forested ecosystems. The resulting effects on human society regarding the provision of important ecosystem services are considered briefly as well. We conclude the section with a

summary of the multiple stressors and forest types together, and highlight important research and information gaps that remain.

More than half of the Puerto Rican archipelago is covered by forests, woodlands and shrublands (Gould et al. 2008a). We have categorized this forest cover in four broad groupings (figure 8) in order to assess outcomes of changing climate stressors on: (1) Coastal Lowland Forests – including lowland moist forests and woodlands and freshwater Pterocarpus swamps (mangrove forests are not discussed in detail here having already been addressed in the previous section on Wetlands); (2) Dry Forests – including forests, woodlands and shrublands in the subtropical dry Holdridge lifezone (Ewel and Whitmore 1973); (3) Karst Forests – including the forests of the northern limestone region; and (4) Montane Forests of the Central and Luquillo Mountains.

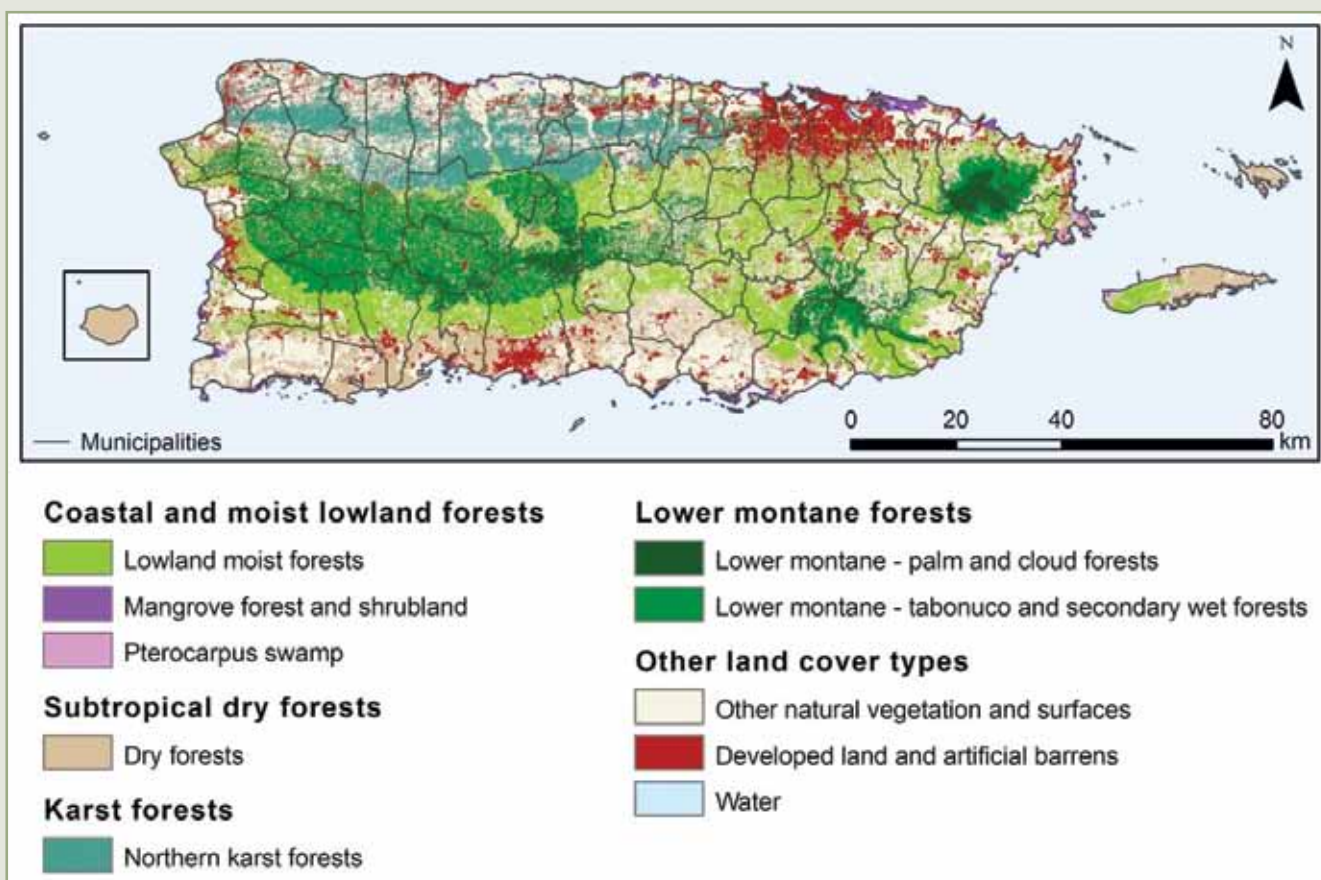


Figure 8 The dominant forest classes of Puerto Rico as considered in this climate change vulnerability report

Non-limestone lowland moist forests are found on the coastal plain and lower mountain slopes below about 150 m in northeastern Puerto Rico, and ranging to 400 m or more in the Central Mountains. These forests and woodlands occupy 165,000 hectares or about 16 percent of the islands, and are typically secondary forests regenerating on former pasture or other agricultural lands with *Spathodea campanulata* being a common nonnative tree. In the coastal wetlands, *Pterocarpus* swamps occupy just 261 hectares, and mangroves comprise some 8700 hectares, for a combined total of 1 percent of the islands. Other forests in coastal wetlands are typically secondary forests regenerating on occasionally or seasonally flooded former pastures.

The dry forests are found near the coast in the northeast on volcanic substrates and somewhat more inland on the south and southwest coasts on limestone substrates. They also occur on the ultramafic substrates of the Susúa State Forest in the southwestern part of Puerto Rico. Together dry forest communities occupy about 70,000 hectares, about 8 percent of the islands. Much of this area is woodland and shrubland and only about 4 percent of the islands are closed dry forest.

The northern Karst forests on limestone substrates occupy over 72,000 hectares, or just over 8 percent of the islands. Forest composition and structure reflect past human uses as well as steep topographic gradients associated with the haystack hills, or “mogotes” typical of karst topography. The majority of the region can be characterized as having steep slopes, with a lesser portion as valley bottoms, followed by summits (Martinuzzi et al. 2007). The summits tend to have drier, less well-developed soils, with the greatest soil moisture and development in the valley bottoms. Summits and slopes tend to have calcareous soils, with deeper, noncalcareous alluvial soils in the valley bottoms. As a whole the forests are very diverse, with a large number of endemic species. Variation in composition and structure tends to correlate with topographic

position, and canopy heights and basal area increase from summit to slope to valley bottom (Lugo 2005b).

The lower montane forests are to be found, depending on location, at elevations above 150 to over 400 m in the four wetter Holdridge life zones that occur in Puerto Rico (Ewel and Whitmore 1973): subtropical wet forest, subtropical rain forest, subtropical lower montane wet forest, and subtropical lower montane rain forest. These forests collectively occupy about 158,000 hectares, or nearly 18 percent of the islands. They include the well described tabonuco, palo colorado, sierra palm and elfin woodland forests of the El Yunque National Forest in the Luquillo Mountains, several forested parks in the Central and Carite Mountains, and forest growing on abandoned pasture and coffee plantations throughout the Central Mountains.

We have identified four major climate change stressors that are likely to affect Puerto Rico’s forests:

- Sea level rise
- Increased severity of tropical storms
- Decreased precipitation/increased drought/increased seasonality
- Increased irradiation/increased mean temperature and extremes

The Working Group 1 report addresses in detail the driving mechanisms behind each of these stressors, as well as observed trends and future projections. In the following paragraphs we will discuss these stressors in the context of each of the four dominant forest categories presented.

Outcomes and Consequences of Climate Change on Puerto Rico's Forests

COASTAL AND MOIST LOWLAND FORESTS – including freshwater *Pterocarpus* swamps and other lowland moist forests and woodlands

Elevational and hydrologic gradients control the occurrence of natural vegetation and also favor certain human activities in the coastal zone. Among them are topographic and associated salinity gradients at or very near sea level that influence the distribution of mangrove species (Lugo and Snedaker 1974); the growth of secondary littoral woodlands under the influence of wind and salt spray along shorelines; the regeneration of secondary semi-evergreen seasonal forest on abandoned pastures and hills up to 100 m; and the development of coconut plantations on relatively level terrain. The northeastern sea coasts were originally occupied by littoral woodland and mangroves (Wadsworth 1950), freshwater swamp forests, and different types of subtropical dry forests. *Pterocarpus* formed extensive stands in freshwater swamps and extended to higher elevations along riparian corridors. Species associated with drier conditions include *Bursera simaruba* and *Guaiacum officinale*, which were likely prevalent on less protected coastal slopes and hilltops, and *Bucida buceras* which also grows in coastal basins and along streams (Gill 1931, Little and Wadsworth 1964). In protected locations, species associated with moist forests such as *Calophyllum calaba*, *Manilkara bidentata*, *Tabebuia heterophylla*, and *Mastichodendron foetidissimum* were likely common.

PTEROCARPUS FORESTS

In the Caribbean, swamps formed by *Pterocarpus officinalis* trees (hereby *Pterocarpus* forests) occur in topographical depressions influenced by freshwater inputs, particularly in low-lying coastal areas (Bacon 1990). Adapted to flooded ecosystems, *Pterocarpus* forests occur in river floodplains, coastal basins and subtropical rain

forests in Puerto Rico (Alvarez-Lopez 1990). Early assessments of the Puerto Rico flora described *Pterocarpus officinalis* as an abundant species covering most of the mountainous region of the island (Bates 1929, Alvarez-Lopez 1990). However, during the early 1900's, Puerto Rico lost most of its *Pterocarpus* cover to deforestation driven by agricultural practices. By 1980, the total area of *Pterocarpus* forests in Puerto Rico was estimated to cover only 238 ha in 15 locations (Cintrón 1983), while the most recent estimate calculates their extent to 261 hectares based on 2000 Landsat imagery analysis and classification (Gould 2008a). This increase in wetland cover can be attributed to the abandonment of agricultural practices in coastal plains and the associated reestablishment of natural hydrological cycles (Martinuzzi et al. 2009). Nevertheless, *Pterocarpus* forests now occur in genetically isolated populations typically restricted to the coast, abutting mangrove ecosystems (Eusse and Aide 1999, Rivera-Ocasio et al. 2007), an important factor when considering the amount of biodiversity implied in a particular forest. The remaining stands of *Pterocarpus* forests in Puerto Rico are highly diverse, including basin and riverine forests in coastal and mountainous areas. In the Humedal Punta Viento Natural Ecological Reserve, located in the town of Patillas, a groundwater-fed spring provides a small *Pterocarpus* stand enough freshwater to survive in spite of being encroached on by mangroves in a coastal basin site that receives less rainfall than the Guánica Dry Forest (Alvarez-Lopez 1990, Van Bloem et al. 2007). Over the next decades, these remaining stands of *Pterocarpus* forests face a new set of threats, mainly because of environmental changes driven by sea level rise.

Stressors and consequences to *Pterocarpus* forests

The importance of hydrology in wetland ecosystems is well known (Mitsch and Gosselink 2007). The pulsating nature of the wetland's flooding and drying periods transfers energy and materials through the system driving many aspects of the ecosystem structure and function in the process (Odum et al. 1995). It is precisely this close relation between hydrology and the ability

to maintain a functional ecosystem what makes freshwater forested wetlands in coastal plains particularly vulnerable to climate change. For *Pterocarpus* forests, stressors related to increased temperatures – such as sea level rise and increased variability in precipitation patterns – could have a profound effect in the hydrological processes of the wetland.

Salt-water tolerance and sea level rise

The majority of the remaining stands of *Pterocarpus* forests in Puerto Rico are located on the coast, restricted to the limits of their physiological distribution in terms of salinity tolerance (Eusse and Aide 1999). This proximity to the ocean represents yet another threat for these remaining stands, due to the increased risk of saltwater intrusion. Research conducted on *Pterocarpus* forests has shown that increased soil and water salinity affects litter, flower, and fruit production and that salinities above 14‰ can kill populations of these trees (Eusse and Aide 1999, Rivera-Ocasio et al. 2007). In addition, salinity affects recruitment and growth, and even small changes (~1‰) reduced nodulation in the roots of seedlings (Saur et al. 1998, Fougny et al. 2007, Rivera-Ocasio et al. 2007, Dulorme et al. 2009). Still, this species has several adaptations that allow the tree to tolerate and avoid lower level salinities (Eusse and Aide 1999). For instance, their buttress roots create mounds of sediment that modify the micro-topography of the forest by providing areas of higher elevation around trees (Koponen et al. 2004). In addition, they accumulate excess of sodium in the rachis of the leaf, away from photosynthetic tissue, and have a shallow root system that is likely driven by a strategy to avoid the denser saltwater in the lower depths of the water table (Medina et al. 2008). Nevertheless, the increasing presence of salinity in the environment creates stressful conditions that disrupt the normal ecological processes of *Pterocarpus* forests.

Over the course of this century, sea level rise will bring more salt water into *Pterocarpus* dominated ecosystems in Puerto Rico. Our current understanding of how these important

wetlands will respond is the prediction that they will either migrate landward or be lost, according to the Brinson et al. (1995) model of coastal habitat migration. During long term events of salt water intrusion into coastal wetlands, freshwater species can be substituted by salt tolerant species, such as mangroves, and the zonation of existing mangroves forests can also change according to the migration of species according to their salt tolerance (Lugo 2006). In small islands like Puerto Rico, landward migration of coastal ecosystems could be limited by the concentration of human populations in the coast, poor land use practices and the further development of areas adjacent to the coast (Helmer 2004).

Coastal wetlands like mangroves forests can cope with the inundation threat of sea level rise by increasing their relative elevation to the sea through vertical accretion of peat, in some cases by up to 4 mm year⁻¹ (McKee et al. 2007, McKee 2011). Other studies suggests that coastal swamps will be unable to cope with the projected rates of sea level rise (3-5 mm year⁻¹, IPCC 2007) although there is still some debate on the different methodologies used to measure accretion rates and draw substantial conclusions (McKee 2011). The accretion of sediments in *Pterocarpus* forests as a coping strategy against sea level rise has received limited research attention and, therefore, needs further study. However, in the case of *Pterocarpus* forests, the threat of increased inundation periods could be secondary to saltwater intrusion, which can continue to affect the ecosystem even after the retreat of an inundating tide. Furthermore, the effect of salinity in the production of organic matter in *Pterocarpus* forests (Eusse and Aide 1999) could hinder the ability of these ecosystems to establish accretion rates capable of coping with long term sea level rise.

Droughts and rainfall events

Regardless of the uncertainty or disagreements in climate models that seek to predict and quantify changes in precipitation patterns related to climate change, most models agree on the expected long term trends for the Caribbean region (Neelin et al. 2006, Allan and Soden 2007).

The general agreement states that regions that lie outside the convection zones of atmospheric circulation – particularly the region of Central America and the Caribbean – are expected to go through a significant drying trend over the next 100 years (Campbell et al. 2011). IPCC (2007) data show that the maximum number of consecutive dry days in the Caribbean is decreasing. This result is consistent with the decreasing trends of precipitation over the last 50 years in Puerto Rico, where higher air and sea surface temperatures affect the hydrological cycle at a smaller scale.

Coupled with this long-term drying trend, warmer sea surface temperatures are likely to increase the frequency and intensity of pulsated rainfall events like hurricanes and tropical storms. For instance, the most active hurricane season ever recorded in the Atlantic Ocean – which included devastating storms like Hurricane Stan in Guatemala and Hurricane Katrina in New Orleans – occurred during the record breaking sea surface temperatures of 2005 (Trenberth and Shea 2006). The 2011 hurricane season was the third most active on record, tied with the 2010 season (Strachan 2012), and brought unusual amounts of rain to Puerto Rico during the late summer months.

Extreme variability in the quantity and temporal distribution of precipitation in the Caribbean (as directly related to storm events) could affect ecological processes like recruitment, root development and seedling survival in forested wetlands (Lopez and Kursar 2007). Regarding *Pterocarpus* forests, the predicted conditions can interact to exacerbate salt water intrusion events, particularly among riverine forests sites. For instance, if annual rainfall is concentrated in pulsated rain events that will become more frequent and intense during the two peaks of rainy seasons observed in the Caribbean (Comarazamy and González 2011), and these events are followed by increasingly dry periods, tidal influence can be intensified on riverine wetlands by the opening of the river mouth during the pulsated rain event and the subsequent lack of freshwater inputs during the extended dry periods. Hydroperiods affected under altered precipitation patterns

can alter important life history events like seed distribution and establishment (Lopez and Kursar 2007). *Pterocarpus* trees produce floating seeds that are dispersed through the landscape via hydrochory (dispersal of seeds by water) near the end of the flooding period. This adaptation allows seeds to reach areas of higher elevation in the complex microtopography of the forest and establish during the following dry season (Alvarez-Lopez 1990, Lopez 2001). However, prolonged flooding periods can affect germination of seeds by reducing the oxygen content of the soil and depleting the seeds' reserves, reducing the overall success of hydrochory as an adaptation strategy. In contrast, if heavy rainfall becomes more common during the dry season, establishment of *Pterocarpus* seedlings will likely be facilitated by this adaptation {Lopez, 2007 #41}.

In the context of sea level rise, freshwater inputs delivered by precipitation and its associated runoff have not yet been discussed as a potential mediator of saltwater intrusion in *Pterocarpus* forests, though they have for coastal dune plants (Greaver and Sternberg 2007, 2010) and hardwood hammock tree species (Sternberg and Swart 1987, Ish-Shalom et al. 1992). The benefits of freshwater inputs to the resilience of *Pterocarpus* forests to saltwater intrusion needs further research attention due to the possibility of catchment-scale hydrological restorations as possible strategies to manage these forests in the light of climate change-related events.

Each of the discussed climate change-related stressors has the potential to affect *Pterocarpus* forests in distinct ways, with the added complexity brought by the interactions between them (Lugo 2006). Between 2004-2009, over 630,000 acres of forested wetlands were lost in the tropical and subtropical regions of the United States (U.S. Fish and Wildlife Service 2009). As for mangroves forests, there is a lack of data of the ecosystem's capacity for carbon storage (Donato et al. 2011), making Caribbean wide studies on the amount of carbon stored in freshwater forested wetlands important to better understand the consequences of this loss. Studies of the hydrology, biodiversity and ecosystem processes across varying scales in

the Caribbean could help us have a clearer picture of the future of these wetlands and develop useful management strategies for long term disturbances related to the changing climate of the earth.

LOWLAND MOIST FORESTS

Forest occurring on noncalcareous substrates within the subtropical moist lowland Holdridge life zone (Ewel and Whitmore 1973) occupy 165,000 hectares or about 16 percent of Puerto Rico (Gould et al. 2008a). These are typically very young to mature secondary forests regenerating on former pasture or other agricultural lands on the coastal plain, hills, and lower slopes of the eastern and north central part of the island. They are a mix of native and non native species. Of the top four species in terms of importance values recorded by the US Forest Service Forest Inventory and Analysis in a 2003 survey, the nonnative *Spathodea campanulata* had the highest value, followed by the native species *Guarea guidonia*, *Andira inermis*, and *Cecropia schreberiana* (Brandeis et al. 2007).

Stressors and consequences to lowland moist forests

Sea level rise will likely affect only a small portion of these forests, but this includes littoral forests on beach strands, coconut plantations, and floodplain forests that may experience increased salinity, or altered flooding regimes. A potentially more serious stressor to these forests is increased seasonality, lower levels of precipitation or extensive drought. Effects may be to reduce growth rates, alter species composition and increase the likelihood of fire. The most abundant species in moist lowland forest are not well adapted to extensive dry periods and increased mortality, opening of forest canopies would likely lead to an increase in fine fuels (grasses) and increased occurrence of fire. Increasing storm frequency and severity could also impact these forests. Although they are well adapted to storms and recover quickly, the combination of storm damage (loss of canopy, downed limbs, mortality) and drought would enhance fire danger (Gould et al. 2008b).

These moist lowland forests serve as habitat for a number of common native bird, amphibian, and reptile species, as well as a number of migratory bird species (Gould et al. 2008a). Loss in forest area or shifts in composition, fruiting and phenology would likely affect a number of species. Additional research is needed in this area, as the particular impacts of climate change would have to be assessed on a species by species basis.

SUBTROPICAL DRY FORESTS

About 40% of the tropics and subtropics are covered by open or closed forest. Of this 42% is dry forest, 33% is moist forest and about 25% is wet and rain forest. The dry forests account for about 22% in South America and 50% in Central America. The subtropical dry forest life zone (Ewel and Whitmore 1973) covers approximately 17% of Puerto Rico and its adjacent islands and cays. It includes the outlying islands of Mona, Desecheo, Culebra, Caja de Muertos and the majority of Vieques. On the main island of Puerto Rico it covers southwestern Puerto Rico from Santa Isabel to Cabo Rojo and a small area near Ceiba and Fajardo. It is the driest of the life zones, with a mean rainfall of about 600 to 1,000 mm per year. Dry forests vary in species composition and structure depending on soil types, which vary across the life zone (Ewel and Whitmore 1973).

Generally, dry forests are smaller and less complex floristically and structurally than wet forests. The vegetation tends to form a complete ground cover and, on most soil types, is deciduous. Leaves are often small and succulent or coriaceous, and species with thorns or spines are common. Tree heights do not usually exceed 15 meters and the crowns are broad, spreading and flat. Plants are usually low in moisture content and the wood of most species is hard and durable. In these forests the seasonality of rainfall is a dominant ecological factor and patterns of growth and reproduction are synchronized with the availability of water. In most tropical and subtropical dry forest, two dry periods are characteristic, a minor one in the summer months and a major one in the winter (Ewel and Whitmore 1973).

Sutropical dry forest varies in structure and species composition depending on substrate types, which vary across the life zone. Substrates in the life zone include limestone, volcanic, alluvial and ultramafic igneous (Gould et al. 2008a). The subtropical dry forest has been converted and fragmented in large part to agriculture and grazing, urban and rural development, and tourism. Remaining protected areas in this life zone include the Guánica Commonwealth Forest, the Cabo Rojo, Laguna Cartagena, Culebra, Desecheo and Vieques National Wildlife Refuges, the Mona, Monito, and Caja de Muertos Natural Reserves, among others. The integrity of these natural areas is threatened by encroaching adjacent development, invasive species, and fire.

Stressors and consequences to subtropical dry forests

The principal climate related stressors or threats to the dry forests in Puerto Rico include those associated with precipitation, increased temperature, and increased storm severity. While it is not necessarily clear what the changes in precipitation will be, there is consistency in the predictions concerning increases in temperature. The areas containing seasonally dry tropical forests are expected to receive increases in temperature from between 2 to 4° C by 2100 (IPCC 2007). Even in the absence of changes in precipitation, this warming will result in a reduction in soil moisture availability, or in other words, increasing drought (Meir and Pennington 2011). Increased severity of tropical storms is predicted to result from warming sea surface temperatures (Emanuel 2005). Sea level rise may affect dry forest communities in coastal areas. Increased temperature/Decreased precipitation/Increased drought

Dry forests in Puerto Rico typically are subject to a primary dry season, from December to April. The severity and extension of this dry season is of particular concern in that it may affect phenology (flowering and fruiting patterns) and the successful establishment of seedlings. While it varies among species, there is general agreement that in dry forests the

availability of moisture plays a major role in seedling recruitment and survival. Seeds from most dry forest tropical species mature in the dry season and are dispersed at the beginning of the wetter season when moisture is available for germination and growth (Ewel 1980; Singh and Singh 1992). Vegetative regeneration is an important mechanism in disturbed dry forest sites, and would become even more important when regeneration by seed is affected by changes in the seasonality of precipitation (Murphy and Lugo 1986). This sensitivity to changes in moisture will make dry forests particularly vulnerable to climate change, potentially eliminating the more drought sensitive species and resulting in shifts in species composition in these forests (Condit et al. 1996). The increased dependency on vegetative regeneration or coppicing will likely cause shifts in species composition to species with a greater ability to resprout. This could have consequences for the breeding success of faunal species that depend on fruiting and flowering resources, such as frugivorous birds (Faaborg 1982; Faaborg and Arendt 1992; Dugger et al. 2000).

Species composition may also be affected by differing growth rates as a result of decreasing moisture availability and increasing concentrations of CO₂. One study has indicated that growth of a dry forest tree may be reduced by 12% under a medium emission scenario and as much as 21% under a high emission scenario. This is particularly important due to the aerial extent of dry forests in the tropics. If tree species exhibit differing rates of growth reduction, then species composition in those forests may be affected (Brienen et al. 2009). Tree mortality may be increased by increasing length and intensity of drought. Trees may respond in differing ways to moisture stress, either through stomatal control to maintain leaf water potential or through maintaining a water supply from the soil. The former reduce the risk of hydraulic failure but increase the risk of mortality by “carbon starvation.” Some studies indicate that the major cause of mortality in seasonally dry forests is hydraulic failure (Meir and Pennington 2011). Shifts in species composition may occur as a result of this increased mortality.

Increases in temperature and increased drought periods have been shown to result in the increased potential for more frequent and intense wildfires. While in Puerto Rico most wildfires are human-related, an extended and more severe drought can create conditions conducive to more intense and larger fires. High intensity fires may lead to significant loss of woody vegetation, and if seed sources are not available, regrowth of native woody vegetation may be restricted (Meir and Pennington 2011). This often permits the dominance of invasive species, and in dry forests of Puerto Rico such as Guánica this includes African forage grasses. With successive burning these grasses expand into intact forest. Germination and survival of native forest seedlings and saplings is low due to high water deficit, high temperatures and high light levels (Wolfe and Van Bloem 2012).

Restoration of degraded dry forests may become more difficult. Dry forests that have been cleared or degraded often develop into exotic grassland communities that are maintained by fire and are difficult to reforest. Areas that are replanted are subject to high mortality from fire, but also from increased moisture stress and temperature (Wolfe and Van Bloem 2012). Studies have shown that successful restoration projects can be high maintenance and therefore costly, requiring mulching, irrigation or both. The application of such treatments can increase survival significantly (Martinez and Van Bloem 2009). Increased temperatures and more intense and prolonged droughts can therefore make restoration a more costly endeavor.

Sea level rise

It is anticipated that rising seas will affect coastal morphology, causing mangroves to move inland and encroach on dry forest, with consequences for the species that depend on that habitat (Kerr 2009, Blunden et al. 2011). Resident and migratory birds that rely on dry forest for breeding and over-wintering, respectively, could be particularly vulnerable if dry forest does not expand into new areas at the same rate it is converted to estuarine habitats. For example, Rodriguez Colón (2012) investigated North American migrant songbirds

that depend simultaneously on interconnected mangrove and dry forest habitat in the south coastal region of Jobos Bay National Estuarine Research Reserve, and concluded that these populations will be imperiled by sea level rise if dry forest habitat is reduced, degraded, or eliminated. Avian populations in other coastal dry forest areas in Puerto Rico may face a similar threat.

Increased severity of storms

Most models indicate that while storm frequencies may not increase, they do agree that storm intensity will increase. The physical impacts of this increased intensity include increased damage from high winds and increased landslides and flooding. This may result in changes in species composition and structure of the forest. The structure of Caribbean dry forests is shorter and contains a larger proportion of multi-stemmed trees than other neotropical dry forests. Following disturbances such as hurricanes, dry forests resprout near the base. Studies in the Guánica dry forest have shown that hurricane-induced tree sprouts have the longevity and growth characteristics to contribute to the structure of the forest (Van Bloem et al. 2005). More intense hurricanes may result in a structure that is comprised of a greater proportion of multi-stemmed species and, in addition, the species composition may shift towards a greater proportion of species that have the ability to sprout. More intense storms may also result in mudslides and landslide that open the area for invasion of non-native species.

KARST FORESTS

The northern Karst forests on limestone substrates occupy over 72,000 hectares, or just over 8 percent of Puerto Rico. Aside from the protected Luquillo Mountains these represent the largest area of contiguous forest on the island. The steep topography of the haystack hills region and the underground drainage of the limestone affect both the hydrology and the human use of the landscape. In spite of the steep terrain the land was heavily used for agriculture in the last century and nearly all forests in this region are secondary forests on abandoned agricultural land (Chinea 1980, Rivera

and Aide 1998, Aukema et al. 2005). In spite of the past human deforestation much of the reforested land is characterized by native species, and reflects natural gradients in soil characteristics and site moisture associated with topographic variation. Hill tops are well-drained and relatively dry, hill slopes are steep, well drained, but with more soil moisture, and valley bottoms typically have deep humid soils. There is a north-south gradient in rainfall in the Karst region, with more rainfall in the higher elevations of the southern portion of the region and less rainfall in the north (Lugo and Castro 2001).

Stressors and consequences to karst forests

Given that strong site moisture gradients are already present within the karst region, these forests may to some extent be well-buffered against changes in temperature and precipitation. Small increases in dry season length, occasional droughts, or reductions in annual rainfall may not affect dry-adapted species on hill tops – and moist adapted species may remain sheltered in valley bottoms that continue to receive adequate runoff. Extensive drought or reductions in annual rainfall that are significant enough to alter the subterranean hydrologic system and dry out valley bottoms could have significant effects by decreasing growth rates and increasing canopy openness and mortality – leading to increased likelihood of fire and shifts in species composition, structure, and ecological function. Increased storm severity and accompanying damage could further exacerbate these effects (Peng and Wang 2012).

LOWER MONTANE FORESTS

Montane forests cover a total habitat area of about 158,000 hectares, or nearly 18 percent of Puerto Rico, and include elevations above ~400 m in the Central and Carite Mountains, as well as above ~150 m in El Yunque National Forest (ENYF). Within this broad elevation gradient, specific forest types are distinguished by edaphic conditions, combined with rainfall and topographic relief, as defined by Holdridge life

zone associations (Ewel and Whitmore 1973). At lower elevations subtropical wet forests dominate, where average annual rainfall can vary between 2000-4000 mm, and the weathered soils are derived from volcanoclastic sediments and serpentinite substrates (Ewel and Whitmore 1973, Miller and Lugo 2009). The subtropical wet forest assemblage is characterized by stratified, closed canopies reaching heights greater than 30 m and with a rich diversity of species (Little et al. 1974). The upper elevations are characterized primarily by lower montane wet, subtropical rain, and lower montane rain forest. Abundant annual rainfall (as much as 5,000 mm in EYNF) produces swampy and nutrient impoverished soils resulting in evergreen forest assemblages with trees of 18 m average height. At the stable mountain peaks the forest displays the gnarled and heavily epiphyte-laden characteristics of the elfin forest. Average canopy heights of only 6 m and extremely wet and depleted soils distinguish this cloud forest habitat. More fragile, steeply-sloped mountaintop areas are dominated by palm-brake forests (Ewel and Whitmore 1973, Lugo 2005a, Miller and Lugo 2009).

In the many centuries since European colonization of Puerto Rico, the lower montane forests of the Central and Carite Mountains (excluding EYNF) have gone through a cycle of clearing, conversion to agriculture, and subsequent forest regeneration with the advent of industrial development and agricultural abandonment (Franco et al. 1997). As of the most recent forest inventory in 2004, 57% of mainland Puerto Rico was covered in forest, woodland, or shrubland, with considerable increases in forest cover in subtropical moist, wet, and rain forests, much of which is still in the early stages of development (Brandeis et al. 2007).

Lower montane forests harbor most of the Puerto Rican endemic flora and fauna including birds, amphibians, bats, reptiles, invertebrates, trees, and plant species (Miller and Lugo 2009). In addition, watersheds in these habitats supply water to all major reservoirs in Puerto Rico. Therefore, the resulting effects of climate stressors will be relevant to several important ecological functions and related ecosystem services.

Stressors and consequences to montane forests
The dominant climate change-induced stressors that are likely to have a direct impact on montane forest communities in Puerto Rico include increased severity of tropical storms, decreased precipitation and an associated increase in drought, and increased irradiation and temperature. Indirectly, sea level rise may have an impact as well. Global circulation models currently project an increase of sea surface temperatures in tropical regions of 1-2 °C during the next century (IPCC 2007). This may result in greater cyclonic storm intensity (Emanuel 2005, Shepard & Knutson 2007), and may also cause a decline in precipitation by as much as 50% in some regions, including the Caribbean (Hulm & Viner 1998, Neelin et al. 2006, Gamble & Curtis 2008).

Increased severity of tropical storms

A large body of research allows us to make general predictions about how Puerto Rico's montane forests might respond to changes in the intensity of tropical storms. Lugo (2000) summarized the research regarding the effects of hurricanes on Caribbean forests, identifying 12 dominant biogeophysical outcomes: sudden and massive tree mortality; delayed patterns of tree mortality; alternative methods of forest regeneration in gap vs. landslide areas; changes in plant successional direction due to novel dispersal opportunities and recruitment sites; high species turnover and opportunities for species change in forests; diversity of age classes; faster biomass and nutrient turnover; species substitutions and changes in turnover time of biomass and nutrients; lower aboveground biomass in mature vegetation; creation of carbon sinks; selective pressure on organismal reproduction; and convergence of community structure and organization.

Should the intensity of hurricanes increase, Lugo (2000) predicts that they will cause more damage (*i.e.*, larger gaps and landslides) and reset the recovery trajectory further each time. This will lead to a greater average abundance of shade-intolerant secondary species in forests over time, as mature forests yield to the augmented

pressures of cyclonic disturbance. Consequently, the quantity and average height of aboveground biomass in these secondary forests will decrease due to the recurrent interruptions of vegetation growth. And species that better reproduce under disturbance conditions will thrive at the expense of species that require long periods of stability in order to mature. Long-term data collected from the Luquillo Forest Dynamics Plot, a 16-hectare grid of tabonuco forest located in EYNF, corroborate some of these predictions. Since 1990, repeated monitoring of trees, seedlings, and reproductive flowering/fruitleting have demonstrated that forest community dynamics are clearly affected by the close connection between hurricane damage and light availability (Zimmerman et al. 1994, Uriarte et al. 2004, Uriarte et al. 2009). The animal populations associated with these plant communities are also vulnerable. Wunderle (1995), for example, reported a homogenizing of understory and gap assemblages of birds in the EYNF, when comparing the results of post-Hurricane Hugo (1989) monitoring surveys with prior results. This pattern persisted even after new gaps and the forest understory regained their unique foliage profiles. More frequent and intense cyclonic storms could therefore result in permanently altered faunal assemblages and food webs.

The impacts of cyclonic storms on tropical forest communities must, however, be placed in the context of the legacy effects of human land use (Chazdon 2003, 2008). The recovering forests of Puerto Rico exhibit legacies of land use in the form of altered species composition that persist for decades (*e.g.*, Thompson 2002, Garcia-Montiel 2002). Although human disturbance promotes secondary species that are able to colonize more rapidly after human disturbances (Grau et al. 2003), Uriarte et al. (2009) found that the interaction of the legacy of past human use and the contemporary natural disturbance caused by hurricanes will probably result in a forest community that includes both primary and secondary species in a composition not previously witnessed. Thus, continuing interactions of humans and hurricanes are expected to remix native and introduced plant and animal species

into novel communities adapted to anthropogenic environmental conditions (Lugo and Helmer 2004, Lugo 2009).

Decreased precipitation/increased drought

Drought might seem an unlikely event in Puerto Rico's moist and wet lower montane forest communities. Yet several studies in the Luquillo Mountains have highlighted the impacts of droughts on both aquatic and terrestrial systems (Covich et al. 2000, Beard et al. 2005, Heartsill-Scalley et al. 2007). As mentioned earlier, climate models based upon field and satellite data predict a decrease in rainfall of 5-50% over the next 100 years for the Caribbean and Central America (Neelin et al. 2006). If precipitation in the region declines as anticipated then the frequency of short-term droughts is also likely to change, with an increase in the number of rainless or low-rain days per observation period.

Seed production and seedling recruitment in tropical forests are closely linked to inter-annual variation in climate, indicating the potential sensitivity of these processes to global and regional anthropogenic influences (Wright 2005, Wright et al. 2005, Wright and Calderon 2006). Changes in climate could directly affect relative competitive abilities of species specialized to different environmental niches, or indirectly affect recruitment via effects on pathogens and herbivores. In contrast to dry forests, decreased precipitation in Puerto Rico may ultimately boost greater seed production in lower montane forests, because a reduction in average seasonal evapotranspiration and cloudiness would lead to increased overall irradiation and likely an increase in flowering/fruitlet fecundity in lower montane forests (Wright 2005, Zimmerman et al. 2007). Seedling establishment and growth are also likely to be affected by periods of lower or no precipitation, depending upon the degree to which shade tolerance and drought sensitivity are correlated. Any increase in drought frequency could cause drought-insensitive secondary species to become even more common in the community (as has been shown in many temperate species, see

Sack 2004, Niinemets & Valladares 2006). On the other hand, if shade and drought tolerance are not related, then we can expect a pronounced change in drought frequency to encourage different, novel assemblages of species and distribution patterns. Either way, the probable result of a drier climate combined with the effects of land use history and hurricane disturbance is a change in the composition, abundance, and distribution of species in Puerto Rico's lower montane forests.

Sea level rise

As for sea level, the impacts of this stressor are most obvious for coastal areas (Nicholls and Cazenave 2010): in recent decades there has been a massive shift in Puerto Rico towards an industrial and service-dominated economy, which has resulted in rapid urban expansion in low-lying zones (Lopez Marrero et al. 2001, Lopez Marrero 2003). It is worth considering if the potential climate-induced displacement of human communities in coastal habitats will trigger increased competition for resources on mid-upper elevation lands and forested environments. The intensity of development for housing, recreational, infrastructure, and large, continental-style strip malls and shopping centers in Puerto Rico is already considerable in the lower cordillera forests, fragmenting important landscapes with human infrastructure (Helmer 2004). Should these development pressures migrate upslope in response to sea level rise, the conversion of forest to built environment will further reduce and fragment lower montane forest habitat.

Increased irradiation and temperature

Changes in local and regional climate can lead to increased vulnerability of cloud forests (Mulligan 2010). Although development is not likely to directly encroach on the higher elevations, there is evidence to support a coupling of land use and air temperatures in lowland regions with orographic cloud formation in tropical montane forests (Scatena 1998, Still et al. 1999, Lawton et al. 2001, Ray et al. 2006). Modeling of Costa Rican cloud forests demonstrated that the

orographic cloud bank intersected the mountains at the lowest elevations, covered the largest land surface area, and remained longest on the surface in the montane regions when the lowland and premontane regions were completely forested. In contrast, deforestation raised the surface sensible heat fluxes, warming the air temperature and lowering the dew point of air masses, ultimately reducing the cloud forest area covered with fog in the montane regions by as much as 13% and raising the orographic cloud bases by 75 m (Ray et al. 2006).

In Puerto Rico, the importance of lowland land cover on the height of the cloud base has also been documented. Scatena and Larsen (1991) reported that immediately following the severe deforestation of the Luquillo Mountains by Hurricane Hugo in 1989 the cloud condensation level was temporarily lifted by several hundred meters. According to Lugo (2005a), the daytime heat produced by the ring of urban infrastructure outside the National Forest affects the cloud condensation level of the Luquillo Mountains, and is potentially modifying the mountains' climate as well. Increases in temperature and solar irradiation may ultimately enhance the heat-island effects that accompany deforestation and urban expansion in coastal areas, with consequences for ecosystems and species at the highest elevations (Pounds et al. 1999; Colwell et al. 2008). In a pantropical study of hydrological processes in montane cloud forests, Bruijnzeel, Mulligan, and Scatena (2010) concluded that epiphytes and bryophytes in the upper parts of the forest canopy are particularly susceptible to climatic warming and drying, given their exposed position and dependence on precipitation inputs for their moisture and nutrient needs. If simultaneously subjected to increasingly intense tropical storm disturbance as well, it is probable that cloud forest vulnerability will be compounded even further.

Areas of Greatest Vulnerability

Biological communities that are restricted to environments with specific temperature and precipitation ranges, independent of forest type, are most vulnerable in the short-term to the

projected changes associated with a changing climate. This includes habitats located at the "extremes" – coastal lowlands, high elevation peaks, and the dry forests. While some species may potentially migrate upslope (e.g., Colorado trees, *Cyrilla racemiflora*, see Scatena 1998), species already bumping up against the upper limits of their range may not be so fortunate, and could be diminished or lost from Puerto Rico altogether due to the lack of suitable environmental conditions, or the biological environment (e.g., pathogens, competition from congeners). Fluctuations in fruiting/flowering phenology and upward shifts in vegetation could in turn create niche vacancies for previously suppressed or opportunistic exotic species to subsequently occupy (Platt and Connell 2003).

Directional changes in forest dynamics will in turn be determinant of how well upper elevation communities harbor animal populations. Two avian examples from the lower montane forests are the endemic Elfin-woods Warbler and the Puerto Rican Sharp-Shinned Hawk. As with high elevation plants, it follows that climate change might further restrict the birds' range as a result of habitat loss due to hurricane damage, or an altered prey base (Delannoy 1997, Anadón-Irizarry 2006). Dry forest avifauna that could potentially be affected by climate change include endangered species such as the Yellow-shouldered Blackbird and the Puerto Rican Nightjar, species whose distribution is restricted primarily to the arid habitats along Puerto Rico's southern coast (Atlas 2009; Vilella and Gonzalez 2009). Similarly, (Pounds et al. 1999) implicated dramatic declines in anuran populations in Costa Rica with recent warming of global sea surface temperatures and a corresponding movement upward of the orographic cloud base.

Certain lowland species are at risk not necessarily because of environmental barriers associated with temperature and precipitation gradients, but rather because of the lack of available habitat due to the presence of humans and their associated infrastructure. As discussed with regards to *Pterocarpus* forests, which are already severely limited in geographic scope, burgeoning urban

populations in adjacent coastal areas could effectively halt the landward migration of the *Pterocarpus* in the face of rising sea level (Helmer 2004). There is an obvious need for more research to support the link between climatic change and the consequent impacts on biodiversity. Even so, a warming climate will almost certainly create challenges for high elevation, coastal, and dry forest species situated in insular settings like Puerto Rico.

Societal Consequences

Up to this point we have discussed the biophysical and ecological outcomes and consequences that would likely occur in Puerto Rico's forests as the direct results of various climate change stressors. There may also be important consequences for human communities. In addition to the high toll of emotional and economic damage caused by destruction of built infrastructure, human life, and property (Pielke et al. 2003, Pielke et al. 2008), an increase in hurricane intensity and the accompanying deterioration or loss of habitat would potentially reduce the ability of Puerto Rico's forests to provide essential ecological services. These services include absorbing storm impacts of wind and rain, conserving soil resources and processing organic matter, storing carbon, supplying millions of gallons of water, filtering urban air pollution and regulating air temperatures, affording opportunities for recreation and tourism, and functioning as essential habitat in the life cycle of estuarine organisms that contribute to the coastal food chain (Lugo 1994, 2005a, Scatena et al. 2002).

Taking water yield as an example, Bruijnzeel, Mulligan, and Scatena (2010) reported that the impact of climate change on the water balance of cloud-affected forests is dominated by the anticipated changes in rainfall. Therefore, if Puerto Rico experiences an overall drying trend as is currently projected, the supply and flow of water from upland to lowland areas will likely be diminished. With public demands for fresh water increasing – water withdrawal from streams draining the El Yunque National Forest increased by 70 percent from 1994 to 2004 (Cook et al.

2007) – any reduction in the forests' capacity to supply abundant water could have unfavourable consequences for the island's human population.

Harder to anticipate are the outcomes that will ensue as a result of changes in species composition, structure, and growth rates, due to increased temperatures, drought, solar irradiation, and fire frequency. It is reasonable to assume that novel forest communities in Puerto Rico will continue to protect soils, cycle nutrients, support wildlife, store carbon, maintain watershed functions, and mitigate species extinctions, as put forward by Lugo (2009). Yet there will clearly be changes in the types of and the extent to which these services will be provided, the details of which are not yet well understood.

Forested ecosystems also have cultural, historic, aesthetic, and economic values that will change in response to climate stressors. In El Yunque National Forest and southwestern Puerto Rico, for example, activities such as bird watching and wildlife photography bring tourists, both local and foreign, and contribute to the local economy. Many people come searching for a particular species or experience that is afforded by these unique habitats. Climate stressors that result in the decreased abundance of and, therefore, visibility of high profile forest species may in turn affect the island's tourism industry.

Society's vulnerability to changes in the natural environment is determined in large part by numerous socio-economic and political factors acting at diverse temporal and spatial scales (Turner et al. 2003, Uriarte et al. 2011). Accordingly, climate-induced changes to ecosystem services must be examined in the context of contemporary land use practices as well, for loss in habitat and service provision will be amplified by other threats to natural resources, including urban and rural development.

Research Gaps and Information Needs for Puerto Rico's Forests

There are currently a broad range of institutions and agencies engaged in multi- and interdisciplinary

research endeavors in Puerto Rico. These efforts are aimed at investigating the long-term changes in disturbance regime and climate (including natural and human perturbations), and their effects on floral and faunal assemblages, biogeochemical dynamics, and ecosystem services. Yet several large knowledge gaps remain, particularly with regards to the specific details of habitat loss, shifts in fruiting/flowering patterns, and altered species composition. The linkages between climate change, ecological function, and the provision of ecosystem services need considerable illumination as well.

Additional environmental monitoring of all forest types will help fill these gaps. It is especially important in lowland and coastal areas where the combined stressors of human development pressures and climate change are likely to have the most significant impacts on forested landscapes. Karst areas, too, are lacking in data compared to lower montane and dry forests. More data from more sites will improve our ability to interpret the scales and rates at which climate-induced stressors affect forests, the degree of resilience to these pressures, and the thresholds beyond which irreversible change occurs. Directed studies focused on individual stressors are not sufficient; understanding of the combined, synergistic effects of multiple stressors on different forest types will be crucial to developing a nuanced model of the system dynamics that drive ecological transitions, and thereby improve society's ability to predict the consequences. Finally, clarification of the relative impacts of similar climate change stressors on diverse forest ecosystems of different spatial scales will help better identify areas and species of highest priority. In an era of rapid climatic change, this knowledge can then be translated into policy mechanisms aimed at adaptively managing forested ecosystems into the future.

Summary of Puerto Rico's Forests and Climate Change

Puerto Rico's dominant forest types (coastal and lowland and *Pterocarpus* forests; dry forests; karst forests; and lower montane forests) will all be affected by one or more of four major stressors

associated with a changing climate: sea level rise, increased severity of tropical storms, decreased precipitation/increased drought, and increased irradiation/temperatures. Complex interactions among these stressors make it difficult to tease out simple cause and effect relationships among climate drivers and the resulting impacts on forested ecosystems. Nevertheless, we can still draw some general conclusions about the anticipated outcomes and consequences (Table 3).

All forest types are likely to see alternations in flowering and fruiting phenology. The establishment and survival of seedlings will be affected as well, which will result in changes in species composition, distribution, and abundance. Over the long term, increased seasonality coupled with cyclonic storm impacts will signal directional changes in forest regeneration pathways. This will ultimately lead to novel communities that harbor unique assemblages of plants and animals, and exhibit altered forest structure and ecological functions. Biological communities located at the extremes of moisture, temperature, and elevation gradients – mountain peaks, dry forests, and coastal lowlands – are most at risk. Increased solar irradiation and temperatures and the effects on cloud condensation will impact forest communities at the highest elevations. Increases in the intensity and length of droughts and increased wildfires are a serious concern in dry forest communities. In coastal areas salt water intrusion will be a factor, as sea level rises and inundates lowlying forests. Development pressures could further complicate the ability of lowland forests to adapt. Forested ecosystems also have cultural, historic, aesthetic, and economic values that will change in response to climate stressors. The delivery and flow of important forest ecosystem services may be compromised by climate-induced alterations, with potentially detrimental effects for the human communities that depend on them.

FOREST TYPE	STRESSORS					BIOPHYSICAL OUTCOMES					SOCIETAL CONSEQUENCES
	Sea level rise	Increased storm severity	Decreased precipitation/increased drought	Increased solar irradiation/temperature	Salt water intrusion	Increased seasonality/changes in flowering & fruiting phenology, seedling establishment	Increased wildfires	Elevated cloud condensation level	Changes in species composition, distribution, and abundance	Novel plant and animal assemblages with unique structure and function	
Pterocarpus forests	✓	✓	✓		✓	✓			✓	✓	✓
Lowland moist forest & woodlands	✓		✓		✓	✓			✓	✓	✓
Dry forests	✓	✓	✓	✓	✓	✓	✓		✓		✓
Karst forests		✓	✓	✓		✓	✓		✓	✓	✓
Lower montane forests	✓	✓	✓	✓		✓		✓	✓	✓	✓

Table 3 Summary of outcomes/consequences of climate change stressors on Puerto Rico's dominant forest types

AMPHIBIANS AND REPTILES

Introduction to Amphibians and Reptiles

Amphibians

The extant amphibians (from the Greek “amphi” or both ways and “bios” or life; Class Tetrapoda, Sub-Class Lissamphibia) are tetrapods that include frogs, salamanders, and caecilians. Classification of living amphibians includes three Orders (in decreasing order of species richness): Anura (from the Greek “an” or without and “oura” or tail), with the familiar frog and toad forms; Caudata (from the Latin “cauda” or tail), with a long body plan, tail, and four (some with only two) limbs; and Gymnophiona (from the Greek “gymnos” or naked and “ophis” or snake because it was believed that these amphibians were most closely related to snakes). Species in Gymnophiona are frequently called caecilians from the Latin “caecus” or blind, which refers to the small eyes or complete absence of eyes in some species. Caecilians are the least known amphibians with fewest species, and characterized by an elongated body with skin folds that facilitates borrowing (similar the external body plan of an earthworm), the body lacks limbs, and has a short tail.

Amphibians are ectotherms—as opposed to endotherms like humans—and regulate metabolism mostly by external environmental regimes of temperature: in simple terms, as ambient temperature raises or lowers amphibians can raise or lower their body temperature as needed. They also produce eggs with several permeable jelly membranes (similar to fish eggs) that make amphibians highly dependent of water and humidity for reproduction and normal development of embryos. External fertilization and free-swimming larvae are predominant among amphibians. Amphibians are characterized also by a humid permeable skin that lacks hair, scutes, scales, and any structure for protection from external ambient variables and factors (Duellman & Trueb, 1994). Their skin is full of glands for various purposes (from hydration to defense), but that must be humid for normal physiology and gas exchange, most like breathing through skin. This makes an amphibian

virtually like a fish out of the water. Humid conditions are most prevalent during nighttime hours, which may explain why amphibians are mostly nocturnal in habits. The diet of adult amphibians mostly includes animal prey, while the diet of aquatic larvae mostly includes vegetable matter. Amphibians are distributed worldwide except in the coldest Polar Regions, highest mountaintops that are mostly frozen, and in strictly marine environments (Duellman & Trueb, 1994; Wells, 2007).

Notable exceptions to these descriptions do exist and some species of amphibians live in deserts (e.g., the Australian frog *Neobatrachus centralis*), have internal fertilization (e.g., the Puerto Rican Common Coquí *Eleutherodactylus coqui*), are ovoviviparous (*i.e.* females retain the eggs in oviducts and “give birth” to juvenile replicas of adults like the Puerto Rican frog *Eleutherodactylus jasperī*), are diurnal in habits (e.g., the Central American frog *Oophaga pumilio*), inhabit salty mud flats (e.g., the Southeast Asian frog *Fejervarya cancrivora*), and are fully aquatic (e.g., the Bolivian frog *Telmatobius culeus* from Lake Titicaca) (Duellman & Trueb, 1994; Wells, 2007). In the Caribbean, only members of the Order Anura (frogs and toads) are represented

Reptiles

The extant reptiles (from the Latin “reptile”, neutral of “reptilis”, or creeping, crawling; Class Tetrapoda) are tetrapods that include lizards and snakes, turtles, crocodiles, and tuataras. Specifically, the extant reptiles include four Orders (in decreasing order of species richness): Squamata (from the Latin “squama” or scale for their skin covered by scales), which includes lizards, snakes, and amphisbaenians; Testudinata (from the Latin “testa” or shell, an ossified carapace), which includes turtles, tortoises, and terrapins; Crocodylia (from the Greek “kroke” or pebbles and “drilos” or worm, which referred originally to the Nile crocodile presumably for its basking behavior), which includes crocodiles, alligators, caimans, and gharials; and Rhynchocephalia (from the Greek “rhynchos” or beak, snout and “kephalē” or head), which includes the tuataras. The Order Squamata is subdivided further into

two Suborders: Lacertilia (from the Latin “lacerta” or lizard) and Serpentes (from the Latin “serpens” or snake). Although snakes and some lizards lack limbs, all reptiles evolved from a four limb (tetrapod) ancestor.

Reptiles, like amphibians, are also ectotherms and regulate metabolism mostly by external environmental regimes of temperature. The protection brought in by their impermeable skin, however, makes reptiles somewhat more independent of humid conditions, compared with amphibians, for reproduction and normal physiology: reptiles do not have an aquatic larval stage and their dry skin is covered with scutes, bony external plates similar to scales, for protection against dehydration. In general, reptiles are most active during daytime hours, but nocturnal species (e.g., snakes) are common. The diet of reptiles generally includes animal material, vegetable material, or both. Internal fertilization is the norm among species and eggs are usually deposited in burrows or under debris in the ground (Vitt & Caldwell, 2009). Temperature-Sex Determination (TSD), instead of chromosomal-sex determination, occurs in reptiles in which males or females are produced more frequently than expected along portions of a vertical thermal gradient within the underground nest (Janzen, 1994). High prevalence of TSD in reptiles occurs most frequently in turtles and crocodilians; a low incidence of TSD is prevalent in the species-rich lizard Families Iguanidae and Polychrotidae; and a lack of TDS is notable in snakes (Valenzuela 2004).

The egg produced by reptiles, unlike amphibians, is an amniote egg (a membrane protected egg that is fertilized internally in the female). Different membranes of this egg are specialized for specific functions and provides a structure that is rather independent of external environmental conditions: gas exchange and protection from external environmental conditions (egg shell); internal protection (chorion); excretion of embryonic waste (allantois); provide nutrients to the developing embryo (yolk); and keeps an adequate aqueous environment (amniotic liquid) for normal development. Consequently, this amniote egg represents a major evolutionary

adaptation—only shared by birds and mammals—to life in dry land, making reptiles independent of water for reproduction as almost all resources for normal development are enclosed in the egg. Some species of reptiles live mostly in aquatic environments, including the open oceans, but none is fully aquatic. Consequently, reptiles need to always return to dryland to lay eggs and for normal development of embryos. Reptiles are distributed worldwide except in the coldest Polar Regions and highest mountaintops that are mostly frozen (Vitt & Caldwell, 2009)..

Exceptions to these descriptions do exist and many species of reptiles are ovoviviparous (e.g., *Boa* spp.), some are obligate parthenogenic (e.g., populations consist of only one gender; the brahmini blind snake, *Ramphotyphlops braminus*, for example) and prefer humid and cooler environments over drier and warmer environments (i.e., forest interior lizard like the Puerto Rican Yellow-Chinned anole, *Anolis gundlachi*, versus open habitat species like the Puerto Rican grass anole, *Anolis pulchellus*). In the Caribbean, members of the Order Testudinata, Crocodylia, and Squamata are the ones represented.

The Herpetofaunal Problem

Despite the facts that amphibians and reptiles are ectotherms and that they are frequently considered collectively, differences between the two groups are substantial (see above) and their responses to climate change deserve separate analyses, which is beyond this review. Some generalities are shared, however, as their physiology and phenology are most dependent on external environmental variables related with climate change like ambient temperature and humidity, rainfall, hydroperiod, and processes affecting these variables (e.g., sea-level rise, disturbances from storms, pathogenic infections, anthropogenic activities related with land use, storms and hurricanes, among others). How precisely each of the two groups will respond to climate change challenges scientists for various reasons. For example, in Puerto Rico, seasonal variation in temperature and rainfall is small (compared to continental and temperate areas), and shows a similar annual pattern: mean

monthly temperature and monthly total rainfall is somewhat higher between May and November and lower during late January and early April. In coastal ecosystems, the relative contribution of climate variables to activity patterns in amphibians and reptiles, and between amphibians and reptiles, is difficult to assess as to make formal generalizations because of the similarity in the seasonal variation of climatic variables and the similarity of the activity patterns despite physiological, behavioral, and ecological differences among species (N. Ríos-López, unpubl. data). Some general principles may exist, however, based on the differences in physiological requirements between amphibians and reptiles: in general, the abundance and distribution of amphibians is mostly influenced by humidity while the abundance and distribution of reptiles is mostly influenced by ambient temperature (Pianka, 1986; Duellman, 1999; also see Ríos-López and Aide, 2007 for a discussion from Puerto Rico).

Unfortunately, a straightforward analysis of the direct effect of these climate change variables on amphibians and reptiles may be misleading because a myriad of interacting factors exist that may counteract each other (e.g., Saenz et al., 2006), exacerbate responses to climate change (e.g., Pounds et al., 2006), and because of the uncertainty of how long the effects of climate change will remain as currently projected (note, however, that IPCC [2007] documents warming and sea level rise effects, due to anthropogenic activities, to last for more than a millennium because this is the timescale required for removal of carbon dioxide from the atmosphere). The next two examples, using the most referenced climate change variable, temperature, illustrate the complexity for predicting responses to climate change by amphibians and reptiles.

In amphibians like the Puerto Rican Common Coqui (*Eleutherodactylus coqui*), Stewart & Woolbright (1996) documented a gradual decrease in species abundance, from $>24,000$ coquis ha^{-1} in the lowlands to $< 2,500$ coquis ha^{-1} in high elevation areas along a 1000-m elevation range. This difference between a high temperature and a low temperature area is presumably due to a decrease

in prey availability with elevation (Stewart & Woolbright, 1996). Low temperature, however, increases developmental time of embryos in egg clutches (Townsend & Stewart, 1985), and decreases metabolism and growth rate, increases time to maturity, and increased age at first reproduction in *E. coqui* (Ríos-López, 1999). As individuals from high temperature areas (i.e., lowlands) grow faster, reach sexual maturity twice as fast as those from low temperature areas (i.e., highlands), and breed more frequently, population size may be higher with increased temperature (Ríos-López, 1999). Most likely, however, a cascading effect due to climate warming may include increased decomposition rates and nutrient cycling in humid areas (i.e., tropical montane forests), increased carrying capacity (i.e., availability of herbivorous insects), and a synergism between increased metabolism and population growth along the altitudinal gradient. If increased biomass of coquies is interpreted as increased productivity, the former scenario could be interpreted as a non-negative effect of warming to ecosystem processes like nutrient, carbon, and energy flows, as increased productivity is frequently associated with increased diversity. Obviously, this is not trivial and climate change brings up diverse consequences to ecological systems and herpetofaunal species.

In reptiles with TSD, increases in ambient temperature will affect sex ratios in nests, nest survival, and normal development and growth of hatchlings (Janzen, 1994; McCallum et al., 2009). In the American Alligator (*Alligator mississippiensis*) temperatures of 30°C and below in the nest produce females, 32°C produces males and females, 33.5°C produces only males (Ferguson & Joanen, 1982, 1983), but temperatures 35°C and above produce 90% females which are usually not viable (Murray, 2002). In contrast, cooler incubation temperatures produce only males while warmer incubation temperatures produce only females in *Trachemys scripta elegans* (Cadi et al., 2004; Tucker et al., 2008), a close relative of the Puerto Rican Jicotea, *T. stejnegeri*. Increased ambient temperature due to climate warming will influence sex ratios, and unless selection in female nest-site choice (i.e., open versus shade areas) to

keep pace with warming, altered sex ratios in nests will have profound consequences for population demography and dynamics (Gibbons et al., 2000). In Puerto Rico, species such as the Hawksbill Sea Turtle (*Eretmochelys imbricata*), which nest under the vegetation in tropical beaches, may not be as affected as other species such as Leatherback Sea Turtle (*Dermochelys coriacea*), Green Sea Turtle (*Chelonia mydas*), and Loggerhead Sea Turtle (*Caretta caretta*), which lay their eggs in nests in open, sandy areas in the beach. The effect of warming can also be different between species (e.g., terrestrial versus aquatic turtle species; McCallum et al., 2009), which requires further study.

The Caribbean Herpetofauna as a Study Model

The herpetofauna is nonetheless an important component for many ecosystem processes, especially in tropical islands. On Caribbean islands, which lack the large mammals that characterize continents, amphibians and reptiles, along with birds, constitute the top predators and are the most abundant and conspicuous land vertebrates (Reagan 1996a; Duellman 1999). In a Puerto Rican rain forest, for example, the combined population density of three species of lizards (Polychrotidae: *Anolis*) and one species of tree frog (Eleutherodactylidae: *Eleutherodactylus*) reached 49,800 individuals ha⁻¹ (Reagan 1996b; Stewart and Woolbright 1996). One of these species, *Anolis stratulus* (Cope), has the second highest density documented for any lizard worldwide with > 2 individuals/m² (Reagan 1996a). Collectively, these species regulate ecosystem processes indirectly through predator-prey interactions as they consume > 550,000 prey items ha⁻¹ d⁻¹, mainly insects (Reagan 1996b). This makes the Caribbean herpetofauna a major component in the local ecosystem energy, nutrient, and carbon flows (Roughgarden 1995; Beard et al. 2003; Hillman et al. 2009). As a result, given that amphibians and reptiles are particularly at risk due to climate change, responses to projected climate change will have profound consequences for herpetofaunal species diversity and ecosystem processes.

Examining responses to climate change by amphibians and reptiles for adequate conservation, management and policy making efforts requires a first exploration of projected changes in climate, both at global and regional scales. Herein, Dr. Neftali Rios-López for the PRCCC reviewed the pertinent literature and examined the relationship between climatic factors and population dynamics, species distribution, species abundance and extinction and on changes in diversity that most likely will occur with predicted climate change. Climate projections from contributions of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007) are briefly discussed when appropriate and responses to temperature, humidity/rainfall, sea level rise, pathogenic disease, and storms by Puerto Rican amphibians and reptiles, whenever possible, are highlighted. Areas where information is needed are also highlighted with suggestions for research agendas for the benefit of herpetofaunal conservation efforts in light of projected climate change.

Climate Change Scenario: Current Status and Existing Vulnerabilities in the Caribbean and Puerto Rico

Temperature

In marine turtles, the capacity for long-distance dispersal is one wonder of the natural world, with some species traveling thousands of kilometers across the ocean (Meylan, 1995). Sea surface temperature and chlorophyll concentrations strongly influence migration routes of marine turtles (Thomas and Dabo, 2005), which suggest that projected increase in sea surface temperature may affect migratory patterns of marine turtles. In addition, increased water temperature and ocean acidification (with increased CO₂ input from anthropogenic sources) may contribute to the death of corals, sponges, and sea grasses, which are highly important food sources for marine turtles. How sea turtles will respond to climatic change remain mostly a matter of speculation, and according to the State of the World's Sea Turtles (SWoT) Report (2006), comprehensive long-term data sets are urgently needed to examine

responses to projected changes in climate by marine turtles.

A low capacity for long-distance dispersal characterize virtually all herpetofaunal species (exceptions include marine turtles), which makes them highly dependent on local environmental conditions for reproduction and survival (Duellman & Trueb, 1994; Gibbons et al., 2000; Root et al., 2003; Vitt & Caldwell, 2009). For example, lowland species with highly patchy, disrupted distribution (e.g., in Puerto Rico, the Dry Forest Anole, *Anolis cooki* [Rodríguez-Robles et al., 2008], *A. poncensis*, and several *Sphaerodactylus* species) and those living in montane areas the ones who will suffer the most with warming (and

Species with limited geographic distribution living in montane areas (i.e., in Puerto Rico: the Dwarf Coqui and the Yellow-Shinned Anole) will be forced to migrate upland to keep up the pace with increased ambient temperature.

precipitation) (Pounds et al., 2006; McCain & Colwell, 2011). Species with limited geographic distribution living in montane areas (i.e., in Puerto Rico: the Dwarf Coqui, *Eleutherodactylus unicolor*, and the Yellow-Shinned Anole, *Anolis gundlachi*) will be forced to migrate upland to keep up the pace with increased ambient temperature. Lowland herpetofaunal species better suited for increased temperature (e.g., in Puerto Rico, the Antillean Coqui, *Eleutherodactylus antillensis*, the Common Grass Anole, *Anolis pulchellus*, or the Crested Anole, *A. cristatellus*) will expand their geographic distribution upland, which suggests a complete replacement of many of the montane, specialized species by lower elevation, generalist species with projected estimates of warming. This could also lead to extinction of high elevation residing species like *E. unicolor*, the Cricket Coqui, *E. gryllus*, and the forest-dwelling *Sphaerodactylus klauberi*, to name a few, if their adaptive capacity is compromised (e.g., Root et al., 2003) and because

of altitudinal shortage of space beyond the highest peaks. Responses to warming by amphibians and reptiles will not be so linear, however, and other factors acting in synergism will influence these.

Many studies have documented population declines and extinction of herpetofaunal species worldwide (Wake, 1991; Blaustein et al., 2010; Gibbons et al., 2000; Reading et al., 2010). Originally, many cases of declining populations of these species have been enigmatic, but recent evidence points at climate change as a main driver for cascading effects on amphibians and reptiles at different temporal and spatial scales (Cary & Alexander, 2003; McCallum et al., 2009; Blaustein et al., 2010; Reading et al., 2010). In amphibians, for example, Pounds et al. (2006) conclude with 'very high confidence (>99%, following Intergovernmental Panel on Climate Change, IPCC) that large-scale warming has been a key factor for amphibian population declines in tropical montane cloud forests in Central America. Pounds et al. (2006) concluded that warming encourages outbreaks of the pathogenic chytrid fungus, *Batrachochytrium dendrobatidis* (Bd), by converging nocturnal and diurnal ambient temperature towards growth optimum conditions of this amphibian-demising fungus, particularly during warm years associated with El Niño events. In extreme warm years, after an El Niño event, the physiology of amphibians may become compromised, the fungus growth at an optimum, resulting in observed drastic population declines and species extinctions in Central America (Pounds et al., 2006).

The phenomenon described by Pounds et al. (2006) may not be exclusive to Central America and it is highly possible that a similar situation occurs with Puerto Rican amphibians (e.g., Burrowes et al. 2004): here, population declines and species extinctions of several amphibians correlate strongly with the the pathogen is first detected, last time of species detection from the wild, years with strong El Niño events, years with largest difference between mean winter temperature and mean summer temperature, and years when the difference between minimum daily temperature (i.e., nocturnal temperature)

and maximum daily temperature (*i.e.*, diurnal temperature) converges towards the thermal optimum growth range of the pathogen Bd (N. Ríos-López, unpubl. data). Increased pathogenic outbreaks with increased sea surface temperature have also been documented for marine turtles: Haines and Kleese (1976) argued that increased outbreaks of diseases in marine turtles peaked during El Niño events, suggesting a synergism between increased sea surface temperature and pathogenic outbreaks.

In reptiles, Readings et al. (2010) documented an alarming and steady trend of declining populations of many species of snakes (which are top predators) from distant countries like the United Kingdom, France, Italy, Nigeria, and Australia. Readings et al. (2010) found that 75% of declining populations are from species characterized by small home range, sedentary habits, sit-and-wait foragers, and most came from well-protected areas. Readings et al. (2010) reasoned that synchronized patterns of declines across regions are indicative of a change in habitat quality (instead of habitat loss) suggesting a common stochastic environmental factor (*e.g.*, climate change). In contrast, Shine (1991) documented a dramatic decline in the Australian common black snakes (*Pseudechis porphyriacus*) that specializes in frogs. Consequently, a plausible hypothesis for most snake population declines in Readings et al. (2010) may include a reduction in the availability of their prey due to a cascading effect from global warming, pathogenic outbreaks among potential prey, and a reduction in the carrying capacity among all habitat areas: the chytrid fungus has been documented in amphibians from each of the countries examined by Richards et al. (2010). Synergism between temperature (and humidity) and pathogenic infections in reptiles may also lead to drastic population declines with projected climate change. For example, the widespread upper respiratory tract disease—a contagious respiratory ailment caused by the bacterium *Mycoplasma agassizii*—is a potential cause of population declines in desert in Southwest U.S.A and in gopher tortoises in Southeast U.S.A (Jacobson, 1993; Smith et al., 1998). **An unidentified bacteria that can cause a similar**

respiratory ailment in snakes have been found in the Puerto Rican Boa (*Epicrates inornatus*), and increased physiological stress due to climate change on the Puerto Rican Boa may exacerbate its response to pathogenic infection with profound consequences for population persistence and species survival (A. Puente-Rolón, per. comm.).

Species of snakes that need high body temperature to regulate their metabolism under hot, sun-lit environments, like most dry forests in Puerto Rico, are a greater risk of overheating because dispersal requires contact with the hot substratum (*e.g.*, Lilliwite, 1987), thus affecting dispersal behavior.

An unidentified bacteria that can cause a similar respiratory ailment in snakes have been found in the Puerto Rican Boa (*Epicrates inornatus*), and increased physiological stress due to climate change on the Puerto Rican Boa may exacerbate its response to pathogenic infection with profound consequences for population persistence and species survival.

In some species like the grass snakes (*Natrix natrix*) the rate of gastric secretion increases with temperature in the range between 25°C and 35°C (Skoczylas, 1970), which the rise in digestive rates increases the frequency of feeding in the snake. If the availability of potential prey decreases with climate change, some snake species will die due to starvation. The projected warming will also increase rates of water exchange in snakes threatening their survival as pulmonary water losses in ventilation increases (Lillywhite, 1987) and because the majority of water loss occurs through skin (Dmiél, 1972).

In a recent study, Gunderson and Leal (2012) compared the locomotor performance of the Crested Anole, *A. cristatellus*, between populations from cooler, humid forests and from dryer, hotter forests in Puerto Rico. The authors estimated

thermal performance curves from sprint speed (a proxy for locomotor performance, which is a temperature-dependent performance trait frequently used to examine the influence of climate change on reptiles) and found similar performance curves between anoles from humid, cooler habitats and hotter, dryer habitats: sprint speed performance increased steadily between ~20°C and 35°C body temperature, and declined sharply beyond 35°C body temperature. The authors found an ambient temperature of 33.4°C in the dryer, hotter forest, and an ambient temperature of 28.9°C in the humid, cooler forest, and concluded that individuals living in the dry forest may be living in their physiological thermal limit with profound consequences for survival with the projected 3°C warming estimate for the 21st century. Individuals living in the cooler, wetter forest will be little impacted (if at all) with the same projected warming as the ambient temperature may raise to 31.9°C, well within the anole operative temperature for normal locomotor capacity (Gunderson and Leal, 2012). Increased temperature in cooler, wetter forests, however, may be detrimental to anole species whose thermal niche is limited to these forests. One such species is *A. gundlachi*, (and presumably other forest-interior species), which has a poor tolerance to high temperature (Rogowitz, 1996, 2003). Therefore, while warming may have little impact on *A. cristatellus* (a species adapted to a wide range of environmental conditions) in a wet and cool forest, warming will be highly detrimental to *A. gundlachi* in the same area. Presumably, the geographic distribution (and abundance) of many other species whose habitat use may be related with their thermal physiology capacity will be compromised in similar ways by the projected level of warming.

Precipitation

Projections from climate models revealed a global increase in the intensity of precipitation events and precipitation extremes (compared with the mean in tropical areas), along with longer periods between rainfall events (Meehl et al., 2007; see Working Group 1 report). This may lead to profound changes in the annual variability

and distribution of rainfall among months. In the Caribbean, for example, summer rainfall (between June and August) is likely to decrease in the Greater Antilles, but changes elsewhere and in winter are uncertain (Christensen et al., 2007). In Puerto Rico, a decrease between 20% and 30% in summer rainfall (between June and August) could occur by the end of the 21st century; a decrease between 5% and 10% in winter rainfall (between December and February); and a decrease between 15% and 20% in annual rainfall (Christensen et al., 2007; see Working Group 1 report). In addition, increased temperature has raised the height for orographic formation of clouds in tropical montane forests, which has reduced the frequency and daily regime of cloud immersion and humidity (Foster 2001; Pounds et al., 2006; Van der Molen et al., 2006; Wu et al., 2006). This phenomenon has been documented in Puerto Rico by Van der Molen (2002) after hurricane Hugo defoliated most cloud forests at the Luquillo Experimental Forest (LEF) in 1989. The cloud base was uplifted beyond the highest peak at the LEF (Wu et al., 2006), which could have reduced daily mist frequency and relative humidity similar to that documented from Monteverde, Costa Rica, due to warming (Pounds et al., 2006).

The projected reduction in rainfall and in forest immersion in clouds due to warming in Puerto Rico will exacerbate responses to temperature by herpetofaunal species, particularly by amphibians. For example, Stewart (1995) monitored a deme of the Common Coqui, *E. coqui*, for 14 years (from 1979 to 1993) in the LEF. Stewart noted a decreased in population size since 1983 and a marked drop in abundance in 1984, for which the species never recovered during the studied period. Interestingly, Stewart (1995) also documented having seen the Puerto Rico Mountain Coqui, *E. portoricensis*, regularly before 1984, after it was seen only twice. At a short time scale, the decrease in numbers of *E. coqui* was correlated with an increase in the frequency of the number of periods of days with ≤3mm of rain (a threshold below which frogs are critically stressed; Pough et al., 1983; Beuchat et al., 1984; Stewart 1995). At a longer time scale, species abundance was correlated negatively with the longest dry period during the previous

year, which revealed a lag-time response between reduced rainfall and changes in population size (Stewart, 1995). Stewart (1995) concluded that rather than total monthly or annual rainfall, it was the distribution of rainfall that determines population dynamics and abundance. While increased humidity is critical to amphibians for normal behavior, other variables (warming) and factors (pathogens) may have likely influenced Stewart's observations, which reflects important interactions between variables driving responses to climate change by amphibians.

The projected increase in ambient temperature means that the height of the cloud base will increase; presumably well above the highest mountain peaks, with a reduction in humidity levels, and the elevation shift of lowland ecosystems into highland areas (and presumably the substitution of highland ecosystems like tropical montane cloud forests). This is particularly relevant for pathogenic infections documented in Puerto Rican amphibians from montane forests. For example, Burrowes et al. (2008a) documented a higher prevalence and infection by *Bd* in populations of *E. coqui* from a 650 m of elevation compared with a population of *E. coqui* at 850 m of elevation at the LEF. They also found a 20% higher prevalence of this pathogen on juveniles compared to that from adults across sites. The authors reasoned that runoff from higher elevation sites is greater compared with runoff at lower elevation sites, which serves as a source and means for the spread of the aquatic zoospores of *Bd* from high elevation areas to lower elevation areas (Burrowes et al., 2008a). The projected decrease in humidity levels at the highest elevation areas at the LEF (and presumably elsewhere in Puerto Rico) would imply the increased prevalence and epidemic spread of *Bd* to species with limited distribution and adapted to humidity and temperature regimes typical to high elevation cloud forests (e.g., *E. unicolor*, *E. gryllus*, *E. portoricensis*, among others). In samples from the mid 1970s, *Bd* has already been found in *E. unicolor*, *E. portoricensis*, and in other species with geographic distribution limited to high elevation montane forests (Burrowes et al., 2008b), most of them inhabiting the forest understory and not the canopy (e.g., *E. gryllus*,

E. hedricki). As Puerto Rican tropical montane cloud forests are centers of high diversity, endemism, and ecologically specialized species of amphibians, the projected decrease in rainfall and humidity regimes, along with warming, will have detrimental consequences for most Puerto Rican amphibians.

In Puerto Rico, studies examining responses to water availability by reptiles in the climate change context have lagged considerably, as far as the author is aware, but a reduction in rainfall and humidity must certainly affect several physiological and behavioral aspects of reptiles, particularly of those with limited geographic distribution in highland areas.

Sea-Level Rise

Sea levels have risen and will continue for centuries, significantly affecting islands in the Caribbean (IPCC, 2007; see Working Group 1 report). There are seven living species of sea turtles (Family Cheloniidae and Dermochelidae) found in all the world's oceans, three of which are frequently found nesting in Puerto Rico (i.e., the Green, *Chelonia mydas*, Hawksbill, *Eretmochelys imbricata*, and Leatherback Sea Turtle, *Dermochelys coriacea*). The latter one is only found during the nesting season, while hawksbills and greens are found in several life stages near Puerto Rican coasts. In sea turtles, a direct consequence of sea-level rise will be loss of coastal area, particularly sandy beaches vital for nesting. For example, Bräutigam and Eckert (2006) and Fish et al. (2005) documented loss of nesting habitat, due to erosion caused by sea level rise, storms, and sand-mining activities, as a major factor influencing declining population of sea turtles. Sea level rise will also impact foraging grounds such as seagrass beds, coral reefs, and the open ocean according to SWoT (2006). The expected increase in tidal height, which accompany sea level rise, may also increase the risk of eggs in nest being flooded (and die) as the available nesting area encroaches between the sea level to the coast and the belt of sandy beaches that remains along urban areas inland.

Sea-level rise due to thermal expansion of warmer seawaters will also lead to salt-water intrusion in coastal areas with increased degradation and loss of larger areas of coastal wetlands worldwide (Allen et al., 1996; Howard and Mendelssohn, 1999; Williams et al., 1999; Nichols, 2004; Rivera et al., 2007). Increased salinity, for example, has been accompanied by landward migration rates of mangroves 12 to 37 times the relative sea-level rise in American Samoa (Gilman et al., 2007), with expected replacement of brackish-water and fresh-water wetland forests by mangroves (Rivera et al., 2007). In coastal Puerto Rico, species richness of amphibians and reptiles increases inland with distance from sea (figure 9), and population size of amphibians decreases with increased ambient salinity (Ríos-López, 2008). Brackish-water and fresh-water *Pterocarpus officinalis* forests, however, are specially important habitat for several species of amphibians and reptiles, as tree holes in these forests provide retreat and breeding sites for amphibians, hummocks formed by buttresses provides breeding sites for amphibians and reptiles, and the architecture of the dense canopy provides important microhabitat for reptiles, including the densest Puerto Rican anole, *A. stratulus*. The loss of *Pterocarpus* forests will be highly detrimental for amphibians and reptiles in coastal areas because *Pterocarpus* forest characteristics suitable for amphibian and

reptile reproduction and survival are not shared by mangroves (see forest section and box for more information on climate change and *Pterocarpus* forests). In addition, responses to forest loss will also be exacerbated by sea-level rise and salt-water intrusion because a slight increase in water salinity (between 6 ppt and 8ppt) result in impaired osmotic physiology and metamorphosis, morphological deformities, and low larval survival in native and introduced amphibians (Ríos-López, 2008).

Responses to sea-level rise by amphibians and reptiles will also be exacerbated considering the fact that more than 70% of the world's human population live on or near coastlines (Mitsch & Gosselink, 2007) and the urban/industrial development inland will exacerbate the level of contraction of populations of amphibians (Ríos-López, 2008) and reptiles (Ríos-López, 2007). If adaptation to these environmental changes does not occur at the rate of current changes in climate, we expect many populations and species with limited geographic distribution (e.g., the Puerto Rican Crested Toad, *Bufo lemur*; several *Anolis* spp.; see Gunderson & Leal, 2012) be destined for extinction if conservation of coastal areas and the establishment of coastal-to-inland corridors beyond urbanized areas are not implemented.



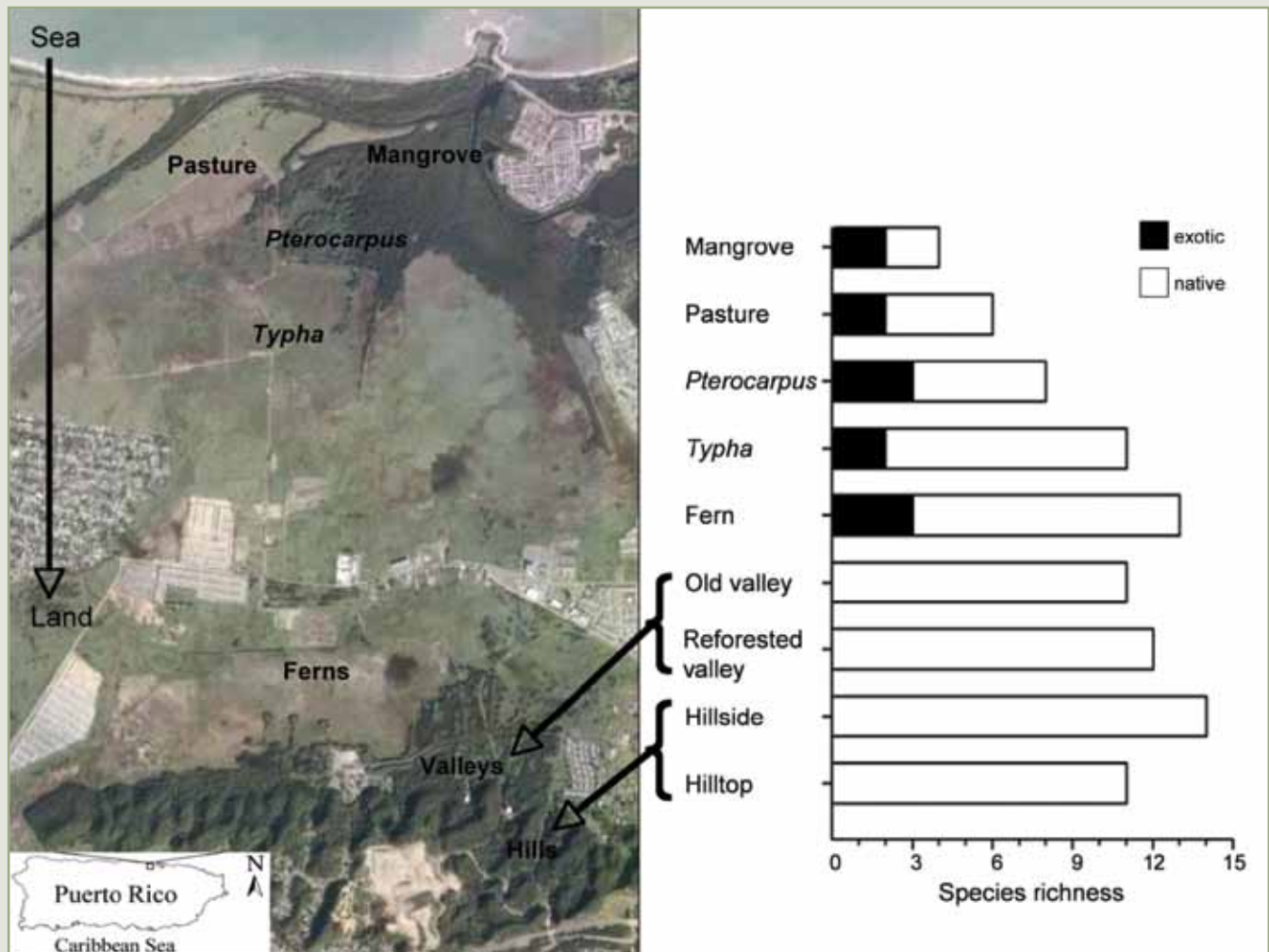


Figure 9 Herpetofaunal species richness increases with distance from the coast. Sea-level rise and salt-water intrusion will force many species to inland migration while urbanization and land-use will set an effective dispersal barrier inland. Many species will be at their physiological limit unless effective conservation measures, including natural corridors from coast-to-inland regions beyond urbanized areas, can be implemented. Otherwise, loss of species and wetland ecosystems will be lost with predicted changes in climate. Other responses include introduced species replacing native species in coastal areas, apparently facilitated by anthropogenic disturbances related with changes in land-use. Synergism between climate change and anthropogenic disturbances brings a complex suit of threats to Puerto Rican herpetofaunal diversity, which requires well planned, multidisciplinary conservation strategies and management plans (from Ríos-López, 2007).

Tropical Storms and Hurricanes

Future tropical storms are projected to be more intense, with larger peak wind speeds, and more precipitation associated with increases of tropical storms (IPCC, 2007; see Working Group 1 report). In coastal areas, frequent and more intense storms will compound the impacts of sea-level rise, increasing erosion of sandy beaches (impacting nesting behavior and nest survival of sea turtles), and increasing the magnitude of tidal storm surges and the duration of sea-water intrusion further inland (impacting amphibians and non-turtle reptiles that frequently breeds and lay eggs in the ground). To illustrate, Losos et al. (2003) addressed the question of how populations of the Cuban Anole, *Anolis sagrei* survived after Hurricane Floyd devastated many small Bahamian islands in 1999. Sea water had inundated these islands apparently for up to 6 hours, but anole populations colonized these islands shortly afterwards (~ two months): these new anole populations, however, consisted of only juveniles. Losos et al. (2003) documented viable eggs of *A. sagrei* and normal development compared with controls (no immersion) after being immersed in sea water for up to 6 hours under laboratory conditions. Similar results has been found in other reptiles (e.g., geckoes) and a combination between resistance to immersion in sea water and the force of the storm surge inland facilitated egg survival and recolonization of impacted islands by reptiles (Losos et al., 2003). However, if the force of these storm surges increases due to the expected increased in the magnitude of storms and hurricanes with climate change (along with the level of coastal exposure to the surges) we would expect less resilient populations of reptiles (and amphibians) in tropical coastal areas. Moreover, we would expect the complete wash out of adult, juveniles, and eggs of species of reptiles, particularly in smaller tropical islands and cays, as suggested by Losos et al. (2003).

In montane forests, an increase in height was documented for orographic formation of clouds after hurricane Hugo defoliated most cloud forest areas in the LEF, Puerto Rico, in 1989 (Van de Molen et al., 2010). Beyond obvious effects of increased temperature and evaporative water loss due to

defoliation and increased tree and stem falls, the increased height of orographic cloud formation reduces the duration of cloud immersion and humidity across the vertical distribution of forests. Woolbright (1991) sampled population sizes of *Eleutherodactylus coqui* before and after Hurricane Hugo stroke Puerto Rico in 1989, and found a drastic population decline of juveniles. This decline was accompanied by drastic decreases in abundance of calling frogs—between 30% and >83% reduction—of species of *Eleutherodactylus* inhabiting montane forests (*E. wightmanae*, *E. portoricensis*, *E. richmondi*) (Woolbright, 1991, 1996). Presumably, reduced humidity and increase temperature after Hurricane Hugo were highly detrimental to juveniles of *E. coqui* (which will have profound consequences for population resilience with the expected increase in storm and hurricane frequency and magnitude due to climate change).

Also in tropical montane cloud forests from Puerto Rico, species of amphibians frequently associated with the canopy layer like the tree-hole breeder, *Eleutherodactylus hedricki*, and the bromeliad-dweller, *E. gryllus* will be significantly affected by stronger and frequent storms and hurricanes that damage . Forest-interior species of reptiles like the Puerto Rican Giant Anole, *Anolis cuvieri*, the Dwarf Anole, *Anolis occultus*, and ground-dweller reptiles the live bearing Puerto Rican Galliwasp, *Diploglossus pleii*, may also be impacted significantly from large changes in ambient and ground temperature, and reduced humidity after increased storm and hurricane damage due to climate change.

Research and Information Needs

1. Effective conservation and management of important ecosystems for amphibians and reptiles requires research agendas that address the following knowledge gaps:
2. Optimal thermal and hydric physiology and correlated habitat use for herpetofaunal species, particularly amphibians from montane forests and forest-interior and fossorial species of reptiles.

3. Genetic diversity data and selective data, particularly for herpetofaunal species with limited geographic distribution and patchy distribution.
4. Long-term monitoring of herpetofaunal species, particularly snakes, ground-dwelling lizards, amphibians from montane cloud forests, and marine turtles.
5. Predictive habitat modeling that generate detail species distribution maps based on known or inferred species physiology and habitat-use ecological requirements (e.g., bioclimate, elevation, vegetation type, among other environmental parameters) to examine responses to climate change by herpetofaunal species.
6. Studies from the population, community, and ecosystem ecology perspectives of introduced herpetofaunal species in relation to herpetofaunal assemblages in coastal and montane areas most likely to be affected by climate change.

Amphibians and Reptiles will be affected significantly by projected warming, changes in precipitation pattern, a reduction in humidity in tropical montane cloud forests, sea-level rise, tropical storms and hurricanes. Species from coastal ecosystems and from montane humid and wetter forests will be most affected due to space limitation for migration with climate change from a coast-to-inland spatial shift in environmental conditions and a lowland-to-highland shift in environmental conditions up to the highest mountain peaks.

Summary of Climate Change Outcomes/ Consequences on Puerto Rico's Amphibians and Reptiles

Responses to predicted climate changes by herpetofaunal species, with emphasis on Puerto Rican species, were examined from published literature, discussions, and unpublished data. Species of amphibians and reptiles regulate their thermal physiology and metabolism with changes in external, ambient climate variables (*i.e.*, ectotherms). Consequently, they will be affected significantly by projected warming, changes in precipitation pattern, a reduction in humidity in tropical montane cloud forests, sea-level rise, tropical storms and hurricanes. Species from coastal ecosystems and from montane humid and wetter forests will be most affected due to space limitation for migration with climate change from coast-to-inland spatial shift in environmental conditions and from lowland-to-highland shift in environmental conditions up to the highest mountain peaks. Most information deals with responses to increased ambient temperature, followed by precipitation and pathogenic infections (an indirect consequence of climate change) by amphibians, with little information on reptiles. Recommendations for much needed research agenda include studies addressing the thermal and metabolic physiology for a wider range of herpetofaunal species, particularly reptiles, along with long-term monitoring of population dynamics and climate change. Conservation efforts and the development of effective management plans must be focused at coastal ecosystems, particularly fresh and brackish-water wetlands, and at tropical montane cloud forests. Planned conservation actions are urgently needed and must include natural corridors from coastal-to-inland areas beyond current urbanized areas; more difficult to develop are plans oriented at conserving species limited to tropical montane cloud forests as climate change may have pushed many herpetofaunal species to their physiological thermal limit. It is recognized that species losses will be inevitable and use of limited conservation resources should be prioritized, possibly at species and areas with greater probability for long-term persistence.

CLIMATE CHANGE STRESSORS AFFECTING SEA TURTLES

Increasing temperatures may impact sea turtle migratory patterns, sex ratio in embryos, severity of infections, and feeding grounds (e.g., death of sea grass beds, sponges and corals).

Sea level rise may result in loss of nesting habitat, flooding of nests, and changes in foraging grounds.

Increase in the severity of storms might be confounded with sea level rise to cause serious erosion of beach nesting habitat.



INTRODUCTION TO MARINE SYSTEMS

The following sections are about coral reefs, seagrasses, bioluminescent bays, coastal and pelagic fishes, and marine mammals and the two major ways they are affected by climate change. First, the overall increase in global surface temperatures is evident regionally based on increasing sea surface temperatures around Puerto Rico and the rest of the Caribbean. The continued uptake of heat has wide-ranging implications for marine resources as will be discussed in each of the following sections. Generally, as described by Kennedy et al. 2002, temperature changes in coastal and marine ecosystems will influence organism metabolism and alter ecological processes such as productivity and species interactions. Species are adapted to specific temperature ranges. As temperatures change, species' geographic distributions will expand or contract, creating new combinations of species that will interact in unpredictable ways. Species that are unable to migrate or compete with other species for resources may face local or global extinction (Kennedy et al. 2002). Thermal expansion of the ocean, together with melting of land ice, is resulting in rising sea levels. Climate change is also likely to alter patterns of wind and water circulation in the ocean environment. Increases in ocean temperatures are changing the strength and direction of currents, and may influence the vertical movement of ocean waters (*i.e.*, upwelling and downwelling), increasing or decreasing the availability of essential nutrients and oxygen to marine organisms. Reductions in the supply of nutrients usually limit the primary production at the base of the food chains that support marine resources (especially fisheries). Increasing temperatures can also increase incidence and virulence of disease. Changes in ocean circulation patterns can also cause substantial changes in regional ocean and land

temperatures and the geographic distributions of marine species. Other climate stressors acting on marine systems are changes in the hydrological cycle (more intense downpour events and more sustained dry days) that may increase the risk of coastal flooding or drought. There is also the possibility that warmer conditions may result in more intense hurricanes (tropical cyclones) and storms, resulting in greater storm surges and greater physical disturbance of coastal environments. The second major way that climate change is expected to affect marine resources is through changes in seawater chemistry. More specifically, changes in oceanic concentrations of carbon dioxide and the resulting affect on ocean acidity. Recently, marine scientists have started to realize the substantial implications of ocean acidification (Wootton et al. 2008). Ocean acidification is the process whereby hydrogen ion concentrations (pH) in the ocean increase (acidification) due to absorbance of carbon dioxide from the atmosphere released during the burning of fossil fuels and other manmade activities (NOAA 2008). Changing pH levels potentially have vast consequences for marine ecosystems because of the critical role pH plays in mediating physiological reactions. Furthermore, many important groups of marine organisms have a skeleton of calcium-carbonate, which dissolves when it reacts with free hydrogen ions (Wootton et al. 2008). Hence, declining pH could interfere with critical processes such as reef building, carbon sequestration via phytoplankton sedimentation, and consumer-resource interactions. Marine plankton is a vital food source for many marine species and its decline could have serious consequences for the marine food web (Turley 2008).

Working Group 1's report on each of the climate stressors provides more details of the science, trends, and projections for these stressors. Figure 10 is a generalized summary of climate change effects on oceanic and coastal ecosystems.

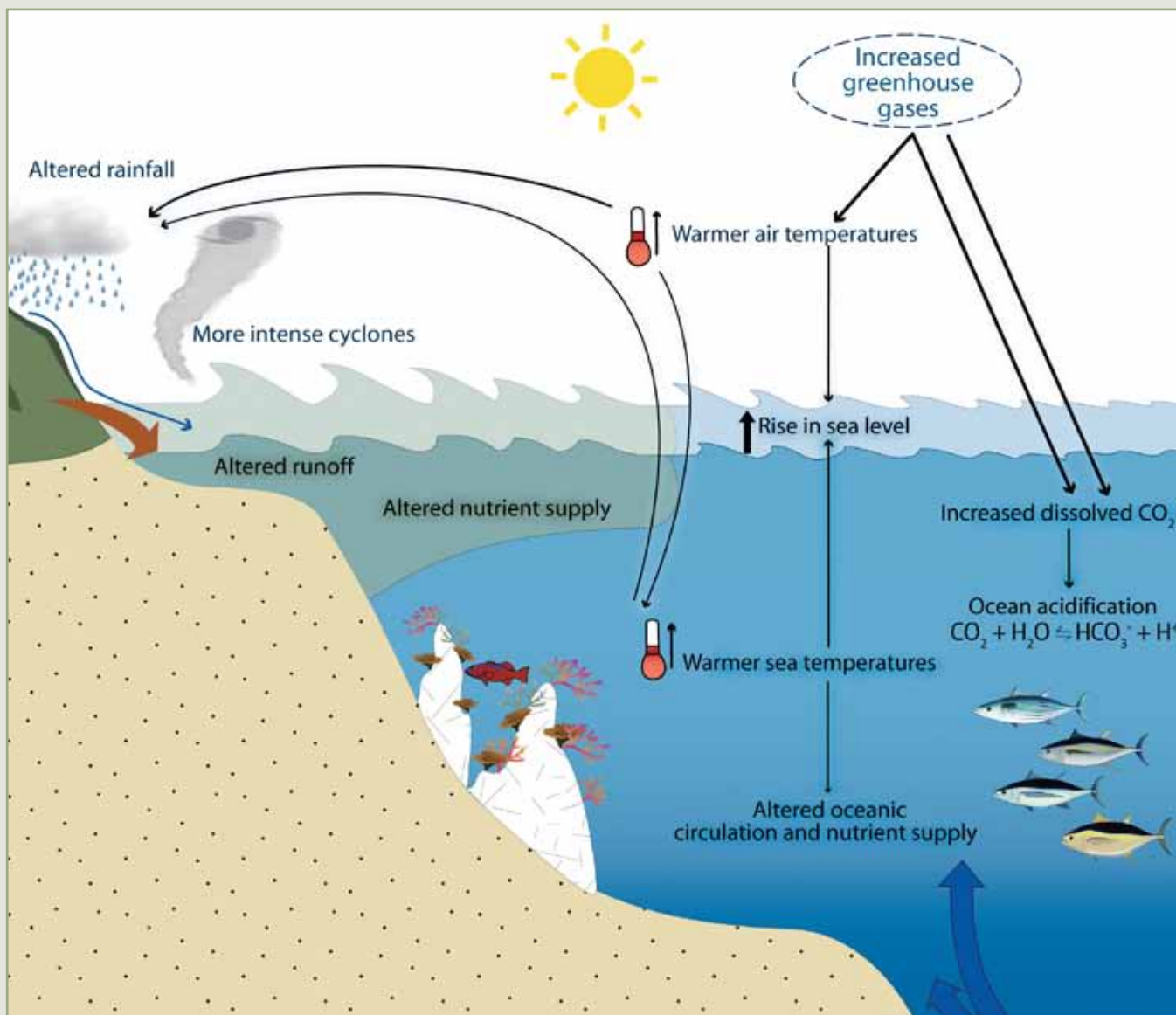


Figure 10 Generalized effects of increased greenhouse gases on oceanic and coastal ecosystems in the tropics. Adapted and printed with permissions from Bell JD, Johnson JE and Hobday AJ (eds) (2011) *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia.

CORAL REEFS

Introduction to Coral Reefs

Coral reefs, known as the rainforests of the oceans, are unique ecosystems in that they are defined by both biological ("coral" community) and geological ("reef" structure) components. Coral reefs are made of limestone (calcium carbonate) that is secreted as skeletal material by colonial animals (coral polyps) and calcareous algae. Reef building



Ecosystem Services of Coral Reefs

- Tourism and recreation
- Coastal protection
- Fisheries
- Biodiversity
- Medicine
- Mental well-being

Figure 11 Ecosystem Services of Coral Reefs

growth. Due to their high biodiversity and uniqueness, these structures are some of the most studied marine ecosystems.

Coral reefs provide a number of values to humans, as well as the health of the biosphere (figure 11). Reefs support fisheries, and reef structures provide natural breakwaters that protect shorelines, other ecosystems, and human settlements from wave activity. Humans use reefs and their products extensively for food, building materials, pharmaceuticals, the aquarium trade, and other uses. In addition, due to their beauty and novelty, reefs have become a major part of the tourism product for the Caribbean region. As such, coral reefs form part of our economic foundation. Unfortunately, these valuable ecosystems are being rapidly degraded by localized human activities

such as coastal development, sedimentation, overfishing, and marine pollution (UNEP 2004). Approximately 36% of Caribbean coral reefs lie within 2 km (1.2 mi) of the coast and this makes them highly susceptible to pressures arising from coastal population centers (Burke and Maidens 2004). The following provides a description of some main stresses affecting coral reef systems world-wide.

Sewage Pollution

It is estimated that less than 20% of sewage water generated in the Caribbean region is treated before entering the ocean (Burke and Maidens 2004). Untreated sewage is a major source of nutrients entering coastal waters which, under normal circumstances, would be devoid of nutrients. High nutrient conditions favor algal growth at the expense of the corals (Souter and Linden 2000), because coral reefs thrive in low nutrient (oligotrophic) waters. Sewage pollution has been shown to have rapid negative and often irreversible impacts on coral reef surrounding waters' environmental and microbiological quality over very large spatial scales (Bonkosky et al. 2009). This has also had paramount negative implications on coral reef benthic community composition (Hernández-Delgado et al. 2010), often on threatened Elkhorn coral (*Acropora palmata*) stands (Patterson-Sutherland et al. 2004, 2010) (Hernández-Delgado et al. 2010, 2011).

Land Use and Land Cover Change

The conversion of land to agriculture increases soil erosion and sediment delivery to coastal waters, bringing with it pesticides and nutrients. Nearly a quarter of all the land area draining into the Caribbean is agricultural land (Burke and Maidens 2004). Increased sediment causes stress on coastal ecosystems in a variety of ways. It screens out the light needed for photosynthesis (Te 1997, Goh and Lee 2010), decreases the amount of suitable substrates for juvenile corals (Goh and Lee 2010), can have pronounced negative physiological impacts on corals (Vargas-Ángel et al. 2007), and in extreme cases, the interaction of high sediment loads with eutrophication (Meesters et al. 1998;

Weber et al. 2012) can completely smother corals (Rogers, 1990), often over very large temporal and spatial scales (Perry et al. 2008, Perry et al. 2009), which make damages permanent and irreversible over human temporal scales (Lybolt et al. 2011). Traditionally, sediments and nutrients coming from the land were filtered by mangrove forests and seagrass; however, the loss of these important areas is widespread throughout the Caribbean (Jameson et al. 1995). Sediment and nutrient impacts continue to increase due to current coastal urban and tourism development trends (Hernández-Delgado et al. 2012), particularly the construction of steep non-paved roads on small islands (Ramos-Scharrón 2012, Ramos-Scharrón et al. 2012) and following extreme rainfall events (Larsen and Webb 2009).

Marine-based sources of pollution

Marine-based sources of pollution, including oil discharge and spills; sewage, ballast and bilge discharge; and the dumping of other human garbage and waste from ships, are a cause for great concern in the Caribbean region (Burke and Maidens 2004), particularly given the escalating geographical extent of localized impacts by the cruise ship industry across the region (Hernández-Delgado et al. 2012).

Fisheries

Coral reefs and associated habitats provide important commercial, recreational and subsistence fishery resources globally. Fishing plays a central social and cultural role in many island communities and can represent a critical source of protein. However, coral reef fisheries, though often relatively small in scale, may have disproportionately large impacts on the ecosystem if not conducted sustainably (NOAA 2009). And fisheries have been rarely sustainable (Pauley et al. 2002). Therefore, fisheries have also impacted coral reefs over very large temporal and spatial scales (Jackson 1997, 2001). Rapid human population growth, demand for fishery resources, use of more efficient fishery technologies, and inadequate management and enforcement have led to the depletion of key reef species and habitat damage

in many locations world-wide. Furthermore, fishermen typically target the largest fish on the reef since these have the highest market value. The depletion of larger fish leads to a reduction in the average size of the targeted species, and can cause fishermen to fish for lower valued species, removing even more components of the coral reef food web (McManus et al. 2000). The removal of certain species can significantly alter the reef structure (Roberts 1995, Hawkins and Roberts 2004). For example, herbivorous fish are responsible for controlling algae growth on the reef and if these fish are removed from the system, algae can flourish and reduce coral cover (Bohnsack 1993). But also, declining benthic biodiversity and environmental conditions of coral reefs (Jones et al. 2004), as well as climate change-related massive coral mortality events (Pratchett et al. 2006, Pratchett et al. 2008). The increasing temporal and spatial scale of reef ecological turnover events across the Caribbean region (Aronson et al. 2002) has caused major ecological change across coral reefs (Gardner et al. 2003) and associated nursery habitats that might have largely influenced the long-term declining trends in Caribbean-wide reef-based fisheries (Paddock et al. 2009) and reef fish functional redundancy (Bellwood et al. 2004). In addition to scientific investigations revealing declining reef quality, socioeconomic studies have also documented fishers' perceptions through generations of observation that fish are less abundant and coral reef health has declined (e.g. Griffith et al. 2007).

Storms and Hurricanes

Storms and hurricanes are part of the natural variability of coral reef systems. However, hurricanes can cause extensive damage to coral reefs (Stoddart 1985, Harmelin-Vivien 1994, Salazar-Vallejo 2002), for example as described for Hurricane Gilbert in Jamaica (Bacon 1989), for Hurricanes David, Frederick and Hugo in the US Virgin Islands (Rogers et al. 1982), for Hurricane Hugo in Guadeloupe (Bouchon et al. 1991), for Hurricane Lenny in St. Lucia (Wulf 2001) for Hurricane Mitch in the Mexican Caribbean (Bahena et al. 2000), and for Hurricane Georges in Puerto Rico (1998) (Causey et al. 2002). Depending on

factors such as hurricane intensity, trajectory, coastal morphology, reef depth and position in relation to hurricane trajectory, and interactions with different anthropogenic factors (*i.e.*, coastal pollution), hurricanes may reduce the physical complexity of coral reefs and the abundance of living corals (Goenaga, 1992, Steneck 1994). These effects are greatest at shallow depths where wave action is greatest. However, shallow corals are adapted to wave action and hurricanes can cause considerable damage in deeper water where corals seldom experience wave action (Harmelin-Vivien and Laboute 1986). Hurricanes may also cause extensive impacts on tropical forests, which could in turn have significant indirect consequences on coastal coral reef ecosystems (Lugo 2000, Lugo et al. 2000) through the transport of eroded sediments to coastal waters from impacted forest areas. Thus, storms and hurricanes are considered threats to coral reefs because of the damages that occur. When combined with additional anthropogenic stresses on the ecosystems, the impacts of hurricanes linger a lot longer than they did in the past. The threat becomes great when we consider the frequency and intensity of the disturbance and the time to recover. With more and more stresses on coral reefs existing today, the adaptive capacity of reefs may be compromised.

Unsustainable Tourism

The tourism industry, a sector of major importance to the regional economy, can also threaten the reefs in a number of ways (Hernández-Delgado et al. 2012). Dive boats can damage reef structure with their anchors, divers can cause physical damage, and resort development and operations can increase pollution and sewage in coastal waters, as can the construction of tourism infrastructure and facilities (roads, marinas, airports). Also, the expanding cruise ship industry can also increase environmental and socio-economic impacts, including habitat destruction, increased recreational misuse, increased pollution, increased exploitation of water resources, altered quality of life and livelihoods of local communities, and revenue leakage, among others (Hernández-Delgado et al. 2012). Under current climate change trends and under projected coastal urban and tourism development in Puerto Rico, most of this

development will be carried out in areas highly vulnerable to sea level rise and to the impacts of extreme events such as storm tides, and therefore at risk for significant long-term negative economic impacts.

The cumulative impacts of natural stressors, in combination with a diverse array of localized human impacts, fishing, and climate change, have caused significant coral reef community phase shifts (Knowlton 2001, Hughes et al. 2004), as well as a significant loss of functional redundancy (Micheli and Halpern 2005; Nyström, 2006; Hoey and Bellwood 2009). Consequently, coral reefs are considered to be in crisis (Bellwood et al. 2004). This has been well-documented and has stimulated numerous publications on the future of coral reefs (*e.g.*, Hoegh-Guldberg 1999; Knowlton 2001, McClanahan et al. 2002) and their vulnerability to climate and environmental change (Bryant et al. 1998, Hughes et al. 2003). The causes of this crisis are not only related to the above-mentioned stress factors, but are a complex mixture of both human-imposed and climate-related stresses, and include factors such as coral disease outbreaks, which have suspected, but unproven, connections to both human activities and climate factors (Miller et al. 2006, Cróquer and Weil 2009a, b, Miller et al. 2009, Weil and Cróquer 2009, Weil et al. 2009, Hernández-Pacheco et al. 2011). Notably, by 1998, an estimated 11% of the world's reefs had been destroyed by human activity, and an additional 16% were extensively damaged in 1997–98 by coral beaching (Wilkinson 2000). Conditions of coral reefs have further deteriorated over the past decade as well (Wilkinson and Souter, 2008).

Status of Puerto Rico Reefs

The most extensive coral reef systems in Puerto Rico are found on the Southwestern and Northeastern shelf, although coral communities can be found in other areas (García-Sais et al. 2003; Hernández-Delgado 2005). On the Northeastern coast of Puerto Rico, the insular platform is partially protected from waves by a chain of emerging fringing reefs which provide protection to the coast, thus creating calm waters and favorable conditions for the formation of sandy beaches. There are fewer coral reef formations

along the rest of the Northern and Northwestern coasts because coastal waters receive substantial amounts of sediment and nutrients from discharges from the largest and fastest flowing rivers in Puerto Rico (Goenaga and Cintrón 1979). This inhibits coral growth and development by reducing photosynthesis (due to the effects of turbidity on light penetration) and increasing respiration and mucus production. Similarly, the island shelf of these coasts is narrow, exposing the coasts to strong waves. However, on Puerto Rico's North coast – in the municipality of Vega Baja – a substantial development of biogenic coral reefs has been identified which is still in excellent condition because strong wave action has allowed for its survival (Hernández-Delgado et al. 2011). For example, during the 2005 bleaching episode, which caused a massive mortality of corals through the northeastern Caribbean, including Puerto Rico (Hernández-Pacheco et al. 2011), due in part to a post-bleaching mass white plague-like coral mortality event (Miller et al. 2006, Miller et al. 2009, Eakin et al. 2010), corals growing under strong currents exhibited higher colony survival rates, probably facilitated by higher oxygenation and planktonic food supply (Hernández-Delgado et al. 2007). The rest of the eastern, southern and western sections of the Puerto Rico shelf support extensive reef systems representative of northeastern Caribbean reef biodiversity (Hernández-Delgado 2005).

Puerto Rico is surrounded by approximately 500,000 ha of coral reef ecosystems, where depth does not exceed 20 meters (Puerto Rico Coastal Zone Management Program 2009). In 2007, the DNER's Coral Reefs Management and Conservation Program commissioned a study to determine the economic value of coral reefs and associated environments in Eastern Puerto Rico, specifically in Fajardo, Arrecifes La Cordillera, Vieques, and Culebra. According to estimates, the value of these resources is \$1.853 billion, or \$4.2 million/linear km of coastline. The findings showed that tourism and recreation are the activities that derive the most value (ETI 2007) from the coral reef ecosystem.

Despite their high value, the coral reefs of Puerto Rico have been degrading rapidly during

the past decades due a combination of natural and anthropogenic factors. Their current state rated among the most critical in the Caribbean, particularly due to the unchecked urban and industrial development on the coast during the past 40 years (Causey et al. 2002). Natural factors associated with degradation have also been well-documented. These include factors such as extreme rainfall events (Goenaga and Canals 1979), hurricanes (Goenaga 1990), and mass mortality of the Long-spined sea urchin (*Diadema antillarum*), which fostered major algal overgrowth (Ruiz-Ramos et al. 2011, Vicente and Goenaga 1984) on reefs.

Other natural factors which have resulted in mass coral mortality events have included outbreaks of white band disease, black band disease, white plague, yellow band disease, and mass bleaching (Bruckner and Bruckner 1997, Weil et al. 2003, Weil 2004, Hernández-Delgado 2005, Bruckner and Bruckner 2006, Bruckner and Hill 2009, Cróquer and Weil 2009a, b, Weil et al. 2009, Hernández-Pacheco et al. 2011, Weil and Rogers 2011). The extraction of corals also poses a danger to Puerto Rico's reefs. Although the removal of coral is banned in Puerto Rico, some people destroy them for ornamental or commercial purposes.

There have been several important reviews of anthropogenic impacts on coral reef ecosystems in Puerto Rico (McKenzie and Benton 1972, Loya 1976, Goenaga 1988, 1991, Goenaga and Cintrón 1979, Goenaga and Boulon 1992, Hernández-Delgado 1992, 2000, 2005, Ballantine et al. 2008, García-Sais et al. 2003, 2008, Hernández-Delgado and Sandoz-Vera 2011). These authors have consistently pointed out that declining water quality (due mostly to increased sedimentation, turbidity and eutrophication, and sewage pollution) and fishing are the primary human factors that have resulted in chronic reef degradation. For a more detailed review of the current status of Puerto Rico's coral reefs see García-Sais et al. (2008).

Outcomes and Consequences of Climate change on Puerto Rico's Coral Reefs

Climate change has had significant deleterious impacts to coral reefs across the Caribbean region, including Puerto Rico (Wilkinson and Souter 2008). Although in the very long-term climate change has the potential to yield some benefits for certain coral species in specific regions, such as the expansion of their geographic ranges to higher latitudes, most of the short-term effects of climate change are highly stressful rather than beneficial (Buddemeier et al. 2004). The following sections summarize some of the expected negative impacts of climate change on coral reef ecosystems.

Sea Level Rise

Sea level rise is and will continue to be a major cause of concern for coral reef ecosystems considering their state of degradation throughout the region, particularly towards the end of the 21st century. The consistent decline of the most significant reef-building species across the region suggests that overall reef accretion rates might be slower than in the past. If the vertical growth rate of corals is likely to be slower than the increase in sea level rise, then the ability of reef ecosystems to

keep pace with the forecasted sea level rise trends might be deeply compromised (Veron et al. 2009). There is already evidence that current mortality trends in the Star coral, *Montastraea annularis*, species complex in Puerto Rico as a result of recurrent mass coral bleaching events and mass coral mortalities may drive this species to extinction within the next three to four decades (Hernández-Pacheco et al. 2011). Current percent cover loss of this species, as well as *M. faveolata*, reaches values of 70% to 97% at some locations (Hernández-Delgado, in preparation). Therefore, losing the most critical reef building species across Puerto Rican reefs may result in a significant decline in overall reef accretion. Under current predicted increasing sea level rise, reduced reef accretion may result in increased vulnerability of coastal communities to erosion, storm surge, and increased SLR. Further, SLR will result in flooded coastal urban zones, which will include flooding of sewage and storm water systems, sewage treatment facilities, and other sources of pollutants. Coastal waters adjacent to urban centers will likely have higher turbidity, poorer microbiological water quality, and potentially higher nutrient concentrations. Reefs adjacent to these areas will likely have lower chances of survival and ability to keep pace with sea level rise than remote or oceanic reefs.

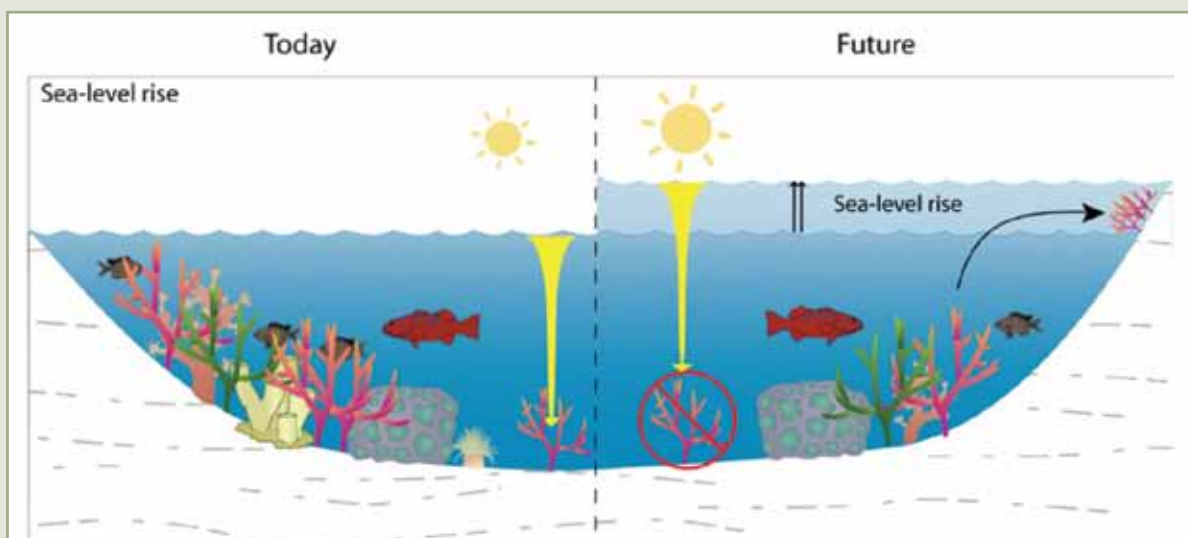


Figure 12 Effects of projected sea-level rise on coral reefs. Where corals and other reef building organisms are healthy, reefs should keep up with rising sea levels. Unfortunately, the combined effects of increased sea surface temperatures and ocean acidity are likely to mean that corals in some places will not grow fast enough to maintain their positions in the water column with the projected rapid sea-level rise. Some coral reefs may 'drown' as sea levels increase, but new areas may also be colonised where conditions for coral growth remain favourable. Printed with permissions from Bell JD, Johnson JE and Hobday AJ (eds) (2011) *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia.

While coral reefs may be fairly resilient ecosystems, the cumulative effects of the threats discussed in this document are taking a toll on coral reefs throughout the Caribbean and could reduce coral's adaptive capacity to respond to climate change-induced sea level rise. If this were to occur, we could see increased coral mortality or smaller geographic extents of coral reefs. The ecological, physical, and societal consequences could be great considering all the ecosystem services of coral reefs previously mentioned. A critical societal impact would be the reduced ability of corals to protect our shorelines. In addition, because wave energy could increase, beach and coastal property erosion could also increase. The consequences of this are locally specific. However, they will depend on seven factors (as identified by the WG 2 Coral Reef Subcommittee): (1) rate of sea level increase; (2) rate of coral reef accretion; (3) benthic community structure; (4) health of corals; (5) increase in coastal erosion; (6) sediment movement; and (7) area of island (north coast is tipping) and energy.

The vulnerability of Puerto Rico's coral reefs to sea level rise will vary. Corals with reduced growth rates due to thermal stress and ocean acidification, or corals with naturally slow growth rates in marginal environmental conditions (e.g. deeper water), may have a high vulnerability to the accelerating rise in sea level. However, in order to know which of Puerto Rico's reefs are most vulnerable, more research is necessary. There is a need to address historical changes in coral skeletal extension, density, and calcification rates for different coral species using sclerochronological methods, comparing different depth zones, and under different environmental conditions, as a function of: (1) sea surface warming (using SST satellite data and Oxygen isotopic signals for calibration and further historical and modelling analysis), (2) changes in pH from coral skeletons (using Boron as a proxy signal), and (3) historical changes in land use patterns. Also, there is a need to assess actual coral growth rates for different species under different conditions and as a function of net bioerosion rates to assess actual net reef accretion. These will provide data to parameterize mathematical models of

reef accretion rates as a function of SLR under different climate and environmental degradation scenarios. See figure 12 for a summary of sea level rise impacts to coral reefs.

Increasing Temperature

One of the key characteristics of reef-building corals is their mutualistic symbiosis with populations of dinoflagellates (*Symbiodinium*; zooxanthellae). These tiny plant-like organisms occupy vacuoles within cells associated with gastrodermal tissues of corals, imparting an overall golden-yellow to brown color to their animal host. Zooxanthellae photosynthesize while they are living within the cells of the host coral, and produce organic carbon. This carbon is then transferred to the coral, where it fuels growth, reproduction, and calcification. As a result of this abundant energy, corals are able to grow and calcify rapidly, providing in return much-needed inorganic nutrients to the zooxanthellae, and calcium carbonate to the reef community as a whole. This beneficial relationship between the corals and zooxanthellae, termed symbiosis, breaks down under stressful situations. Sudden reductions in salinity, or increases in chemical toxins, sea surface temperatures or solar irradiance, will cause corals to turn brilliant white as the zooxanthellae are expelled from the coral tissues (Hoegh-Guldberg 1999). This phenomenon is referred to as coral bleaching. Deprived of their energy source, corals become much more susceptible to competitors, such as macroalgae (seaweeds), starvation, disease, and death (Harvell et al. 1999, Diaz-Pulido and McCook 2002, Diaz-Pulido et al. 2009). The most direct evidence of stress caused by climate changes on coral reefs comes in the form of mass coral bleaching often due to stressful conditions as a result of prolonged sea surface warming. A small increase of 1.0°C, particularly during periods of 8 weeks or longer, can trigger a mass bleaching event (Buddemeier et al. 2004, Eakin et al. 2010). Bleaching events lasting 8-12 weeks or longer may trigger significant coral mortality (Eakin et al. 2010). Based on current trends, climate models have shown that coral bleaching will become an annual event by the year 2020 (Hoegh-Guldberg, 1999, Hoegh-Guldberg et al. 2007, Hoegh-Guldberg

and Bruno, 2010). A PRCCC WG 1 analysis by Dr. Jorge Corredor found that an increase of 1.17° C (2.1°F) over a 50 year period can be expected for sea surface temperatures around Puerto Rico. Additionally, SST above the threshold for coral bleaching will be exceeded over a third of the year (Hoegh-Guldberg 1999) (see PRCCC WG 1 report).

Notably, no incidents of mass coral bleaching were formally reported in the Caribbean before 1983 (Glynn, 1996). However, according to Reefbase (2012), from the early 1980s to 2012 more than 4000 observations had been reported. One of the earliest incidences was documented during the 1982-83 El Niño-Southern Oscillation (ENSO) (Glynn 1988). Further, bleaching incidents have also been recorded for 1987 and throughout 1998 (Williams et al. 1987, Williams and Bunkley-Williams 1988, Goenaga et al. 1989, Hernández-Pacheco et al. 2011), including Puerto Rico (Williams et al. 1987, Williams and Bunkley-Williams 1988, Goenaga et al. 1989, Williams and Bunkley-Williams 1990, Vicente and Goenaga 1990, Hernández-Delgado and Alicea-Rodríguez 1993; Hernández-Delgado 2000; Hernández-Delgado et al. 2000). More recently, in 2005, Caribbean reefs again experienced mass bleaching. Massive decline of corals across the entire Caribbean basin, with the average hard coral cover on reefs reduced by 80%, from about 50% to 10% cover, in three decades mostly as a combined result of hurricane impacts and Caribbean-wide scale factors, probably associated to climate change (Gardner et al. 2003). The large-scale white plague-like condition that occurred following the 2005 record-breaking SST across the northeastern Caribbean and subsequent bleaching event caused a 60 to 80% loss in % coral cover (Miller et al. 2006, Miller et al. 2009), particularly impacting reef-building species such as the Star corals, *Montastraea annularis*, species complex (Hernández-Pacheco et al. 2011).

Mass bleaching of corals in the past two decades has been clearly linked to ENSO events (Hoegh-Guldberg 1999, Glynn 2000). These have increased in frequency, severity, and duration since the 1970s (Stahle et al. 1998, Mann et al. 2000). This combination (sea surface warming and intense

ENSO events) has resulted in a dramatic increase in coral bleaching (Glynn 1993, Brown 1997, Wilkinson 2000). A rising baseline in warm-season SST on coral reefs (Fitt et al. 2001, Lough 2001) suggests that physiological bleaching is at least partly to blame in the three most significant mass bleaching events in the Caribbean in 1987, 1998, and 2005. Each mass bleaching event over the last three decades has caused major coral mortality in different localities. Although, data indicate that coral bleaching was much worse during the 1982-83 El Niño than in 1997-98. Temperature extremes during the two events were similar (Glynn et al. 2001, Podestá and Glynn 2001). The difference in responses to these comparable events offers some support for the idea that corals or coral communities can adapt to higher temperatures over decades, either through adaptive bleaching (Baker 2003) or through evolutionary selection for more heat/irradiance-tolerant corals that survive bleaching events (Glynn et al. 2001). This is a debatable point, however, as adaptation occurring over such a short time period seems unlikely and no evidence of an acclimatization response has been found to-date.

The 2005 Caribbean bleaching event, which resulted from increased sea temperatures of up to 31.8 °C (89.2°F) at depths of 30 meters (98.4 feet) and about 33.1 °C (91.6 °F) on some reef crest zones off eastern Puerto Rico (Hernández-Delgado et al. 2006). In late 2005, the coral bleaching in the south and west of Puerto Rico was devastating, being more evident on the reefs where the *Montastraea annularis* species complex was dominant in terms of substrate coverage (Hernandez-Delgado, as quoted in Garcia-Sais et al. 2008). This bleaching episode was followed by a massive outbreak of white plague, which caused deaths and a reduction of between 60 and 80% of live coral cover in Eastern Puerto Rico. This bleaching episode has alerted many stakeholders to the susceptibility of Puerto Rico's coral reefs to the impact of climate change as it is predicted that increasing sea surface temperatures will result in more intense bleaching episodes. The impacts of the bleaching depend on the frequency, severity, and spatial extent of the bleaching event. While corals can recover from these events, the frequency

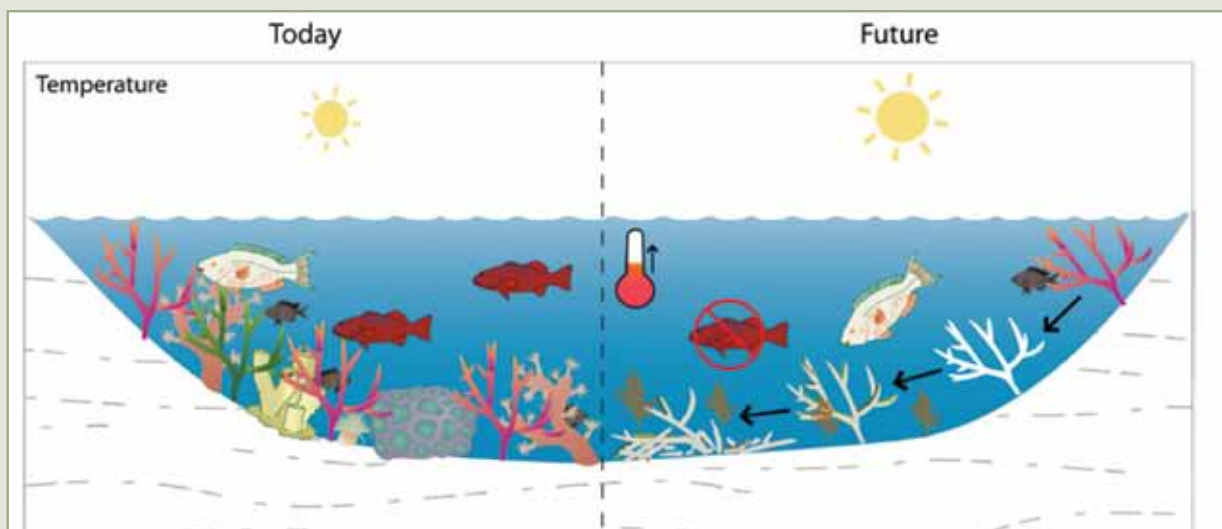


Figure 13 Effects of projected increases in sea surface temperature (SST) and light on coral reefs. Under present-day conditions, short periods of warmer-than-average maximum SST cause bleaching events. Healthy coral reefs recover from these disturbances and the abundance of corals remains high. As SST increases by 1°C or more above preindustrial levels, bleaching events are expected to become more intense and frequent, with the loss of corals, reef structure, and associated fauna, and increases in macroalgae, over time. Printed with permissions from Bell JD, Johnson JE and Hobday AJ (eds) (2011) *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia.

and severity of exposition to higher temperatures will increase coral mortality (figure 13). It should be noted that depending on the species of coral and the depth at which they are located; we might see an increase or change in growth rate of corals as well. Further, mass bleaching events have been shown to trigger significant declines in coral reef fish abundance and diversity (Pratchett et al. 2006, Pratchett et al. 2008). Climate-related factors, in combination with long-term fishing impacts, have been pointed out as a cause of long-term reef fish declining trends across the wider Caribbean region (Paddack et al. 2009).

Apart from the coral mortality and habitat fragmentation impacts of coral bleaching, discussed earlier, thermal expansion of the ocean from increasing sea surface temperatures and ice melt water will result in an increase in the pressure gradient which could cause changes in upwelling patterns (Bakun 1990). In the Caribbean, upwelling areas off the Guianas-Brazil Shelf, downstream of island passages, and off Venezuela are known to influence fishery production. Changes in upwelling or other circulation patterns could significantly affect large-scale reef connectivity, thereby affecting the dispersal and transport of larvae and nutrients, and potentially having

long-term impacts on the distribution of corals and associated reef species across the wider Caribbean. Connectivity could also be compromised by the increased fragmentation of reef habitat (due to the effects of coral bleaching and ocean acidification). Changes in the spatial and temporal scales of connectivity have implications for the management of coral reef ecosystems, especially the design and placement of no-take marine-protected areas (Munday et al. 2009b). The size and spacing of protected areas may need to be strategically adjusted if reserve networks are to retain their efficacy in the future.

While there is not much information available on how increased SST will affect metamorphosis, survival rate, and other aspects of larvae or juvenile reef species, increased temperatures may negatively impact these (Bassim & Sammarco, 2002, 2003). Nozawa and Harrison (2007) found two different effects of elevated temperature on the early stages of recruitment in scleractinian corals; a positive effect on larval settlement and a negative effect on post-settlement survival under prolonged exposure. Edmunds (2004) also found increased coral recruitment rates, but increased post-recruitment mortality in St. John, USVI, with

increasing SST. Studies on species such as the sand dollar (*Arachnoides placenta*) show that temperatures of or greater than 31°C (87.8°F) negatively affect larvae and juveniles (Chen and Chen 1992).

Increasing sea surface temperatures off the coast of Puerto Rico could cause corals physiological stress. This added stress could increase coral susceptibility to disease (and therefore an increase in virulence of bacterial and fungal pathogens). The most profound and widespread changes in Caribbean coral reefs in the past 30 years have been attributed to disease; however, the reasons for this sudden emergence and rapid spread are not well known (Buddemeier et al. 2004). Twenty three diseases and syndromes affecting corals have been identified in the Caribbean, and in most cases, the pathogen causing the disease is not known (Weil 2004, Weil and Rogers 2011). Disease outbreaks and consequent mortality among corals and other reef organisms have been a major cause of the recent increase in coral reef degradation (Epstein et al. 1998, Harvell et al. 1999, Rosenberg and Ben-Haim 2002). Although diseases and syndromes of corals and other reef organisms remain incompletely characterized (Richardson and Aronson 2002), they are known to be caused by both bacterial and fungal agents. These diseases are commonly lethal, but they exhibit a wide range of rates of progression. Most appear to affect some species more than others, but few, if any, are species-specific (Buddemeier et al. 2004).

Two specific outbreaks have radically altered the ecology of Caribbean coral reefs (Richardson and Aronson 2002). One disease killed more than 97% of the black-spined sea urchin (*Diadema antillarum*) (Lessios 1988), some populations of which are now beginning to recover, like on several reefs on the north coast of Jamaica (Aronson and Precht 2000), St. Croix (Miller et al. 2003), and the North Coast and island of Culebra in Puerto Rico (Ruiz-Ramos et al. 2011). Another disease, white band disease (WBD), has killed much of the elkhorn (*Acropora palmata*) and staghorn (*A. cervicornis*) coral throughout the Caribbean. These were dominant reef-building corals in the Caribbean for tens of thousands to hundreds

of thousands of years (Gladfelter et al. 1978, Aronson and Precht 1997, 2001, 2002).

Other bacterial diseases of Caribbean corals, including black-band disease, “plague,” and “white pox,” have caused significant coral mortality (Richardson 1998, Richardson et al. 1998a, Richardson et al. 1998b, Patterson et al. 2002). A disease caused by a fungus of terrestrial origin, *Aspergillus sydowii* (Geiser et al. 1998), has killed large numbers of sea fans and sea whips (Kim and Harvell 2001).

Prior to the 1980s, the most important reef herbivores in the Caribbean were parrotfish, surgeonfish, and the black-spined sea urchin (*Diadema antillarum*), but in many areas the fish populations had been greatly reduced (Hughes 1994). When a disease outbreak destroyed most of the *Diadema* populations throughout the Caribbean in 1983–84 (Lessios 1988), acute episodes of coral mortality (due to hurricanes and other factors) combined with the absence of crucial herbivores to convert coral-dominated Caribbean reefs to seaweed-dominated communities (Hughes 1994, Aronson and Precht 2000).

Warming can increase the virulence of pathogens because optimal water temperatures for those infectious agents for which data are available are at least 1°C (2°F) higher than the optima of their coral hosts (Harvell et al. 2002). Recent increases in the frequency and virulence of disease outbreaks on coral reefs are consistent with this prediction, suggesting that the trend of increasing disease will continue and strengthen as global temperatures increase (Buddemeier et al. 2004).

The ecosystem-level impacts of mass mortality of corals from increased sea surface temperatures include an increase in algae and therefore a change in benthic community structure (Hernández-Delgado, in preparation; Hernández-Pacheco et al., in preparation). Corals can recover after short periods of stress but as the length and severity of the stress increases so does coral mortality. Changes in reef biodiversity as a result of these events

depend on whether the reef has been already undergoing reef degradation. More research is needed to determine how the tropical fish that inhabit the coral reefs will respond to temperature increases.

Increased Carbon Dioxide

The impacts of anthropogenic climate change so far include decreased ocean productivity, altered food web dynamics, reduced abundance of habitat-forming species, shifting species distributions, and a greater incidence of disease (Hoegh-Guldberg and Bruno 2010). Although there is considerable uncertainty about the spatial and temporal details, climate change is clearly and fundamentally altering ocean ecosystems. This has occurred mostly as a result of increased sea surface temperature and mass coral bleaching (Hoegh-Guldberg and Salvat 1995). Another cause of concern for coral reefs from climate change is “the other CO₂ problem” – ocean acidification.

Photosynthesis and respiration by marine organisms affect seawater carbon dioxide concentration, but the overwhelming driver of carbon dioxide concentrations in shallow seawater is the concentration of carbon dioxide in the overlying atmosphere. Changes in the carbon dioxide concentration of seawater through well-known processes of air-sea gas exchange alter the pH (an index of acidity) and the concentrations of carbonate and bicarbonate ions. Surface seawater chemistry adjusts to changes in atmospheric carbon dioxide concentrations on a time scale of about a year. Projected increases in atmospheric carbon dioxide may drive a reduction in ocean pH to levels not seen for millions of years (Caldeira and Wickett 2003).

Many marine organisms, including corals, use calcium and carbonate ions from seawater to secrete calcium carbonate skeletons. Reducing the concentration of either ion can affect the rate of skeletal deposition, but the carbonate ion is much less abundant than calcium, and appears to play a key role in coral calcification (Langdon 2003). The carbonate ion concentration in surface water will decrease substantially in response to future atmospheric carbon dioxide increases,

reducing the calcification rates of some of the most important calcium carbonate producers, including corals.

However, calcification rates of corals also depend on other factors such as temperature (Kleypas et al. 1999). The estimated average decline in reef calcification rates is 6–14% as atmospheric carbon dioxide concentration increased from pre-industrial levels (280 ppmv) to year 2004 values of 370 ppmv (Buddemeier et al. 2004). However, studies have shown that while declining saturation state from ocean acidification may be suppressing calcification rates, increasing temperatures may be enhancing them. This is evident by calcification rates of large heads of the massive coral *Porites* that increased rather than decreased over the latter half of the 20th century (Lough and Barnes 1997, 2000; Bessat and Buigues 2001). Temperature and calcification rates are correlated, and *Porites* corals have so far responded more to increases in water temperature (growing faster through increased metabolism and increased photosynthetic rates of their zooxanthellae) than to decreases in carbonate ion concentration (Buddemeier et al. 2004). The temperature enhancement is thought to be a short-term effect, because the coral calcification response to temperature is not linear; rather, it reaches a maximum near the coral's optimal temperature, and then decreases at temperatures higher than that optimum. Thus, in order to boost calcification, the temperature increase must remain below the corals' upper thermal limit. The projected changes of Puerto Rico's seawater chemistry are expected to affect coral reefs because the rate of calcification of corals and crustose coralline algae is highly

sensitive to declining carbonate ion concentrations (Kleypas and Langdon 2006). Furthermore, processes such as bioerosion are likely to increase as the concentration of carbonate ions decreases (figure 14). The critical carbonate balance of coral reefs degrades when atmospheric concentrations of carbon dioxide exceed 450ppm and maintenance of carbonate coral reef systems may be too much above 350ppm (below our current concentration of 395 ppm). Experimental studies

(Kleypas and Langdon 2006) and field studies (De'Ath et al. 2009, Cooper et al. 2008, Tanzil et al. 2009) indicate that substantial decreases in calcification are expected to occur in reef systems that are more fragile and degraded. In other words, healthy reef systems stand a better chance against ocean acidification, although they are not buffered completely from negative effects. The reduction in calcification rates at low carbonate

report, Puerto Rico can expect to experience heavier downpour events and more consecutive dry days. Mathematical models have unequivocally shown that average rainfall is expected to significantly decline across the wider Caribbean region, increasing the frequency of drought conditions (see PRCCC Working Group 1 report). Increases in heavy precipitation (high magnitude, acute events) can lower salinity and increase

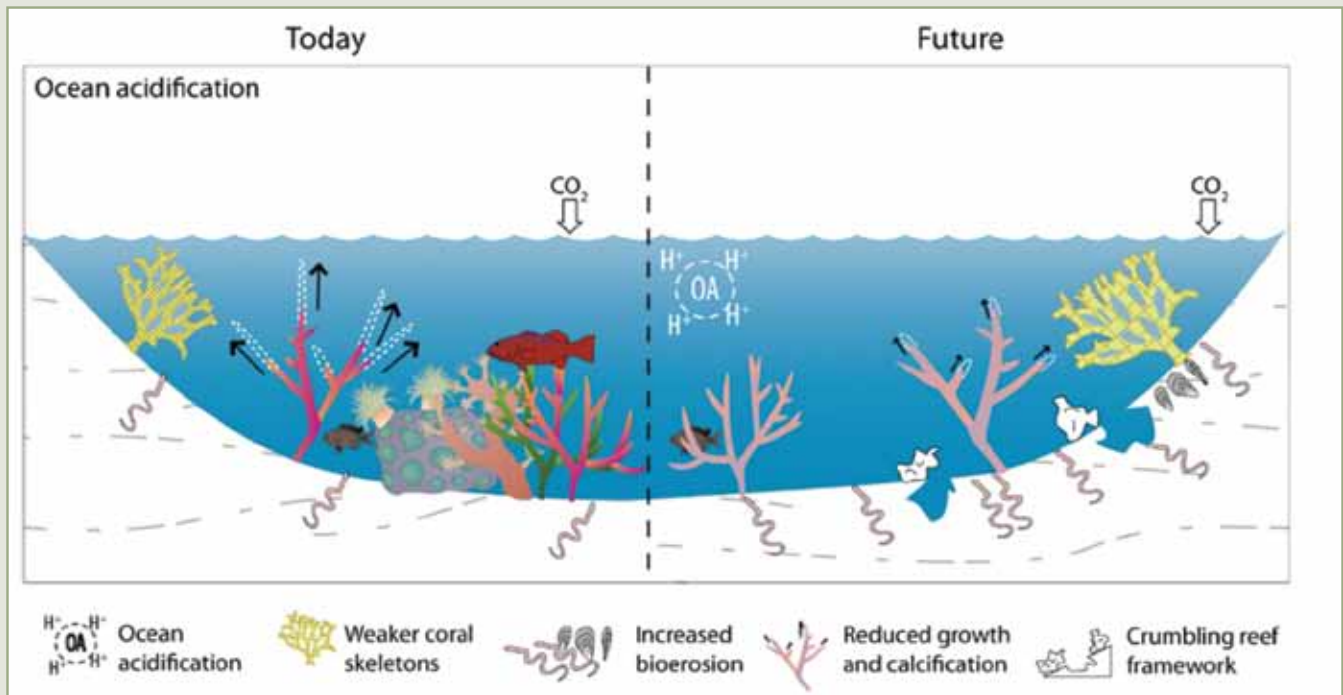


Figure 14 Effects of projected ocean acidification (OA) on coral reefs. The rising concentration of carbon dioxide (CO₂) in the atmosphere from the burning of fossil fuels is acidifying the world's oceans and decreasing concentrations of carbonate ions. Reduced calcification of reef-building corals and crustose coralline algae when CO₂ exceeds 450 ppm is expected to change the balance of reef processes from net construction to net erosion, leading to loss of corals and reef frameworks. Printed with permissions from Bell JD, Johnson JE and Hobday AJ (eds) (2011) *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia.

ion concentrations suggests that corals, and the reefs they build, are highly vulnerable to ocean acidification, and that increases in atmospheric CO₂ above 450 ppm are likely to result in erosion of some coral reefs. This outcome will have important societal consequences for the ecosystem services coral reefs provide to Puerto Rico, such as fisheries and coastal protection (see Table 4).

Precipitation Changes

Climate change is expected to bring about changes in precipitation. According to the PRCCC's WG 1

sediment discharge and deposition near river mouths, sometimes leading to mass mortalities on nearby coral reefs (van Woesik 1991, Coles and Jokiel 1992). Supporting this are findings from other studies that have shown that algal biomass is highest in nearshore habitats, especially in the vicinity of river mouths (Roberts 1997). Even under reduced long-term average rainfall conditions, extreme rainfall events such as those seen since 2010 can produce large amounts of rainfall and runoff in localized areas on very short temporal scales. If the frequency and/or severity of extreme precipitation increases, this can lead to increased runoff events around the island and

increased sediment and nutrient inputs to coastal ecosystems, as has already been documented (Larsen and Webb 2009). This leads to decreased light availability (in quantity and quality) and the resulting physiological stress can have low energy and polyp stress effects (Erftemeijer et al. 2012). Additionally, corals may need to use more energy to expel the sediment cap that the runoff brought to the reef. This chain of events may lead to a decrease in productivity and growth of corals and a change in species composition (community structure) and/or a reduction in coral cover. Runoff can also increase the amount of pollutants that get to corals and those pollutants can decrease productivity. The heavier the downpour, the greater the outflow of land-based sources of pollution and the more damage that can be done to the reefs. Increased runoff could also lead to an increase in nutrient loads from land which causes algal blooms and/or eutrophication to occur (Cloern and Jassby 2010). The result is less sunlight penetration to corals, which, as mentioned previously, can be devastating to coral reef ecosystems. Whether sediment, nutrients, or other pollutants reach the reefs from downpours depends entirely on soil conservation practices on land, urban development, riparian buffers, wetland conservation, and conservation of other natural systems. Therefore, if downpours increase as a result of climate change, coral reefs can still be protected if land-based sources of pollution are controlled properly.

On the other hand, if Puerto Rico experiences increased drought conditions due to changes in precipitation, this could lead to a decrease in freshwater flows or a change in the timing of freshwater runoff to coastal waters. This could increase coral growth and productivity. This potential climate change outcome needs more study as there are many areas with a freshwater lens in Puerto Rico that have healthy and/or resilient corals. On the other hand, the frequency and intensity of droughts are also expected to increase, which may cause changes in vegetation cover and land use that can lead to erosion and sediment stress when rains return (Buddemeier et al. 2004).

Tropical Storms and Hurricanes

Kjerve *et al.* (1986) point out that our perception of the ability of coral reefs to withstand hurricane damage may depend largely on how long it has been since the previous hurricane. It is thought that Caribbean reefs require about eight years to recover from a storm (Gardner et al. 2005). However, climate change may result in increases in the intensity of storms and changes in ENSO and precipitation patterns (see PRCCC Working Group 1 Report)(Maul 1993). These will in turn affect turbidity, salinity, and runoff; altering the oceans on a large scale, changing their circulation patterns, chemical composition and increasing advection (Harley et al. 2006), negatively impacting coral reefs. Increased storm activity and intensity will hinder the ability of coral reefs to recover. In fact, some studies conducted in the region already show that while some recovery of reef in deeper waters occurs after storms, there is no noticeable recovery in nearshore areas (Roberts 1997).

If Puerto Rico experiences an increased intensity of storm events and hurricanes (waves and wind being the primary concerns from these events), there could be increased coral mortality. In addition, coral reef growth may not be able to keep pace with these destructive events (other climate stressors influence this as well). Coral mortality from storms is caused mostly by physical damages (Goenaga 1992). Mortality, net loss, and recuperation are possible outcomes of the physical damages and all three lead to changes in base structure (figure 15). With recuperation, corals reestablish and grow in new areas by movement and fragmentation (asexual reproduction).

If the frequency of storm events does not change, then our coral reefs may have a chance to bounce back. The big question is how much time reefs need between storm events to return to previous conditions. There is a possibility that there has been acclimation of our Puerto Rico reef communities to storm events, but more research is needed in this area. With a background of chronic stress from non-climate impacts like unsustainable land use practices and overexploitation of key functional groups like

herbivores, combined with climate stressors like acidification and higher sea surface temperatures, more intense tropical cyclones could also act as key agents for change in coral reef habitats. The described compounding of threats has the potential to lead to sudden change in ecological state (from coral dominated to macroalgae dominated, for instance (Hughes 1994), where any single factor could well cause the collapse of Puerto Rico's coral reef systems.

Increased Dust from Arid Regions

The Sahara is the major source of mineral dust (60-200 millions of tons per year) on Earth. Mineral dust is eroded mineral soils from the Sahara Desert and the transition zone (Sahel) between the Sahara Desert and tropical forests to the south. This mineral, or Saharan dust, is lifted by convection to high altitudes where it is transported by the trade winds across the Atlantic Ocean to the Americas and the Caribbean basin. Besides depositing nutrients utilized by Atlantic phytoplankton and other organisms, the dust also contains harmful contaminants. Viable pathogenic microorganisms, metals, heavy metals, pesticides, polychlorinated biphenyls (PCBs), and polycyclic

aromatic hydrocarbons are found in the dust. A known coral pathogen, the fungus *Aspergillus sydowii*, which produces the disease aspergillosis in sea fans, is transported by Saharan dust.

Stressors to Caribbean corals, such as coral reef diseases, appear to coincide with African dust production as well as other factors (Shinn et al. 2000, Garrison et al. 2003, Weir-Brush et al. 2004). Based on data recorded in Barbados, the years of highest cumulative dust flux occurred in 1983-1985 and 1987 (UNEP/GPA 2006). This has also been linked to increasing aridity and desertification in Northern Africa (Prospero and Lamb 2003). Various peaks in the dust record at Barbados and elsewhere in the western Atlantic coincide with benchmark perturbation events on reefs throughout the Caribbean (UNEP/GPA 2006). Because climate change is a global phenomenon, the Saharan Desert will also be affected by climate changes. However, how the dust emissions in Africa might change is not currently known. Some global climate models predict a wetter North Africa and some a drier. The mechanisms by which dust may affect corals include direct fertilization of benthic algae by iron or other nutrients that may interact with ammonia and nitrite, as well as nitrate-

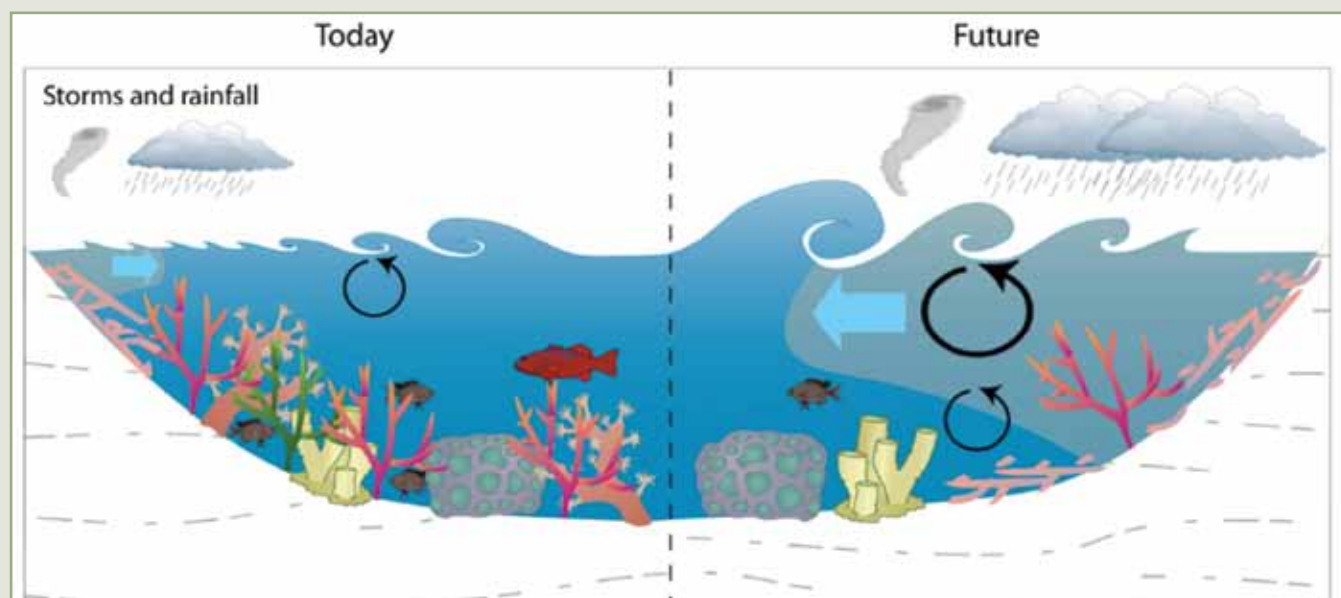


Figure 15 Effects of stronger cyclones and heavier rainfall on coral reefs, which are expected to lead to greater loss and degradation of habitat through damage by more powerful waves, reduced salinity and increased turbidity of coastal waters. The effects of stronger cyclones and increased rainfall are also expected to interact with higher sea surface temperatures, increased acidification and local factors, such as poor catchment management, to cause severe problems for coral reefs. Printed with permissions from Bell JD, Johnson JE and Hobday AJ (eds) (2011) *Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change*. Secretariat of the Pacific Community, Noumea, New Caledonia.

rich submarine ground water, and broadcasting bacterial, viral and fungal spores that may be sources of pathogens (Shinn et al. 2000, Garrison et al. 2003).

Research Needs and Information Gaps

There is a need to expand coral reef long-term monitoring efforts at selected representative localities to identify climate change-associated impacts and impacts associated with other localized human stressors, such as high water turbidity, sedimentation, eutrophication, and fishing. Also, special attention should be placed on monitoring high-energy reefs to test hypotheses about thermal resistance of corals under high energy conditions. There is a need to address long-term ecological changes on deeper water corals, which appear to be more resilient than those from shallower zones. There is also a need to provide special attention to the long-term response of reef fish communities to habitat degradation. There is also a need to foster low-tech coral aquaculture and reef rehabilitation. According to Hernández-Delgado and Suleimán-Ramos (2012), low-tech coral aquaculture and reef rehabilitation approaches in PR have proven to be successful, reliable, and cost-effective tools to conserve and restore Staghorn coral, *Acropora cervicornis*, populations with minimum intervention and maintenance.

Summary of Coral Reefs and Climate Change

Coral reefs, known as the rainforests of the oceans, are unique ecosystems that provide a number of values to humans, as well as to the health of the biosphere. Reefs support fisheries and reef structures provide natural breakwaters that protect shorelines, other ecosystems, and human settlements from wave activity. Humans use reefs and their products extensively for food, building materials, pharmaceuticals, the aquarium trade, and other uses. In addition, due to their beauty and novelty, reefs have become a major part of the local and international tourism product for Puerto Rico. As such, coral reefs form

part of our economic foundation. Unfortunately, these valuable ecosystems are being rapidly degraded by localized human activities such as coastal development, sedimentation, overfishing, and marine pollution. The most extensive coral reef systems in Puerto Rico are found on the Southwestern and Northeastern shelf, although coral communities can be found in other areas. Climate change has had significant harmful impacts to coral reefs across the Caribbean region, including Puerto Rico. Sea level rise is and will continue to be a major cause of concern for coral reef ecosystems. The consistent decline of the most significant reef-building species across the region suggests that overall reef accretion rates might be slower than in the past. If the vertical growth rate of corals is likely to be slower than the increase in sea level rise, then the ability of reef ecosystems to keep pace with the forecasted sea level rise trends might be deeply compromised.

Perhaps more of an immediate concern is that the beneficial relationship between corals and their symbiotic zooxanthellae breaks down under stressful situations. Sudden reductions in salinity, or increases in chemical toxins, sea surface temperatures, or solar irradiance, will cause corals to turn brilliant white as the zooxanthellae are expelled from the coral tissues. This phenomenon is referred to as coral bleaching. Deprived of their energy source, corals become much more susceptible to competitors such as macroalgae and other stressors, which can lead to starvation, disease, and death. The most direct evidence of stress caused by climate changes on coral reefs comes in the form of mass coral bleaching often due to stressful conditions resulting from prolonged sea surface warming. Based on current trends, climate models have shown that coral bleaching will become an annual event by the year 2020 and that the temperature of the ocean will exceed the threshold for coral bleaching over a third of the year. Another concern with increasing SSTs is that Puerto Rico's corals could suffer from physiological stress increasing coral susceptibility to disease (and therefore an increase in virulence of bacterial and fungal pathogens). The most profound and widespread changes in Caribbean coral reefs in the past 30 years have been

attributed to disease; however, the reasons for the sudden emergence and rapid spread of disease are not well known.

Another cause of concern for coral reefs from climate change is “the other CO₂ problem” – ocean acidification. The projected changes in Puerto Rico’s seawater chemistry are expected to aggressively affect coral reefs because the rate of calcification of corals and crustose coralline algae is highly sensitive to declining carbonate ion concentrations. The reduction in calcification rates at low carbonate ion concentrations suggests that corals, and the reefs they build, are highly vulnerable to ocean acidification and that increases in atmospheric CO₂ above 450 ppm are likely to result in erosion of some coral reefs.

Increases in heavy precipitation (high magnitude, acute events) can lower salinity and increase sediment discharge and deposition near river mouths, sometimes leading to mass mortalities on nearby coral reefs. The heavier the downpour, the greater the discharge of waters containing land-based sources of pollution to nearshore waters and the more damage these can cause to the reefs. On the other hand, if Puerto Rico experiences increased drought conditions as part of changes in precipitation, this could lead to a decrease in freshwater flows or a changing in the

timing of freshwater runoff to coastal waters. This could increase coral growth and productivity. This potential climate change outcome needs more study as there are many areas with a freshwater lens in Puerto Rico that have healthy and/or resilient corals. On the other hand, increasing frequency and intensity of droughts may cause changes in vegetation cover and land use that can lead to erosion and sediment stress when rains return.

There is a need to expand coral reef long-term monitoring efforts at selected representative localities to address climate change-associated impacts, but also to address impacts associated with other localized human stressors, such as high water turbidity, sedimentation, eutrophication, and fishing. Also, special attention should be placed on monitoring high-energy reefs to test hypotheses about thermal resistance of corals under high energy conditions.

All existing information leads to the conclusion that coral reefs have very high vulnerability to further increases in sea surface temperatures, sea level rise, heavy downpour events, and ocean acidification (Table 4). While coral reefs may be fairly resilient ecosystems, the cumulative effects of the threats discussed are taking an alarming toll on coral reefs throughout the Caribbean and could reduce their adaptive capacity to climate change.



Coral Reefs and Climate Change	BIOPHYSICAL OUTCOMES								SOCIETAL CONSEQUENCES	
	Reduced reef accretion	Increased coral mortality	Altered food web dynamics	Shifting species distributions	Greater incidence of disease	More frequent and widespread annual coral bleaching	Physical damages	Increased algal growth and changes in community structure	Decreased light availability	
Sea Level Rise	✓	✓		✓		✓			✓	✓
Increased Sea Surface Temperatures	✓	✓	✓	✓	✓	✓				✓
Increased Tropical Storm and Hurricane Intensity	✓	✓					✓		✓	✓
Increased Precipitation and Increased Intensity of Downpour Events		✓	✓		✓			✓	✓	✓
Increased Carbon Dioxide	✓	✓	✓	✓			✓			✓
Increased Saharan Dust to the Caribbean from Africa					✓			✓	✓	✓

Table 4 Summary outcomes/consequences of climate change stressors on Puerto Rico's coral reefs

SUBMERGED AQUATIC VEGETATION - SEAGRASSES

Introduction to Seagrasses

Seagrasses are aquatic flowering plants that grow in the soft or sandy bottoms of estuaries and along the coastal margins of tropical, temperate and sub-arctic marine waters (Duarte 2000, Green and Short 2003). They are found throughout the insular Caribbean growing in reef lagoons between beaches and coral reefs, or forming extensive meadows in more protected bays or estuaries. *Thalassia testudinum* is the most abundant species (Duffy 2006) growing in monospecific beds, or intermixed with *Syringodium filiforme*, *Halodule wrightii*, or *Halophila* spp. and macroalgae.

Seagrasses form extremely complex ecosystems that are highly productive, faunally rich and ecologically important (Green and Short 2003). As such, seagrass beds have been recognized as productive fishery areas in the Caribbean (Muehlstein 1989, Muehlstein and Beets 1992). They are important breeding grounds and nurseries for finfish and shellfish population (Nagelkerken *et al.*, 2002). The plants filter suspended sediments, and nutrients from coastal waters, stabilize sediments, dissipate wave energy, and remove carbon dioxide from the ocean-atmosphere system which could play some role in the amelioration of climate change impacts (Barbier *et al.* 2011).

Seven seagrass species have been reported for Puerto Rico, including *Thalassia testudinum*, *Halophila decipiens*, *H. baillonis*, *H. engelmannii*, *Syringodium filiforme*, *Halodule wrightii* (now *beaudettei*), and *Ruppia maritima* (Vicente 1992, Hemminga and Duarte 2000) with the dominant species being *Thalassia* and *Syringodium* (L. Roberson, pers. obs.).

Globally, seagrasses play an important role in maintaining productivity, as they are responsible for approximately 1% of total primary production and 15% of total carbon storage (Hemminga and Duarte 2000). For the seagrass species found in Puerto Rico, Duarte and Chiscano (1999) reported that the average above-ground to below-ground

biomass (AG/BG) was approximately 250/500 g dry wt m⁻² for both *Thalassia* and *Syringodium* and 200/100 g dry wt m⁻² for *Halodule*. The AG/BG average productivity (g dry wt m⁻² d⁻¹) for *Thalassia*, *Syringodium* and *Halodule* were approximately 3.5/2, 3/2, and 7/1, respectively. These biomass and productivity measurements demonstrate that belowground biomass for turtle and manatee grass in Puerto Rico is higher than the global average, while above-ground biomass productivity is similar to the global average for these two species. It also may indicate that local seagrass populations are stressed and therefore invest more production in BG biomass as storage. For shoal grass, the measurements demonstrate its capacity for high AG productivity although its BG productivity was lower than the global average, probably due to the limited development of its rhizome system. In La Parguera, Puerto Rico, González-Liboy (1979) found that the AG productivity of turtle grass ranged from 2-7 g dry wt/m² per day with an average of 5, again indicating the high productivity of the local system. In addition to the productivity of the grasses, the productivity of other components of seagrass meadows may be more than 20-60% of total production (Hemminga and Duarte 2000). For instance, epiphytes in *Halodule* stands may be more productive than the grass, possibly accounting for the high AG productivity measurements in the review by Duarte and Chiscano (1999).

The importance of seagrasses in the marine food webs is greater than the extension of their beds. Material from seagrass beds is exported to areas very distant from the beds and often to deep waters as dissolved and particulate material. Leaves of manatee grass, and to a lesser extent turtle grass, have been observed in depths of thousands of meters. Seagrass leaves have been photographed on sediments in the Puerto Rico trench at depths of 7,860 meters (25,787.4 feet) (Webber and Thurman 1991). At these depths, this material is an important part of the diet of organisms such as echinoderms (*i.e.*, starfish, urchins). Furthermore, accumulation of seagrass wracks on beaches provide significant amounts of nutrients to local biota generating additional production while influencing shore geomorphology by trapping

and binding loose sand particles (Hemminga and Duarte 2000).

Within the beds themselves, organisms such as the green sea turtle and the manatee, both federally protected species in the U.S. Caribbean, feed on seagrass leaves and algae. Tidal embayments containing seagrass beds are important habitat for juvenile green sea turtles in the Caribbean (Musick and Limpus 1997) that feed on the grasses, as well as on jellyfish and sponges. Similarly, juvenile hawksbill sea turtles frequent estuarine habitats although their feeding preference is for sponges on red mangrove roots rather than seagrass (Musick and Limpus 1997). In the Caribbean, research indicates that turtle grass dominates the diet of adult green sea turtles, probably because it is the most abundant seagrass. However, manatee grass, shoal grass, and paddle grass were also found in the stomachs of foraging turtles, as were red and green algal species and one species of sponge (Bjorndal 1997). Adult hawksbills have also been found to consume marine plants, including algae and seagrasses, although sponges dominate the diet of these sea turtles in the Caribbean (Bjorndal, 1997).

The role of seagrass habitats as dominant producers in tropical and subtropical systems enables the development of a rich community of organisms. Garcia-Rios (2001) illustrates the numerous groups of organisms associated with seagrass, including coelenterates, bryozoans, ciliates, flagellates, sarcodines, foraminifera, crustaceans, fishes, echinoderms, mollusks, and algae. *Thalassia* beds in Jamaica were found to be populated by a variety of macrofaunal species, including polychaetes (20), crustaceans (39), mollusks (61), fishes (41), and others (40) (Greenway 1995). Studies of the population biology of decapods in seagrass beds in Dorado, Puerto Rico (Bauer 1985a, c, b) suggest diversities similar to those found in the Jamaica study, as 34 crustaceans species, including shrimp and hermit crabs, reaching densities of 72 individuals per m², were found. In addition, the interaction between seagrass beds and other marine systems such as mangroves and reefs, facilitates trophic transfers and cross-habitat utilization by fishes

and invertebrates (Orth 2007) and has been found to be essential for the health of all the systems involved (Nagelkerken et al. 2002).

Seagrasses provide habitat for numerous highly mobile species. Berrios et al. (1985) performed visual observations of fish populations in seagrass beds dominated by turtle grass and coral reefs in Cayos Berbería and Ratones off the coast of Ponce, Puerto Rico. They found approximately 29 species of juvenile fishes in large numbers, including grunts, parrotfish, and yellowtail snappers. They also found young adults of bluestriped grunt (*Haemulon sciurus*), gray snapper (*Lutjanus griseus*), and schoolmaster (*L. apodus*) to be common in seagrass beds around Cayo Berbería. Adult grunts and snappers were also very common in both reef environments, which Berrios et al. (1985) attributed to the presence of seagrass beds in both reefs. Similarly, Aguilar-Perera (2004) evidenced the importance of seagrasses in La Parguera Natural Reserve as habitat for juvenile populations of species of commercial importance such as grunts and snappers. Jenkins and Hamer (2001) found a relationship between the abundance of post settlement fish and meiofaunal crustaceans in seagrass beds. Due to the greater abundance of prey items in seagrass beds in comparison to bare sandy sediments, post settlement fish were more abundant in seagrass beds.

The complex trophic interactions within seagrass communities are paramount in sustaining juvenile and adult populations of special interest, including commercially important fishery and protected species. However, because the contribution of any particular seagrass species (evenness) is low within a seagrass bed and associated fauna and algae contribute most of the diversity of seagrass habitats, observers are often wrongly inclined to think seagrass habitats do not sustain significant biodiversity (Hemminga and Duarte 2000). Because the fauna of seagrass beds is cryptic and the grasses themselves are not as evident as coral reefs, Orth et al. (2007) estimate that the publicity given to seagrasses is 10 to 100 times less than that given to other coastal habitats. Despite the fact that the economic value of seagrass meadows has been estimated. The

value of marine macrophyte ecosystems (contain macroalgae and seagrasses) has been estimated at \$19,000 per hectare per year (Costanza et al. 1997). This is 23 times higher than the average oceanic and terrestrial values, 3 times more than coral reefs and 10 times more than tropical forests. Therefore seagrass meadows are one of the highest valued ecosystems on Earth. The lack of awareness of the ecological and economic importance of seagrass beds on the part of the general public, resource agencies, and lawmakers may explain the lack of protection afforded to this essential habitat.

Status

Population growth, increased urbanization and the rapidly expanding agricultural and tourist-industrial sectors in the insular Caribbean have increased pressure on the coastline and their seagrasses (Short and Wyllie-Echeverria, 1996). Increased traffic of ships and recreational vessels are causes of anchor damage, trampling, propeller scarring, detrimental shading by marinas and piers, and damage by dredging (Thorhaug *et al.*, 1985; Creed *et al.*, 2003). In the smaller islands, seagrass beds are damaged by illegal sand mining which suspends sediments and alters local hydrodynamics. In St Lucia, seagrass beds have been destroyed by dynamite fishing (Creed *et al.*, 2003) and seamoss (*Gracilaria spp.*) is cultivated in seagrass areas.

Seagrasses are subjected to nutrient pollution mainly from land-based sources of pollution, particularly sewage and grey water (Short and Burdick, 1996,). Increased sediment loading as a result of deforestation, urbanization and agricultural activities has caused major damage to beds. A comparison of seagrass bed community structure between areas of high and low water quality showed a significant difference in biodiversity and below-ground biomass, with higher biodiversity and higher total biomass in areas with high water quality (Roberson, unpub. data). Extensive seagrass beds in the Archipelago Sabana-Camagüey, Cuba, have been impacted by increased salinity in the inner water bodies, due to anthropogenic changes in the hydrological regime (James and Hart, 1993). Indirect activity such as

overfishing of wrasses and triggerfishes off Haiti and the U.S. Virgin Islands results in an explosion of sea urchins which then destroys seagrass bed by overgrazing (Creed *et al.*, 2003). Seagrass beds can also be damaged by hurricanes and from overgrowth of bluegreen algae.

A study of the seagrass system in Guayanilla Bay showed that approximately 17% of the area surveyed was covered with seagrass (Vicente 1992). The two major regions within the study area that were devoid of seagrass were the deepest area in the central bay and the western bay, which was very turbid (Vicente *et al.* 1980). The turbidity in the western bay was due to dredging and filling in the coastal and shallow water areas as part of industrial development in the bay, as well as turbulence from sediment resuspension caused by the power plant's cooling system discharge (Vicente and Rivera 1982). Thus, industrial development that includes ports and nearshore discharges along portions of the coast of Puerto Rico have led to a loss of seagrass beds.

Similarly, a study in Culebra found that commercial, housing, and recreational development and associated construction of docks and other marine facilities led to decreased water transparency from eroding soils and wastewater discharges and increased water turbidity from boating and a resulting decline in seagrass beds (Vicente 1992). In Puerto Rico, Gonzalez-Liboy (1979) found propeller scarring in areas associated with channels between mangrove cays in La Parguera. Gonzalez-Liboy (1979) reported intense impacts to seagrasses in the channel near Magueyes Island that caused significant patchiness of seagrass beds in this area. More recently, Carrubba *et al.* (2003) documented major propeller scar impacts in various locations in La Parguera Reserve, including shallows near Magueyes Island, Cayo Caracoles and Cayo Collado backreefs where 43-74% of the area potentially affected by boat traffic showed damage due to propeller scarring. Other studies characterizing the impacts of mechanical damage to seagrass beds in Cordillera Reefs and Culebra showed that boating activities, in particular transit through shallow areas on the west coast of

Puerto Rico and anchoring practices on the east coast of Puerto Rico and around Culebra resulted in considerable damage to seagrass beds where boaters were concentrated (Carrubba et al. 2003, Otero and Carrubba 2007, 2008). In Cordillera Reefs, based on impacts to seagrass mainly from anchoring, it was estimated that 7%, 14%, and 21% of the seagrass habitats in Palominito, Palomino, and Icacos were impacted (Otero and Carrubba 2007). Mechanical damage to seagrass beds in Culebra resulted in impacts to at least 54%, 25.2%, 12%, 1.7%, 4.6%, 54.3%, and 0.5% of the shallow seagrass beds in Ensenada Honda (near Dewey), Cayo Verde, near Punta Cabras, Costa Bonita near Mosquito Bay, Malena Bay, Dakity backreef and Bay, Fulladosa Bay, and the south shore of Culebrita (Otero and Carrubba 2008). A related study of the impacts of dock construction on the seagrass beds in Culebra found that dock construction and associated long-term mooring of vessels at docks had resulted in the loss of 3.6% of the continuous shallow water seagrass beds in Fulladosa Bay (Otero and Carrubba 2008).

Outcome and Consequences of Climate Change to Puerto Rico's Seagrasses

Climate change represents a relatively new threat, the impacts of which on seagrasses are largely undetermined (Short & Neckles, 1998). Potential threats from climate change may come from rising sea level, changing tidal regime, localized decreases in salinity, damage from ultraviolet radiation, and unpredictable impacts from changes in the distribution and intensity of extreme events (Short & Neckles, 1998). Higher carbon dioxide concentrations may, however, increase productivity thus not all climate change outcomes are negative.

Sea Level Rise (and altered currents/tidal regime)

Rising sea levels could result in changes in light attenuation, wave energy, substrate type, and grazers influencing seagrass beds (Short and Neckles, 1998). Impacts could be positive or negative. A positive impact of sea level rise on

seagrass beds would be fewer disturbances. However, increased sea level could also be negative in terms of less sunlight penetration to the beds. Therefore we would see reduced productivity and growth and eventually a loss of beds and their associated ecosystem services. The growth rates of seagrass rhizomes vary greatly, from a few centimetres per year in *Posidonia oceanica* to more than 5 meters per year in *Halophila ovalis*. The ability of Puerto Rico's seagrass beds to cope with rising seas depends on whether the rate of sea level rise is within the rate of vertical growth of most seagrass species present. According to the PRCCC WG 1 Report Puerto Rico has already experienced a 0.14 cm per year increase in sea level since the 1950s with a detected acceleration in recent years of between 0.2 and 0.3 cm sea level rise per year (consistent with global trends of .18 cm per year and 0.3 cm acceleration). The WG 1 report describes projections for future sea level rise through 2100 that generally range from 0.59 meters to 2 meters. Assuming a linear increase in sea level of 0.2 meters by the year 2050 (note: sea level rise is not linear and will continue to experience accelerations and decelerations), per year that would work out to a 0.5 cm increase by 2050; within the vertical growth of most seagrass species (but higher than some, such as *Posidonia oceanica*). However, if assuming a linear increase in sea level at the upper limit of sea level rise projections as determined by the WG 1 a 0.5 m increase by 2050 would amount to 1.28 cm increase per year, thus reducing the number of species that growth vertically enough to acclimate to the change.

Additionally, seagrass canopies may remain at relatively similar depths for long periods of time, provided they can also trap materials to elevate the sediment surface, such as observed in reef-building species. The rise in sea level will cause a greater inland penetration of seawater in estuaries, and this may result in the displacement of less salt-tolerant submerged macrophyte species by seagrasses. Sea level rise will also lead to coastline regression and sediment erosion (see Beaches section in this report). If seagrasses are unable to migrate at new erosion rates, Puerto Rico will experience widespread losses due to

sediment erosion. Sediment erosion may be aggravated in areas where coastlines are densely populated. Structures and development activities may contribute to the destabilization of the marine sedimentary environment and cause additional seagrass loss (Hemminga and Duarte 2000). In addition, deeper populations are likely to be lost as many species have a narrow depth limit (Carr et al. 2012). Changes in coastal water quality as a result of increased erosion (increased turbidity) as well as coastal development will further increase the loss of suitable deep water habitat. Lastly, changing current patterns or the tidal regime could either erode seagrass beds or create new areas for seagrass colonization (Harlin et al. 1982).

Changes in Precipitation

Changes in the river flow regimes and sediment transport may lead to increased sediment loading, thereby burying seagrass beds, and in localized salinity changes. Some seagrass species have a narrow tolerance for salinity changes, which can trigger major shifts in species composition (Lirman and Cropper, 2003). Salinity in association with nutrient enrichment can also become a stressor when freshwater inputs are drastically reduced.

Increased Temperature

Temperature stress on seagrasses are expected to result in distribution shifts, changes in patterns of sexual reproduction, altered seagrass growth rates, metabolism, and changes in their carbon balance (Short and Neckles 1998). Meadows occurring in thermally stressed environments, like thermal effluence, could be more greatly affected by a 1.5°C change in temperature than other seagrass beds (CANARI 2008). However, temperatures of 35°C or more can prevent some species, from rooting (Vicente 1992). Therefore an increase in sea surface temperatures could lead to a decrease or increase in species range depending on the species and temperature. When temperatures reach the upper thermal limit for individual species, the reduced productivity will cause them to die (Coles et al. 2004). The risk of local extinction could be great.

Much more research is required to allow the formulation of specific predictions for seagrasses under higher temperatures. The direct effects of increased temperatures will depend on individual species' thermal tolerances and on the specific temperature dependency of the many processes that determine growth and reproduction. For species currently living near their upper temperature limit, a further increase in temperature may be fatal. Species living in shallow water and enclosed embayments will be more susceptible and it is likely that temperature stress will exacerbate stresses caused by changes in water quality with sea level rise. In less critical environments, a rise in seawater temperature may have an impact on processes like photosynthesis, respiration, nutrient uptake, flowering and seed germination (Short and Neckles 1998). Such effects will have consequences for the vigor and competitive ability of populations. Therefore, it is likely that the species-dependent impact of temperature increase will alter seagrass distribution and abundance in the long-term.

Elevated temperatures may also increase the growth of competitive algae and epiphytes, which can overgrow seagrasses and reduce the available sunlight they need to survive. Another potential outcome of increased sea surface temperatures is greater prevalence of disease.

Increased Carbon Dioxide and Ocean Acidification

Seagrasses use carbon dioxide (CO_2) for photosynthesis rather than bicarbonate like most marine macroalgae. Atmospheric CO_2 has a complex impact on the availability of dissolved inorganic carbon for seagrass photosynthesis, as the increase in dissolved CO_2 in seawater causes interacting shifts in the equilibrium of the various dissolved inorganic carbon species and pH (Goudriann 1993; Short and Neckles 1998, Feely et al. 2004, Fabry et al. 2008). The overall consequence of rising atmospheric CO_2 will be an increase in both the actual concentration of dissolved CO_2 and the relative proportion of CO_2 to bicarbonate (HCO_3^-). This could, in turn, enhance the productivity of seagrass beds (Unsworth et

al. 2012), which have been shown to experience carbon limitation under present-day conditions (Zimmerman et al. 1995). Similarly, the depth range of seagrasses may be extended, as the higher photosynthetic rates at elevated dissolved CO₂ levels would be conducive to a positive carbon balance at greater depths. Changes may occur in the competition between seagrass species and between seagrasses and macro-algae. The positive effects on seagrass growth may be offset by stimulated growth of epiphytic algae on leaf surfaces. Algal epiphytes respond positively to increased availability of CO₂ but due to their faster uptake rates can form blooms that remove nutrients and block light (Raven et al. 1995) needed by the seagrass host. Overfishing has severely reduced the populations of large herbivores in seagrass habitats that control overgrowth of algae. The loss of herbivorous fishes along with mammalian grazers like sea turtles and manatees will allow algal blooms to go unchecked. Decreased productivity could also occur if there is a loss of algae diversity in the seagrass beds. Furthermore, the algae overgrowth could increase the risk of seagrass removal by waves due to increased drag.

Another affect of climate change on seagrass beds is from ocean acidification. Increasing CO₂ concentrations is expected to have a negative effect on calcification rates of calcifying algae, corals, and other carbonate-dominated systems like seagrass beds, therefore affecting seagrass growth and productivity. Multiple studies have been published that used realistic carbonate chemistry manipulations, results showing decreased recruitment rates under high CO₂ conditions and an increase in non-calcifying algae cover (Kuffner et al. 2008), thus changing population structure and dynamics of submerged aquatic vegetation communities, reduced growth in certain rhodoliths of mixed crustos coralline algae (Jokiel et al. 2008), and reduced coralline algal cover and even complete dissolution when pH is reduced to 7.0 (Martin et al. 2008).

Tropical Storms and Hurricanes

Climate change is causing tropical storms to increase in intensity and possibly in frequency (see

PRCCC WG1 Report). Increased storm and tidal surges, changes in storm intensity and frequency, and subsequent change in river flow regimes and sediment transport will impact seagrass beds (Hassan et al. 2005). Seagrasses grow in low energy environments, and thus, increased turbulence from storms and tidal surges could have disastrous effects by uprooting or burying the plants. Storms also increase turbidity thus resulting in a loss of photosynthesis. During storms not all concerns are from the sea, but also from the land. The increase in rainfall and discharges from rivers can increase sediment loading that may also result in decreased light levels or smothering of seagrasses. Since seagrass species are relatively slow-growing plants (compared to some algae) they need to establish extensive root systems in order to anchor themselves in the sediment, their ability to re-establish after a storm will be dependent on the time interval between storms. Additionally, seagrasses could be further stressed by decreases in salinity brought on by heavy rainfall associated with storms passing through the region.

Other impacts of global climate change on seagrasses

Increased ultraviolet (UV) radiation, changes in surface currents, decreases in biodiversity, increased susceptibility to disease, and loss of critical associated habitats like coral reefs can all have negative and far-reaching impacts on seagrass populations worldwide. Increases in UV radiation due to global climate change will increase the likelihood of damages to the photosynthetic apparatus and DNA in seagrasses. The response of UV radiation will vary by species. As temperature gradients change and increase, so will ocean circulation patterns and intensity. Most seagrass species are reliant on water transport of propagules to suitable habitat and some sites are entirely dependent on propagules from upstream sites to ensure continued survival of seagrass communities. High biodiversity has been shown to act as a buffer to disturbance and increase resilience in a variety of systems, including seagrass beds. Not only species diversity but genetic diversity within species has been found

to increase resilience in seagrasses (Hughes and Stachowicz 2011). All of these stresses combined, plus the stresses previously described, greatly increase the change of infection by deadly diseases, as occurred in the east coast of the United States in the 1970s. As seagrasses become stressed and biodiversity decreases, their susceptibility to disease will increase.

The loss of critical habitat by the development of marinas and other nearshore construction and the loss of water quality puts seagrass communities at high risk of further losses. Puerto Rico has the highest population density in the Caribbean and is rapidly developing coastal areas across the island. This increases the risk and susceptibility of local seagrass populations for biomass loss and extinction, especially when all stressors are combined.

Research Gaps and Information Needs

Effective management of seagrass meadows is essential in order to maintain these valuable ecosystems and their important functions. Controlling human impacts will help maintain healthy seagrasses that are better able to resist or recover from climate change impacts. There are a number of information gaps and research needs that should be addressed so managers can support the resilience of seagrass systems:

1. Information is needed regarding the potential shifts in seagrass habitat with sea level rise and changes in ocean temperatures, including whether or not all species will be able to tolerate changing conditions. This is of particular importance for the dominant species, turtle grass, manatee grass, shoal grass, and star grass, around Puerto Rico, which already exhibit depth zonation to some degree.
2. Long-term observations and monitoring of seagrass meadows are needed. There was a gradual decline of areal distribution noticed during the 1980s and 1990s that was related to elevated sea-surface temperatures observed since the 1980s (Glemarec et al. 1997 as cited in Hemminga and Duarte 2000).

Such observations suggest that expansion and regression of seagrass meadows may follow climate changes, and that widespread changes in the areal distribution of seagrasses as a result of current global change phenomena are not unlikely. Regular assessments are also important in order to identify disturbances to seagrass habitats and to determine management efforts. These assessments should include seagrass abundance (cover, density and/or biomass), habitat extent and species composition (in mixed meadows). Long term observations must also include measurements of coastal water quality and light availability for photosynthesis. These could be of importance as early warnings of disturbances.

3. Productivity and rate of vertical growth measurements of Puerto Rico seagrass. Very little is known about the current status of seagrass beds in Puerto Rico. Density, species composition, biomass and distribution must be measured to provide a productivity estimate per species. Benthic surveys were completed in 2001 as part of a cooperative effort between NOAA's National Centers for Coastal Ocean Science, the U.S. Geological Survey, the National Park Service, and the National Geophysical Data Center, to produce benthic habitat maps and georeferenced imagery for Puerto Rico and the U.S. Virgin Islands, but no detailed studies have been completed since, despite the fact that the surveys showed seagrass communities in more than half of nearshore habitats in Puerto Rico. Improved benthic habitats mapping and marine ecosystems characterizations have been conducted by the NOAA Biogeography branch (Kendall et al. 2006, Zitello et al. 2008, Bauer et al. 2008, Jeffrey et al. 2010).
4. Responses of individual seagrass species to higher temperatures. Large die-offs of beds have occurred in shallow areas at low tide on sunny days where temperatures and UV exposure are high. Community and species responses in Puerto Rico will be critical in understanding the suitability of new habitat added as sea level rises and the impact on the

survivorship of seagrass populations.

5. **Connectedness between populations.** As surface currents shift direction and strength, sources of propagules and genetic diversity will shift or be eliminated. Studies by Hughes and Stachowicz (2004) have shown that in addition to ecosystem biodiversity, genetic diversity within seagrass populations enhances resistance to disturbances and so any limitation in diversity may have a negative impact on seagrass ecosystem resistance and resilience to future disturbances. It should be established where seagrass meadows are ecologically linked to adjacent habitats (e.g. mangroves or coral reefs). Such linkages could be taken into account when designing protected areas and management plans.

Summary of Climate Change and Seagrass Beds

Seagrasses are submerged marine flowering plants forming extensive meadows in many shallow coastal waters worldwide. The leafy shoots of these highly productive plants provide food and shelter for many marine animals (including commercially important species, e.g. prawns), and their roots and rhizomes are important for oxygenating and stabilizing bottom sediments and preventing erosion. The monetary value of seagrass meadows has been estimated at up to \$19,000 per hectare per year, thus being one of the highest valued ecosystems on earth.

Many seagrass habitats have already been severely impacted by human activities, and may be additionally affected by global climate change. Seagrass meadows are especially vulnerable to sediment disturbances, eutrophication or the addition of excess nutrients to coastal areas, light reductions, and temperature increases.

Climate change impacts include potential effects of increasing seawater CO₂ levels, decreasing pH (ocean acidification), increasing temperatures, and rising sea level. These factors can have both positive and negative impacts on seagrass photosynthesis and growth and ecosystem

function, but more data is needed to better predict how climate change will affect seagrass meadows, especially in areas already impacted by other human disturbances. In Puerto Rico the main impact on seagrasses may result from synergistic interactions between increasing temperature and habitat degradation that will push them over their limit of existence, resulting in widespread seagrass loss. Loss of sea grass habitats will not only impact sea grass communities but will have a negative impact on associated coral reef and mangrove habitats as well as ecosystem services.

COASTAL AND PELAGIC FISH SPECIES

Fish have complex life cycles, comprising several distinct life history stages (egg, larva, juvenile and adult), each of which may be affected in different ways by climate change. Over their lifespan, fish typically increase in body size by a factor of 10⁵ (Rothschild 1986), and successive life-history stages may require spatially separated habitats. A prerequisite for population persistence is connectivity among the required habitats, allowing the survivors to mature and return to the spawning grounds to reproduce successfully (Sinclair 1988). Within these stage-specific habitats, fish must experience suitable abiotic conditions, find food for growth, and find shelter to avoid predation or disease.

Climate-driven changes in fish populations may result from four, often interlinked, mechanisms: (i) a physiological response to changes in environmental parameters, such as temperature, (ii.) a behavioral response, such as avoiding unfavorable conditions and moving into new suitable areas, (iii) population dynamics, through changes in the balance between rates of mortality, growth and reproduction in combination with dispersal which could result in the establishment of new populations in new areas or abandonment of traditional sites, (iv) ecosystem-level changes in productivity and/or trophic interactions. In addition, (v) commercial exploitation greatly affects the abundance and distribution of fish and may interact with the effects of climate change.

Climate change will affect individuals, populations and communities through their physiological and behavioral responses to environmental changes (Boesch and Turner 1984). Extremes in environmental factors, such as elevated water temperature, low dissolved oxygen, changes in salinity and pH, can have deleterious effects on fishes (Moyle and Cech 2004). Suboptimal environmental conditions can decrease foraging, growth, and fecundity, alter metamorphosis, and affect endocrine homeostasis and migratory behavior (Barton and Barton 1987; Donaldson 1990; Pörtner et al. 2001). These organism-changes directly influence population and community structure by their associated effects on performance, patterns of resource use, and survival (Ruiz et al. 1993; Wainwright 1994). Projections of future conditions portend further impacts on the distribution and abundance of fishes associated with relatively small temperature changes. Changing fish distributions and abundances will undoubtedly affect communities of humans who harvest these stocks (Roessig et al. 2004).

This section is specific to coastal finfishes (nearshore demersal or bottom-dwelling and nearshore pelagic fishes) and pelagic or offshore oceanic finfishes are assessed independently. This assessment does not include sharks or rays. The effects of climate change on sharks and rays are generally unknown but assumed to be similar to those for finfish occupying equivalent habitat types. For example, reef sharks, such as Puerto Rico's Nurse Sharks (Gatas; *Ginglymostomacirratus*), Caribbean Reef Sharks (Tiburon coralino; *Carcharhinus perezii*), Caribbean Sharpnose Sharks (Cazon Playon; *Rhizoprionodon porosus*), Tiger Sharks (Tintorera; *Galeocerdocuvier*) and Whitetip Reef Sharks (Tiburon oceanic; *C. longimanus*), are highly dependent on coral reefs (Opitz 1996) and are likely to be affected negatively by extensive habitat degradation. Similarly, this assessment does not include invertebrates, which are commercially important in Puerto Rico, and should be included in future assessments. Additionally, fisher livelihoods and climate change are discussed in the PRCCC Working Group 3: Society and Economy report.

Introduction to Coastal Fishes

Coastal fish resources in the Caribbean are linked with mangrove, seagrass beds and coral reef habitats. These three coastal habitats are ecologically connected to each other (Beck et al. 2001) and the marine species that depend on healthy habitat connectivity include lobsters, crabs, shrimps, queen conch, a great variety of estuarine and reef fishes, coastal pelagics (clupeids, carangids) and fishes inhabiting the shelf slope (mainly deep-water snappers and groupers). Coastal fisheries in the insular Caribbean have been defined as reef fisheries (Munro 1983). Estuarine environments are not extensive in the insular Caribbean, with the exception of Cuba and Hispaniola, and commercial fishing is prohibited in the majority of Puerto Rico estuaries. Most of the fishery resources of the island shelves (reef and estuarine fish, lobster, shrimp, conch and others), as well as the deeper demersal resources (mainly snappers and groupers) are considered to have been overexploited since the 1980s, and are coming under increasing fishery pressures throughout the region and are in need of rehabilitation in several islands (Mahon 1987; 1993; Appeldoorn and Meyers 1993; Aiken 1993; Baisre 1993, 2000, 2004; Claro et al. 2001). Moreover, many of the shallow-water environments that these fishery resources inhabit (e.g., mangroves, seagrass, and coral reefs) have been seriously affected by coastal development, pollution, habitat loss, and overfishing (Rogers 1985; Hunte 1988; Bouchon et al. 1987; Mahon 1993; Claro et al. 2004, 2007; Jackson et al. 2001; Hughes et al. 2003; Roesing et al. 2004). On the other hand, some research suggests that following the Caribbean-wide mass mortality of herbivorous sea urchins in 1983-1984 and consequent decline in grazing pressure on reefs, herbivorous fishes have not controlled algal overgrowth of corals in heavily fished areas although they have restricted algal growth in lightly fished areas. Differences among islands in the structure of fish and benthic assemblages suggest that intensive artisanal fishing has transformed Caribbean reefs (Hawkins and Roberts 2004). Examples of coastal fish species found in Puerto Rico are snooks (robalos; Familia Centro-pomidae), snappers (pargos; Familia Lutjanidae),

grunts (roncos; FamiliaHaemulidae), butterflyfishes (mariposas; FamiliaChaetodontidae), angelfishes (isabelitas; FamiliaPomacanthidae), mullets (lisas; FamiliaMugilidae), damselfishes (damiselas; FamiliaPomacentridae), parrotfishes (loros; FamiliaScaridae), blennies (blenios; FamiliaBlennidae), gobies (gobios; FamiliaGobiidae), and puffers (tamboriles; FamiliaTetradontidae) (figure 16). For more detailed lists see Erdman and Grana 2007; Dennis 2004; Appeldoorn et al. 1987.

The commercial fisheries of Puerto Rico can be classified as small scale, multispecific, multigear and mostly artisanal in nature. The fisheries are largely demersal; some fishers also target pelagic species. The demersal fishery harvests for reef, bait, ornamental, and deep-water species; over 155 finfish groups or species and approximately ten species of shellfish. The most prevalent groups in the reef fisheries include snappers, groupers, grunts, mackerels, parrotfish, trunkfish, spiny lobster, and queen conch. The deep-water fishery targets snappers, groupers, and tilefish. Angelfishes, damselfishes, surgeonfishes,

blennies, wrasses, basslets, jawfishes, and other species are ornamental fish targeted by the aquarium trade industry (Valle-Esquivel et al. 2011). Large longline vessels with HMS permits from the continental U.S. only visit the Puerto Rico EEZ for a few days per year at most to target swordfish.

The marine recreational fishery of Puerto Rico has only recently (2000) begun to be systematically evaluated. Data from the Marine Recreational Fisheries Statistics Survey (which is now transitioning to the Marine Recreational Information Program) from the years 2000 – 2011 indicate that the harvest of marine fish by recreational anglers is on average greater than that of commercial fishers in terms of weight. The vast majority of fish harvested in the recreational sector consists of mahi mahi, several tuna species, and mackerels. Reef fish are also targeted, but to a much lesser degree. Over half of all recreational anglers fish from shore, but the greatest diversity and abundance of catch occurs in the private boat mode. Charter boat fish harvest is a very minor component of the overall recreational scenario.

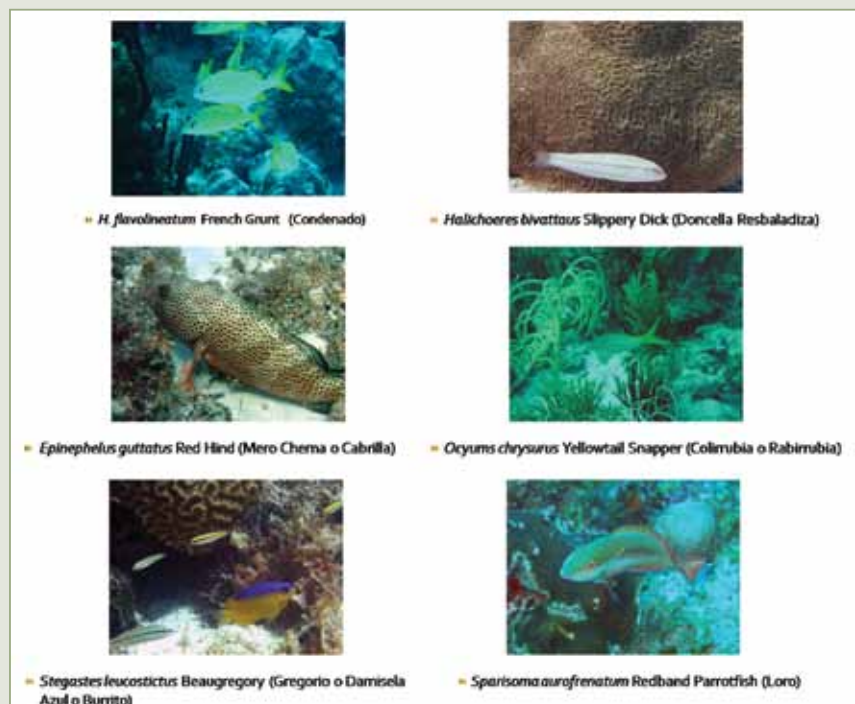


Figure 16 Examples of Coastal Fish Species in Puerto Rico by scientific name, English common name, and Spanish common name. Photos courtesy of NOAA CCMA Biogeography Team.

Outcomes and Consequences of Climate Change on Coastal Fishes

The previously described outcomes and consequences of climate change on mangroves, coral reefs, and seagrass beds directly apply to coastal fish species as these habitats provide them with shelter and food. Coastal fishes (and many species of pelagic fishes) are especially reliant on nursery habitat. A given marine habitat is considered a nursery if juveniles occur at higher densities, have lower rates of predation or higher rates of growth compared to other habitats, and also if the habitat contribution, in terms of juveniles per unit area to the production of adults, is greater than that from other habitats harboring juveniles (Beck et al. 2001). Mangroves, seagrass beds, and shallow coral reefs are important habitats functioning as nursery grounds for several reef associated fishes (Thayer et al. 1987; Baelde 1990; Ley et al. 1999; Nagelkerken et al. 2000). These habitats are used as nurseries by several juvenile fishes for the following reasons: (1) shelter from predators (Parrish 1989); (2) high abundance of food (Odum and Heald 1972; Ogden and Zieman 1977; Laegdsgaard and Johnson 2001); and (3) planktonic larvae reception due to extensive habitat coverage (Parrish 1989).

The most important direct effects on coastal fishes are likely to be due to the projected increases in sea surface temperature and ocean acidification and changes in ocean currents (Munday et al. 2008, Brander 2009). Additional environmental changes and severe climatic events, such as increased severity of tropical cyclones, more extreme rainfall events or drought conditions, and sea level rise could have further direct and indirect effects for some species and life stages. The direct and indirect effects of climate change on coastal fish will vary depending on their biology and ecology. For example, recent effects of climate-induced coral loss on reef fish vary depending on their reliance on live corals for food, shelter and/or recruitment (Pratchett 2008). Butterflyfish, certain species of damselfish, cardinalfish, and coral-dwelling gobies have the greatest dependence on live coral and are directly at risk from loss of corals. Other fish may also be

particularly susceptible to climate change owing to their sensitivity to changes in temperature or ocean chemistry. The potential impact of projected changes on species is moderated by the species ability to alter its physiology, behaviour and/or distribution to cope with changes. Species with a high sensitivity to changes in environmental conditions and habitats, which are unable to adapt, are most vulnerable and potentially at risk of local extinction due to climate change (Adger 2000, IPCC 2001). Examples of ways fish species can adapt include switching to a different prey species, living in slightly different habitats, and evolving increased tolerances. A species-by-species assessment for Puerto Rico is not within the scope of this report, but could be considered necessary for marine conservation and fisheries management.

Increasing Temperature

As described in the coral reef section, temperature increases are already degrading coral reefs worldwide. Fish biodiversity is threatened wherever permanent reef degradation occurs. A significant decrease of fish density and biomass in coral reefs as a result of coral cover reduction is expected, as shown to have occurred in the Archipelago Sabana-Camagüey, Cuba, after several bleaching events, and subsequent increase of algal overgrowth (Claro et al. 2007). Similar results have been reported for New Guinea reefs (Jones et al. 2004).

Changes in water temperature have a major influence on most coastal fish because they have limited capacity to maintain an independent body temperature. Temperature tolerance is a determinant of geographic ranges and the general biology and behavior of fish. Temperature increases are predicted to drive species ranges toward the more cold waters (Parmesan and Yohe 2003) potentially resulting in widespread extinctions where dispersal capabilities are limited or suitable habitat is unavailable (Thomas et al. 2004). Several marine organisms have already been observed shifting their geographic ranges poleward (Holbrook et al. 1997, Parker and Dixon 1998, Perry et al. 2005, Ling et

al. 2009). Also, climate change may strongly influence distribution and abundance of fishes (Wood and McDonald 1997; Brander et al. 2004; Rijnsdorp et al. 2009) through changes in growth, survival, reproduction, or responses to changes at other trophic levels (Brander et al. 2003; Reid 2003 Munday et al. 2009b). These changes may have positive or negative consequences on the productivity and composition of coastal fisheries and thus the nature and value of commercial fisheries. Allison et al. (2005) showed that the distribution of both exploited and non-exploited North Sea fishes have responded markedly to recent increases in sea temperature, with two thirds of species shifting in mean latitude or depth over 25 years. Further temperature rises are likely to have profound impacts on commercial fisheries through continued shifts in distribution and alteration in community interactions (Allison et al. 2005). There is a lack of information on how Puerto Rico's tropical fish will respond to temperature increases.

The main effect of increasing sea surface temperatures on fish is related to increases in their metabolic processes, and their limitations in meeting the associated higher demands for oxygen (Pörtner and Farrell 2008). Metabolic activity for fish increases in direct proportion to moderate increases in ambient temperature (Houde 1989, Jobling 1997, Clark and Johnston 1999, Hunt Von Herbing 2002). However, with increasing SST, there is a decrease in available dissolved oxygen, at the same time a fish's demand for oxygen is increasing. Consequently, oxygen becomes a limiting factor in cardiovascular performance (Farrell 1997), and thus keeping pace with an increased demand for oxygen at higher temperature is the key physiological mechanism controlling fish thermal tolerance (and determining a fish's response to increasing SST). The sensitivity of the aerobic system to increased SST is unknown for most tropical marine species, however, one study found that sensitivity to increasing temperature differs greatly among five species of coral reef fish (Nilsson et al. 2009), suggesting that adults of some species are highly sensitive to small increases in temperatures, whereas

other species may be quite tolerant to increases even of 2.5° C to 3.0° C.

Temperature changes could also affect the reproductive performance of some reef fish (Gagliano et al. 2007, Donelson et al. 2010) and are likely to lead to shifts in the timing of spawning, and possibly falling egg production, in some populations. Increases in ambient temperature, and corresponding increases in food demands, are also expected to affect the survival of offspring, especially during pelagic dispersive phases. Larval fish grow and develop more rapidly at higher temperatures, meaning that they may experience lower rates of mortality. However, under higher SSTs, entire cohorts of larval fish may not be able to obtain sufficient food to sustain their rapid growth and development, leading to more frequent recruitment failure (Sponaugle et al. 2006, Munday et al. 2009b).

Life history traits of some species covary in a predictable way with their latitudinal ranges and temperature gradients. Although there are many exceptions, reef fish species tend to be shorter-lived and reach smaller maximum sizes in equatorial areas compared with the subtropics (Munday et al. 2008). Juveniles are also expected to reach their asymptotic size at a faster rate at higher temperatures. Consequently, we might expect that as SST increases, life history traits of populations in the subtropics will become more like those exhibited in populations already living at higher temperatures (e.g., shorter lived and smaller maximum sizes). It's important to note, however, that life history traits are also influenced by food supply and population density and structure, which vary at a range of spatial scales, and might themselves be influenced by increased SST. Therefore, projecting how life history traits may change as a result of changes in SST is difficult and as yet not done for the coastal waters and fishes around Puerto Rico.

An independent global analysis has concluded that the redistribution of fisheries species associated with increasing SST and shifts in climate are expected to have significant impacts on fisheries production of tropical countries (Cheung et al.

2010). Geographical shifts in the distribution and abundance of major fisheries species, combined with projected changes in primary production, are expected to cause a decline of up to 30% in fisheries production in the areas around Puerto Rico (although possible increases could exist according to the analysis). These estimates do not take into account habitat requirements that will limit latitudinal shifts of many reef species; only generalist species that are loosely associated with coral and reef habitats are expected to move poleward to escape rising SST in the tropics.

Increasing Carbon Dioxide

Ocean acidification is the second major threat to fishes as it may affect the food web as well as affect metabolic and development systems of individuals. There is convincing evidence to suggest that acidification will affect the process of calcification, by which animals such as corals and mollusks make shells and plates from calcium carbonate. Ongoing ocean acidification will reduce growth and survival of many calcifying organisms and affect the food webs that depend on them (Fabry et al. 2008, Doney et al. 2009) (Kleypas et al. 2006: figure 17).

The tropical and subtropical corals are expected to be among the worst affected, with implications for the stability and longevity of the reefs that they build and the organisms that depend on them. Other calcifying organisms that may be affected are components of the phytoplankton and the zooplankton, and are a major food source for fish and other animals. Regional variations in pH will mean that by 2100 the process of calcification may have become extremely difficult for these groups of organisms particularly in the Southern Ocean. Some studies suggest that growth and reproduction in some calcifying and non-calcifying marine species could be reduced due to the projected

changes in ocean chemistry. With two duplicate six-month manipulative experiments, Shirayama and Thorton (2005) demonstrated that a 200 ppm increase in carbon dioxide adversely affects the growth of both gastropods and sea urchins. Thus, even moderate increases in atmospheric carbon dioxide that could well be reached by the middle of this century will adversely affect shallow water marine benthic organisms.

The reduction in ocean pH could also have a range of direct effects on coastal fish, from increased metabolic demands to developmental problems (Pörtner et al. 2004). For instance, reduced calcification could affect the process by which fish develop otoliths (ear bones) (Munday et al. 2011) as they are composed of aragonite, whereas the rest of the fish skeleton is composed of calcium phosphate. Otoliths

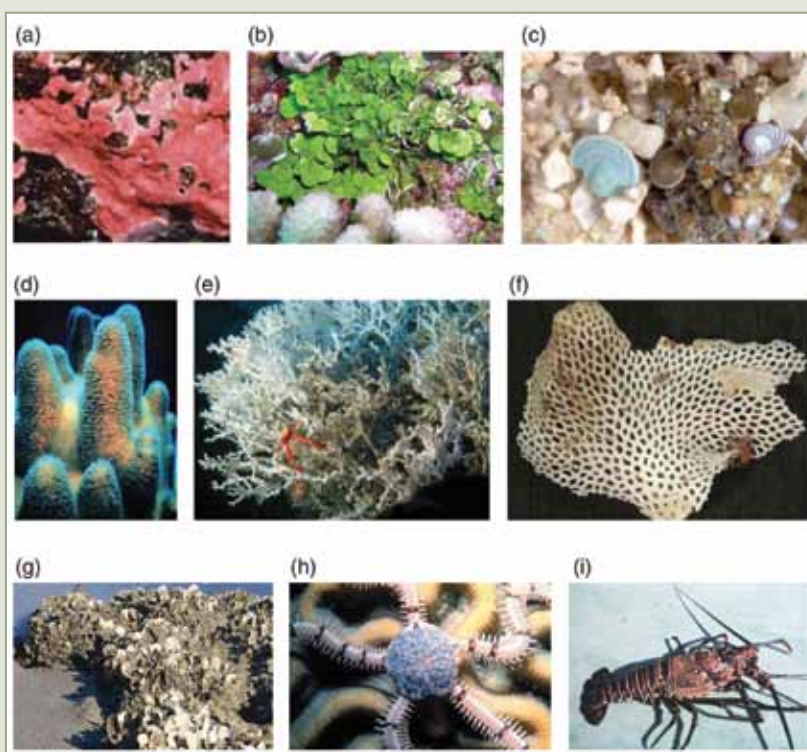


Figure 17 Representatives of major benthic calcifiers: (a) coralline algae (photo by Nancy Sefton; courtesy NOAA/CORIS); (b) *Halimeda* (photo by James Watt; courtesy NOAA/NMFS); (c) benthic foraminifera (courtesy P. Hallock); (d) reef-building coral (*Dendrogyracylindrus*; Cmdr William Harrigan, NOAA Corps; courtesy Florida Keys National Marine Sanctuary); (e) deep-water coral (*Lopheliapertusa*; from 413 m depth off North Carolina. Large red crab is *Eumunidapicta*; urchin below it is *Echinus tyloides*; courtesy S.W. Ross, K. Sulak, and M. Nizinski); (f) bryozoan (courtesy NOAA/Ocean Explorer); (g) mollusk (oyster reef; courtesy South Carolina Department of Natural Resources); (h) echinoderm (brittle star; Larry Zetwoch; Florida

Keys National Marine Sanctuary); (i) crustacean (lobster; Dr. James P. McVey, NOAA Sea Grant Program). The calcification responses of many of these groups have not been investigated. Figure printed with permission from Kleypas et al. 2006.

are important for individual orientation and hearing, especially during the dispersive larval stages. More research is necessary to know whether acidification affects otolith growth or development. Another developmental concern of ocean acidification is the effect that elevated carbon dioxide levels could have on the sensory ability of larvae. Clownfish larvae exposed to waters with reduced pH lose the ability to distinguish olfactory cues from preferred settlement habitat, or to detect and avoid the smell of predators (Dixon et al. 2010), at the end of their larval phase. In other words, their sense of smell is altered by ocean acidification according to studies (Munday et al. 2009a, Dixon et al. 2010). Their sense of smell is what they use for a wide range of important behavior decisions, such as navigation to reefs and selection of settlement sites (Atema et al. 2002, Kingsford et al. 2002, Gerlach et al. 2007). Impairments of this process by ocean acidification could have serious implications for the replenishment of adult populations and patterns of population connectivity in coral reef ecosystems.

From the evidence available, it is not certain whether marine species, communities and ecosystems will be able to adjust or evolve in response to changes in ocean chemistry, or whether ultimately the services that the ocean's ecosystems provide will be affected. Ocean pH has changed very little over the past 800,000 years (Luthi et al. 2008), and so it might be expected that marine organisms lack genetic variation necessary for rapid adaptation to changes in seawater chemistry (Hoegh-Guldberg et al. 2007).

Tropical Storms and Hurricanes

Increasing storm intensity will likely further reduce available fish habitat, e.g. mangroves and seagrasses, which are the main nursery areas for many coastal fishes and invertebrates, as well as coral reefs (Rogers et al. 1982; Gelardes and Vega 1999; Anonymous 2005). The loss of habitat is greater in areas already affected by pollution and unsustainable use of the coastal zone.

Other Climate Change Outcomes for Coastal Fishes

The Caribbean coastal waters periodically experience extensive blooms of algae that impact living resources, local economies and public health. Impacts of harmful algal blooms include human illness and death from ingesting contaminated shellfishes or fish, mass mortalities of wild and farmed fish, and alterations of marine food chains through adverse effects on eggs, young, and adult marine invertebrates (e.g. corals, sponges), sea turtles, seabirds, and mammals. Harmful algal blooms are increasing worldwide in frequency, distribution and impact, with significant threats for the insular Caribbean (Sierra-Beltrán et al. 2004). Recently, blooms have occurred in new coastal areas and new species have appeared (GEOHAB 2001, 2005). Harmful algal blooms are usually associated with upwelling systems, and wind is the main driving force in upwellings. So, variations in the wind regime due to climatic changes could cause short-term variation in upwelling-downwelling cycles (GEOHAB 2005). With temperature increases, mass mortalities due to disease outbreaks are expected, as some have affected major taxa in the oceans. For closely monitored groups like corals and marine mammals, reports of the frequency of epidemics and the number of new diseases have increased recently; this has been discussed in detail in the previous sections. The role of coral community structure and diversity in maintaining productive fish and invertebrate populations is well documented, but links between these aspects and coral diseases are generally unstudied.

Introduction to Pelagic Fish Species

Offshore fish resources are considered to be those caught off the islands shelves. These include small pelagics, mainly sardines, flying fish and ballyhoo, which are also found in coastal waters, some of which are associated with upwellings and highly productive waters more common off continental shelves; medium or large size pelagic predators and migratory fishes (tunas, mackerel, swordfishes, billfishes, sharks and rays); demersal fishes (mainly groupers and snappers); and

bathypelagic fishes inhabiting offshore banks and oceanic cays (fished mainly by Puerto Rico and Hispaniola fishers). Demersal and pelagic species differ in their habitat requirements. Pelagic species remain within the three-dimensional pelagic habitat (figure 18) (although some species, such as herring, require specific demersal habitats for spawning), whereas demersal species display a distinct transition from the three-dimensional pelagic realm of (eggs and) larvae to the two-dimensional habitat of the demersal stages.

The fish resources of deep slopes and banks, which are based on fewer species than those on the island shelves, are in a better situation and in some cases, like in Cuba, they are underexploited. Large offshore pelagic fish resources are generally considered to hold the greatest potential for development in the islands. The (mostly recreational) catch consists of several species

with a wide variety of life histories: tunas, billfishes, dolphin fish, wahoo, king mackerel, and sharks. Most of these species show a marked seasonal availability in the whole region. Dolphin fish are the principal recreational fishing species for private boat anglers in Puerto Rico, and thus have considerable socioeconomic value. Flying fish are also exploited in some of the islands of the Lesser Antilles. The status of offshore pelagic fish resources is highly variable depending on the species. Some of the most important resources (skipjack and other small tuna, and swordfish) are heavily exploited in most areas, but little information is available for stock assessment. The existing information about resource assessment and management of the main fisheries in the Caribbean islands is patchy and much of the information is extrapolated from studies on the same species and types of fisheries elsewhere in the Wider Caribbean.

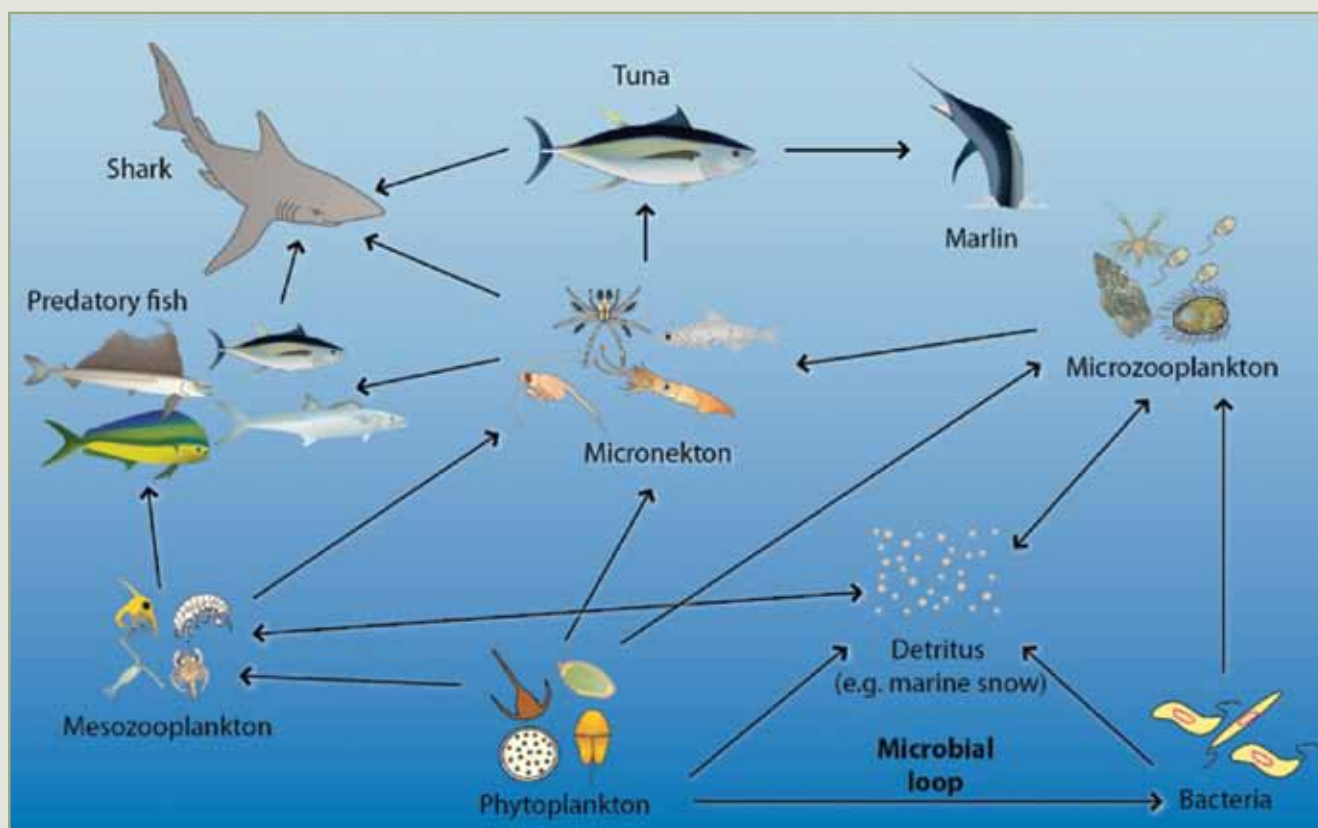


Figure 18 Generalized food web supporting tuna and other large pelagic fish. Note that in the lower levels of the food web, the classical and microbial pathways are linked through formation of 'marine snow' and other detritus. Printed with permissions from Bell JD, Johnson JE and Hobday AJ (eds) (2011) Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Secretariat of the Pacific Community, Noumea, New Caledonia.

Outcomes and Consequences of Climate Change on Pelagic Fishes

Temperature

Perhaps the biggest concern with pelagic fish is plankton abundance, community structure, timing of seasonal abundance, and geographical range (Hays et al. 2005). Plankton consists of microscopic plants (phytoplankton) and animals (zooplankton) that drift in the ocean and form the base of the marine food web. All species of fish feed on plankton during their larval (early) stage and some species continue to depend on plankton into adulthood. Long-term changes in plankton such as those predicted with climate change could have a significant impact on commercial fish stocks (Hays et al. 2005). This could include commercial species like Blue Runner, Wahoo, Yellow Fin Tuna, Dolphin Fish (Mahi Mahi), and Swordfish. Rising sea surface temperatures could also have a significant affect as fish species are very sensitive to slight changes (a few degrees) in ocean temperature and warming could cause migration to new areas or depths (Mimura et al. 2007). The habitat for Dolphin Fish, for example, will become significantly less favourable with just a 1°C (1.8 °F) increase in the average temperature of the Caribbean Sea (Trotz 2009) (figure 17). Pelagic fish distribution can also be impacted by shifts in ocean currents and other oceanographic conditions that help to determine where fish settle out in their larval stages and influence their migration patterns and other dynamics in their adult stages (Johnson and Marshall 2007). While these changes may result in the loss of established fisheries, they may also give rise to new fisheries. See figures 19 and 20 as examples of migration from studies completed by the Caribbean Community Climate Change Centre (5C's).

Temperature changes in the ocean could also create more favorable conditions for the establishment of invasive species as natural ecosystem processes are disrupted (IUCN n.d.). Invasive species tend to out-compete or prey on native species. Although not attributable to climate change, the recent invasion of Lionfish (*Pterois volitans*) in the Caribbean Sea and the effects this has already

had on fisheries in the Turks and Caicos Islands demonstrates the damage that just one marine invasive species can do (Schofield 2009). Some positive effects on pelagic fishes may occur; for example, warmer waters may increase fish larval growth rate and swimming ability while decreasing the age of metamorphosis; all of which could improve the survival of larval fish (Johnson and Marshall 2007).

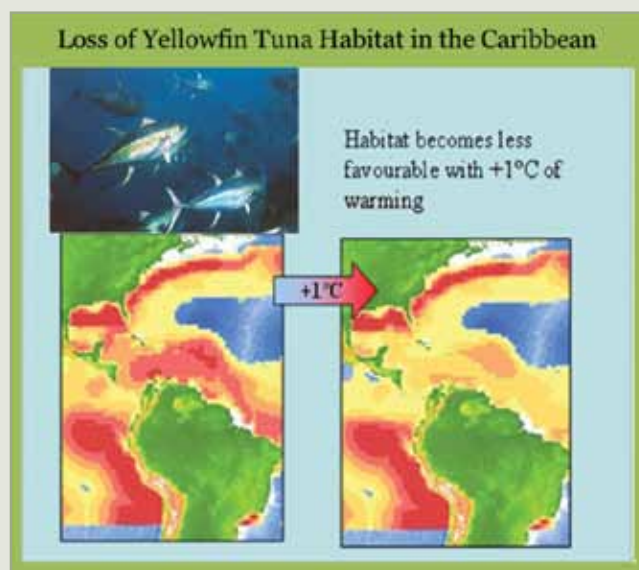


Figure 20: Loss of Dolphin Fish habitat in the Caribbean due to +1°C of warming, courtesy of the Caribbean Community Climate Change Center

Ocean Acidification

The physiological responses to ocean acidification are the same for pelagic fish and coastal fish. However, the ecosystem-level effects of ocean acidification will more greatly affect the coastal ecosystems that support coastal fishes than that of the open ocean. Ocean acidification is expected to reduce the shells of calcareous phytoplankton and zooplankton, making them more fragile and therefore vulnerable to predation. Changes in the complexity of the food web may result as some of these organisms disappear. In order to accurately assess the affect ocean acidification may have on the plankton of Puerto Rico's waters, the percentage of calcareous plankton versus non-calcareous plankton in Atlantic Ocean and Caribbean Sea waters would need to be known. The PRCCC WG 2 was unable to find a reliable source with this information.

Loss of Dolphin Fish Habitat in the Caribbean

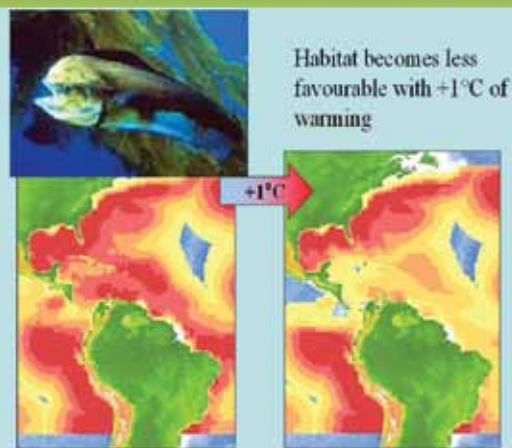


Figure 20: Loss of Dolphin Fish habitat in the Caribbean due to +1°C of warming, courtesy of the Caribbean Community Climate Change Center

Research Gaps and Information Needs

1. More research is needed to test the effect of elevated CO₂ on the early life stages of coastal fish across a broader range of species, and to examine possible synergistic effects of elevated temperature and CO₂.
2. Despite increasing concerns about designing and implementing an integrated approach in coastal conservation and management, the ecological relationships (*i.e.* habitat connectivity) between mangroves, seagrass and coral reefs have received relatively little attention. Fundamental ecological research on the habitat connectivity is urgently needed for the development of sound coastal conservation and management (Aguilar-Perera 2004).
3. Nearshore habitat responses: Additional research is needed on the response of mangroves, seagrasses and coral reefs to climate change stressors, including rising sea levels, increased SST and beach erosion.
4. Fish and invertebrate responses: Relatively little research has been carried out on the physiological and ecological response of tropical fish and invertebrates to climate change stressors such as effects on species distributions, migratory patterns, otolith

development, spawning periods, recruitment success, etc.

5. Estuarine responses: Changes in weather patterns which affect rainfall total amounts and intensity will result in changes in salinity in estuarine nursery areas for fish and invertebrates. Research is needed to understand the effect of this on commercially and recreationally important fish and invertebrate species as well as non-target species.
6. Information on composition of planktonic communities surrounding Puerto Rico and the percentage of calcareous plankton versus non-calcareous plankton.

Summary of the Outcomes and Consequences of Climate Change on Coastal and Pelagic Fishes

Climate-driven changes in fish populations may result from four, often interlinked, mechanisms: (i) a physiological response to changes in environmental parameters, such as temperature, (ii) a behavioral response, such as avoiding unfavorable conditions and moving into new suitable areas, (iii) population dynamics, through changes in the balance between rates of mortality, growth and reproduction in combination with dispersal which could result in the establishment of new populations in new areas or abandonment of traditional sites, (iv) ecosystem-level changes in productivity and/or trophic interactions. In addition, (v) commercial exploitation greatly affects the abundance and distribution of fish and may interact with the effects of climate change.

This section is specific to coastal finfishes (nearshore demersal or bottom-dwelling and nearshore pelagic fishes) and pelagic or offshore oceanic finfishes are assessed independently. This assessment does not include sharks or rays. The effects of climate change on sharks and rays are generally unknown but assumed to be similar to

those for finfish occupying equivalent habitat types. For example, reef sharks, such as Puerto Rico's Nurse Sharks (Gatas; *Ginglymostomacirratum*), Caribbean Reef Sharks (Tiburón coralino; *Carcharhinus perezii*), Caribbean Sharpnose Sharks (Cazon Playon; *Rhizoprionodon porosus*); Tiger Sharks (Tintorera; *Galeocerdocuvier*) and Whitetip Reef Sharks (Tiburón oceanic; *C. longimanus*), are highly dependent on coral reefs and are likely to be affected negatively by extensive habitat degradation. Similarly, this assessment does not include invertebrates, which are commercially important in Puerto Rico, and should be included in future assessments.

Coastal fish resources in Puerto Rico are linked with mangrove, seagrass beds and coral reef habitats. These three coastal habitats are ecologically connected to each other and the marine species that depend on healthy habitat connectivity include lobsters, crabs, shrimps, queen conch, a great variety of estuarine and reef fishes, coastal pelagics (clupeids, carangids) and fishes inhabiting the shelf slope (mainly deep-water snappers and groupers). The previously described outcomes and consequences of climate change on mangroves, coral reefs, and seagrass beds directly apply to coastal fish species as these habitats provide them with shelter and food. Coastal fishes (and some species of pelagic fishes) are especially reliant on nursery habitat. The most important direct effects on coastal fishes are likely to be due to the projected increases in sea surface temperature and ocean acidification and changes in ocean currents.

Additional environmental changes and severe climatic events, such as increased severity of tropical cyclones, more extreme rainfall events or drought conditions, and sea level rise could have further direct and indirect effects for some species and life stages. The direct and indirect effects of climate change on coastal fish will vary

depending on their biology and ecology. For example, recent effects of climate-induced coral loss on reef fish vary depending on their reliance on live corals for food, shelter and/or recruitment. Butterflyfish, certain species of damselfish, cardinalfish, and coral-dwelling gobies have the greatest dependence on live coral and are directly at risk from loss of corals. Other fish may also be particularly susceptible to climate change owing to their sensitivity to changes in temperature or ocean chemistry. The potential impact of projected changes on species is moderated by the species ability to alter its physiology, behaviour and/or distribution to cope with changes. Species with a high sensitivity to changes in environmental conditions and habitats, which are unable to adapt, are most vulnerable and potentially at risk of local extinction due to climate change. Examples of ways fish species can adapt include switching to a different prey species, living in slightly different habitats, and evolving increased tolerances. A species-by-species assessment for Puerto Rico is not within the scope of this report, but could be considered necessary for marine conservation and fisheries management.

Offshore fish resources are considered to be those caught off the islands shelves. These include small pelagics, mainly sardines, flying fish, and ballyhoo, which are also found in coastal waters, some of which are associated with upwellings and highly productive waters more common off continental shelves; medium or large size pelagic predators and migratory fishes (tunas, mackerel, swordfishes, billfishes, sharks, and rays); demersal fishes (mainly groupers and snappers); and bathypelagic fishes inhabiting offshore banks and oceanic cays. Perhaps the biggest concern with pelagic fish is plankton abundance, community structure, timing of seasonal abundance, and geographical range. Long-term changes in plankton such as those predicted with climate change could have a significant impact on commercial fish stocks.

This could include commercial species like Blue Runner, Wahoo, Yellow Fin Tuna, Dolphin Fish (Dorado), and Swordfish. Rising sea surface temperatures could also have a significant effect as fish species are very sensitive to slight changes (a few degrees) in ocean temperature and warming could cause migration to new areas or depths. The habitat for Dolphin Fish, for example, will become significantly less favourable with just a 1°C (1.8 °F) increase in the average temperature of the Caribbean Sea. Pelagic fish distribution can also be impacted by shifts in ocean currents and other oceanographic conditions that help to determine where fish settle out in their larval stages and influence their migration patterns and other dynamics in their adult stages. While these changes may result in the loss of established fisheries, they may also give rise to new fisheries. The physiological responses to ocean acidification are the same for pelagic fish and coastal fish. However, the ecosystem-level effects of ocean acidification will more greatly affect the coastal ecosystems that support coastal fishes than that of the open ocean. Ocean acidification is expected to reduce the shells of calcareous phytoplankton and zooplankton, making them more fragile and therefore vulnerable to predation. Changes in the complexity of the food web may result as some of these organisms disappear. In order to accurately assess the affect ocean acidification may have on the plankton of Puerto Rico's waters, the percentage of calcareous plankton versus non-calcareous plankton in Atlantic Ocean and Caribbean Sea waters would need to be known.

BIOLUMINESCENT BAYS

Introduction to Bioluminescent Bays

Bioluminescent Bays are rare worldwide ecosystems that have intrigued researchers and the community in general due to the display of light. In the world, there are five widely recognized bioluminescent systems and three of them are

in Puerto Rico: Bahía Fosforescente in Lajas, Laguna Grande in Fajardo, and Puerto Mosquito in Vieques. There are also other systems in Puerto Rico where some bioluminescence has been observed (e.g. Monsio José, Lajas; Laguna Joyuda, Cabo Rojo; Bahía de San Juan, San Juan).

Bioluminescence refers to the emission of light by living organisms and is caused by a photochemical reaction involving the oxidation of a protein (i.e. luciferin) in the presence of an enzyme (i.e. luciferase) (Hastings 1983). During this reaction, energy is liberated resulting in the liberation of light. However, to make these systems “glow” the water needs to be mechanically stimulated.

In Puerto Rico the bioluminescence displayed is due to high concentrations of the bioluminescent dinoflagellate *Pyrodinium bahamense* var. *bahamense* (Margalef, 1957; figure 21). However, other bioluminescent dinoflagellates, such as *Ceratium fusus* and *Protoperidinium divergens*, have been also observed (Glynn et al. 1964, Gold 1965). Hernández-Becerril (1995) studied the thecate dinoflagellates present at Bahía Fosforescente and observed the coexistence of *P. bahamense* with others species like *Ceratium furca* var. *hircus*, *Dinophysis caudata* var. *ventricosa*, *Gonyaulax* spp., *Prorocentrum* spp. and *Protoperidinium* spp., among others. Also, high densities of *Cochlodinium polykrikoides* have been observed in the northwest channel of Bahía Fosforescente (Margalef 1961, Burkholder et al. 1967, Cintrón 1969, Cintrón et al. 1970, Seliger et al. 1971, Seixas 1983, 1988, Cedeño-Maldonado 2008). Among these species, *P. bahamense* and *C. furca* have been the most abundant dinoflagellate species in this bay.

Some attempts have been made to understand the dinoflagellate population dynamics in these systems and the mechanisms that sustain their high cell densities. Water circulation patterns and

physiographic conditions have been proposed as important factors in determining the high abundances of species (Margalef and Gonzalez 1958, Coker and González 1960, Margalef 1961, Smayda 1970, Seixas, 1988). It is suggested, in the case of Bahía Fosforescente, that less dense offshore surface water enters the bay driven by the prevailing winds of the region, while denser water exits close to the bottom as a consequence of high evaporation rates (Margalef 1961). The combination of the above current pattern and the shallow and narrow entrance of these types of bays, the absence of riverine discharges, and the

small tidal range make the water mixing rates with the exterior low; conditions considered necessary to maintain high concentrations of dinoflagellates within the bay. This agrees with reports that have found that increased levels of nutrients and vitamin B₁₂ are important factors that trigger dinoflagellate blooms in Bahía Fosforescente (Burkholder and Burkholder 1958, San Juan and González 2000). Furthermore, the diel distribution patterns driven by phototactic responses of these motile organisms may also contribute to their accumulation in the bays (Seliger et al. 1971).

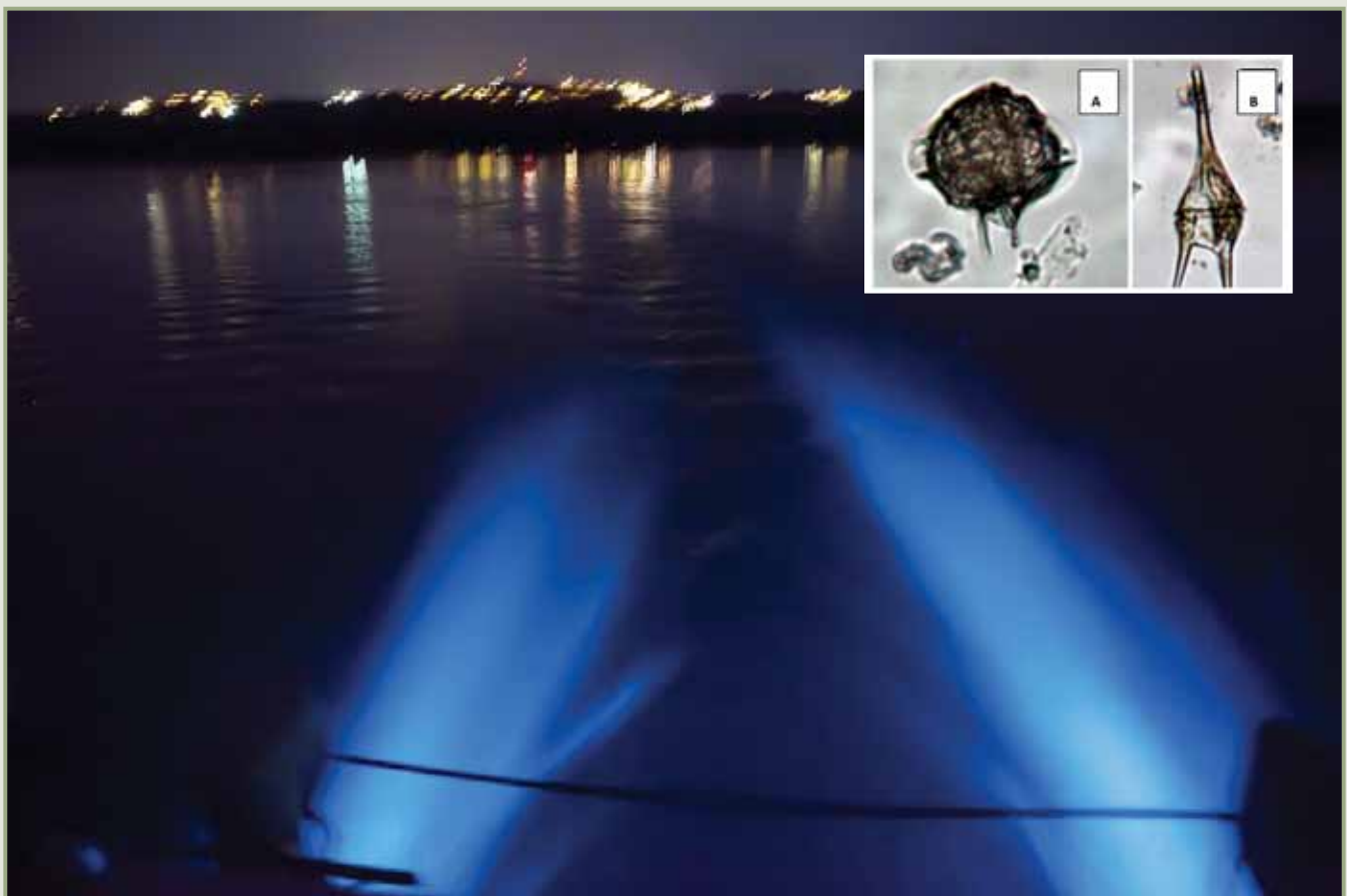


Figure 21 a) *Pyrodinium bahamense* b) *Ceratium furca*. Scale bar = 20µm.

STATUS OF BIOLUMINESCENT BAYS

In recent years, scientists, federal, state and private organizations, and the general public have expressed concerns in relation to the apparent decrease in bioluminescence at Bahía Fosforescente in Lajas. This decline and the associated reduction of *P. bahamense* abundance are accompanied by high densities of a non-bioluminescent dinoflagellate, *Ceratium furca* var. *hircus* (Walker 1997, Seixas 1988, Soler-Figueroa 2006)(Figure 21b and 22a). In contrast, at Puerto Mosquito in Vieques, *P. bahamense* is the predominant dinoflagellate throughout the year (Walker 1997; Soler-Figueroa 2006) with more than 100,000 cells L⁻¹ (Soler-Figueroa 2006; figure 22b).

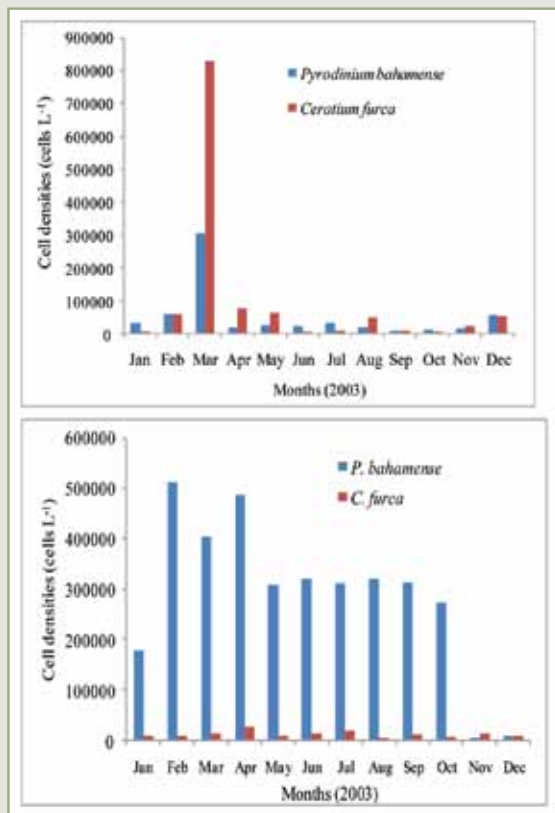


Figure 22 *Pyrodinium bahamense* and *Ceratium furca* cell densities at a) Bahía Fosforescente in La Parguera, Puerto Rico and b) Puerto Mosquito in Vieques, Puerto Rico (Source: Soler-Figueroa, 2006).

The apparent shift in dinoflagellate species dominance observed in Bahía Fosforescente could be considered an indicator of change in coastal ecosystem triggered by natural and/or anthropogenic causes. Increases in boat traffic

and associated pollution, changes in watershed management trends, and changes in nutrient regimes have been cited as potential stressors (Smart et al. 1985). However, research that focuses on the mechanisms at work is needed in order to understand the dynamics of dinoflagellate populations in relation to their fluctuating environment.

The lack of short-term time scale monitoring studies has been one of the major barriers in deciphering what mechanisms drive the fluctuations of phytoplankton species and bioluminescence, as most are monthly sampling efforts (Seixas 1988; Walker 1997; Soler-Figueroa 2006). In addition, most of the studies have been focused on the study of a few phytoplankton species (mainly *P. bahamense* and *C. furca*), and very limited information is available on the phytoplankton community structure and other co-occurring species. Considering that short term changes in the environment modulate the generation times of phytoplankton species within time scales of days to weeks (Smetacek and Cloern 2008), approaches that increase the resolution of phytoplankton sampling, assessment of taxonomic composition, and monitoring of water quality are expected to yield vital information to develop a robust link between potential environmental change, whereas natural or anthropogenic, and the response of the planktonic community in this unique and economically important coastal system.

Potential outcomes and consequences of climate change on Bioluminescent Bays

The dinoflagellates in bioluminescent systems are part of the phytoplankton community. Phytoplankton organisms are one of the main primary producers, providing half of the primary production in the ocean (Falkowski et al. 1998), and represent the base of the trophic food webs mediating the transfer of energy to higher trophic levels. Therefore, any changes in their abundances and distribution, will lead to changes in the trophic interactions of the ecosystem (Stenseth and Myrsetrud 2002, Winder and

Schindler 2004). Also, phytoplankton organisms play a key role in regulating atmospheric carbon dioxide concentrations (CO₂) and are important components of the biogeochemical cycles.

Due to their small size, specific growth requirements, rapid nutrient uptake and growth rates, and vulnerability to grazing, phytoplankton are susceptible to environmental variability (Reynolds 1984). These organisms have been considered a sensitive index of speed and severity of global climate change (Widdicombe et al. 2010) and it has been proposed that their year-to-year variability is a response of disturbances from anthropogenic activity or shifts in the climate system (Cloern and Jassby 2010).

However difficult it may be to determining the impacts of global climate change on phytoplankton organisms, it should be a first priority. The responses of these organisms to changes in the environment can be observed as shifts in their physiological condition, reproduction and mortality, and community species composition (Miranda-Azeiteiro and Marques 2003). Therefore, the expected climate changes such as increases in temperature, enhanced surface stratification, alteration of ocean currents, stimulation of photosynthesis by elevated CO₂, increased heavy precipitation and storm events causing changes in land runoff and micronutrient availability may all produce intertwined responses at the individual, population, and community levels (Hallegraeff et al. 2009). In general, the discrimination of anthropogenic and climate impacts and their interacting effects has been difficult or uncertain. Nevertheless, changes in phytoplankton primary production and composition due to changes in climatic forces such as hurricanes and rainfall (Paerl 1995, Pearl et al. 2006, Adolf et al. 2006) have been reported.

The determination/predictions of the impacts of global climate change on bioluminescent systems and their phytoplankton community is complex. Not only there are few studies related to the phytoplankton community dynamics in these ecosystems, but also there is a lack of consistent long-term monitoring studies that would be

essential to evaluate changes due to global climate trends (Hays et al. 2005, Moore et al. 2008, Marić et al. in press).

When considering the origin of bioluminescent bays, it is important to keep in mind that these systems resulted from the interaction of factors, such as, climatology, physiography, hydrology, geology, chemistry, and finally biology over periods of decades to hundreds of years, if not millennia. Any alteration of the above due to anthropogenic causes or climate changes, may trigger ecosystem shifts that may cause unexpected or even irreversible effects (Interior 1986).

Changes in Precipitation and Storms

The main potential stressors to bioluminescent systems due to climate changes are the increases in heavy precipitation, storms, and hurricanes. The expectation of increases in heavy precipitation and storms, leading to increases in runoff from land to these systems could trigger increments in sediment and nutrient loadings affecting water quality due to changes in the sedimentation (turbidity), productivity, and frequency and extension of salinity shifts. In the case of Bahía Fosforescente, this problem might be compounded due to the decreased vegetation cover in the adjacent watershed (Gilbes-Santaella 2003; unpublished data).

One of the principal determinants of phytoplankton species composition in an ecosystem is the nutrient pool – including ratio, concentration, and forms of available nutrients. It can be anticipated that nutrient alterations in the bioluminescent systems due to hurricanes, precipitation, and terrestrial runoff will have a significant effect by altering its phytoplankton community diversity and composition (Smayda 1997, Buyukates and Roelke 2005, Spatharis et al. 2007). However, the predictions of changes in community composition are complex since the rate of nutrient assimilation by phytoplankton species is controlled by their nutritional preferences, uptake capabilities, and physiological or nutritional status (Anderson et al. 2002), and also depend on other climate related environmental factors, such as light and temperature.

A possible scenario for bioluminescent bays is that the high nutrient loading due to land runoff will lead to increases in diatom groups. Margalef (1978) states that the main phytoplankton life-forms can be sequence ranging from organisms dominating in turbulent, fertile environments (i.e. diatoms) to those found in stratified, nutrient-poor waters (typically dinoflagellates). Also, it has been reported, from microcosms experiments, that the

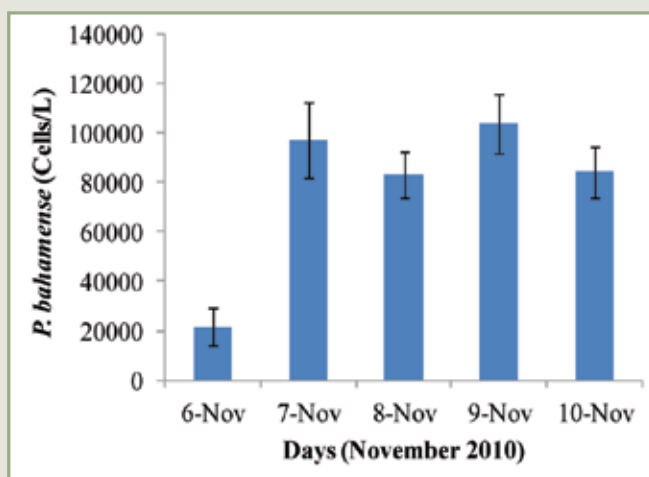
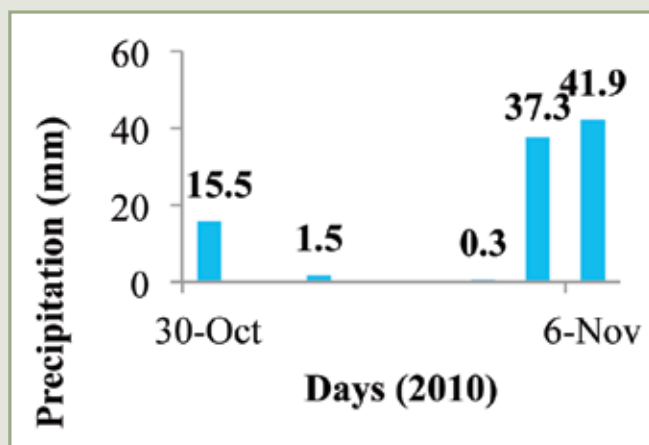


Figure 23 (top) *Pyrodinium bahamense* cell densities during five days on November, 2010. (bottom) Precipitation patterns six days previous the sampling schedule and two hours before the onset of the first sampling day.



growth of marine diatoms has been correlated with large and frequent additions of nitrate (Lomas and Glibert 2000) and high nutrient concentrations (Carter et al. 2005). However, others have concluded that blooms of dinoflagellates occur when humic substances and other nutritional factors enter coastal waters after heavy rainfall (Prakash and Rashid 1968). A scenario similar to

this was recently observed at Bahía Fosforescente when high cell densities of *Pyrodinium bahamense* were observed one day after 97 mm of cumulative precipitation (Soler-Figueroa and Otero 2011; figure 23). Studies based on field observation and micro- and mesocosms experiments are needed to evaluate the links between weather patterns and the abundance, growth, and phytoplankton community composition in bioluminescent bays.

Increased Temperature

Phytoplankton organisms can also be affected due to the warmer temperatures expected from global climate change. Temperature is considered one of the most important physical factors that affect the growth of phytoplankton species by regulating the metabolic processes of these organisms (Morris 1981). It has been proposed and observed that as temperature of the oceans gets warmer, small cell size phytoplankton dominate the community (Daufresne et al. 2009, Moran et al. 2010). However, others have reported that dinoflagellate populations (Lassen et al. 2010) and diatoms (Lionard et al. 2012) will be favored with increases in temperature. Moreover, all these studies have been conducted in the open ocean, and different results can be observed in coastal ecosystems such as bioluminescent bays.

Laboratory experiments are necessary in order to evaluate the impacts of increases in temperature over the phytoplankton community in bioluminescent systems. These experiments are essential to model distinct changes in ecophysiology of phytoplankton species (i.e. *Pyrodinium bahamense*) as conditions change. Growth rates and temperature tolerance under different temperature regimes are species-specific. Therefore, different responses are expected to occur based on the different capabilities of phytoplankters to genetically adapt to a warmer ocean (Huertas et al. 2011).

Research and information needs

Much research is urgently needed in order to understand the impacts of global climate change on

the phytoplankton composition of bioluminescent systems in Puerto Rico, with special emphasis on *Pyrodinium bahamense*. Among the studies needed are:

1. Short-term studies in order to evaluate the response of phytoplankton organisms to different environmental and meteorological conditions. This type of study have been recently proposed to a limited extent (Puerto Rico Sea Grant, Project number: R-I 01-1-J2). Sites other than the Phosphorescent Bay, La Parguera should also be studied to expand knowledge related to geographical difference among sites.
2. Long-term monitoring programs that document the phytoplankton community composition as well as the water quality of these systems. These studies are important in order to relate ecosystem alterations the due to climate change, bioluminescence and phytoplankton community shifts.
3. Controlled experimental studies to evaluate the effects of increasing nutrient concentrations on the phytoplankton community composition. Other highly-valuable experiment-based studies would also focus on the effects of increases in sedimentation and turbulence on the phytoplankton composition of bioluminescent systems.
4. Experiments based on cultures are basic in order to assess the impacts of different temperatures, salinities, and nutrient concentrations to the growth rates and physiology of *Pyrodinium bahamense*. Also, the effects of pH and CO₂ should be evaluated.
5. Modeling efforts based on species and population interaction with the environment could serve as the basis for experimental verification of the status of bioluminescent bays. Either empirical or mechanistic models should integrate weather variables, chemical, physical, and biological cues.
6. Finally, efforts that integrate research and collaboration among different disciplines and agencies will be crucial in order to

protect, conserve and manage these unique ecosystems.

Summary of Climate Change Impacts on Bioluminescent Bays

Bioluminescent Bays are rare worldwide ecosystems. Their displays of light have intrigued people for thousands of years. In the world there are five widely recognized bioluminescent systems and three of them are in Puerto Rico: Bahía Fosforescente in Lajas, Laguna Grande in Fajardo, and Puerto Mosquito in Vieques. There are also other systems in Puerto Rico where some bioluminescence has been observed (e.g. Monsio José, Lajas; Laguna Joyuda, Cabo Rojo; Bahía de San Juan, San Juan). In Puerto Rico, the bioluminescence displayed is due to high concentrations of the bioluminescent dinoflagellate *Pyrodinium bahamense* var. *bahamense*. However, other bioluminescent dinoflagellates, such as *Ceratium fusus* and *Protoperidinium divergens*, have been also observed. In recent years, scientists, federal, state and private organizations, and the general public have expressed concerns in relation to the apparent decrease in bioluminescence at Bahía Fosforescente in Lajas. This decline and the associated reduction of *P. bahamense* abundance are accompanied by high densities of a non-bioluminescent dinoflagellate, *Ceratium furca* var. *hircus*. The apparent shift in dinoflagellate species dominance observed in Bahía Fosforescente could be considered an indicator of change of coastal ecosystem triggered by natural and/or anthropogenic causes. Increases in boat traffic and associated pollution, changes in watershed management trends, and in nutrient regimes have been cited as potential stressors. However, research that focuses on the mechanisms at work is needed in order to understand the dynamics of dinoflagellate populations in relation to their fluctuating environment. The dinoflagellates in bioluminescent systems are part of the phytoplankton community. Phytoplanktonic organisms are some of the main primary producers, providing half of the primary production in the ocean, and represent the base of the trophic food webs mediating the transfer of energy to higher trophic levels (grazers of

phytoplankton). Therefore, any changes in their abundances and distribution, will lead to changes in the food web of the bio bays. Due to their small size, specific growth requirements, rapid nutrient uptake and growth rates, and vulnerability to grazing, phytoplankton are susceptible to environmental variability. The responses of these organisms to changes in the environment can be observed as shifts in their physiological condition, reproduction and mortality, and community species composition. Therefore, the expected climate changes such as increases in temperature, enhanced surface stratification, alteration of ocean currents, stimulation of photosynthesis by elevated CO₂, increased heavy precipitation and storm events causing changes in terrestrial runoff and micronutrient availability may all produce intertwined responses at the individual, population, and community levels.

Predicting the effects of global climate change on bioluminescent systems and their phytoplankton community is complex. Not only are there few studies related to phytoplankton community dynamics in these ecosystems, but also there is a lack of consistent long-term monitoring studies that would be essential to evaluate changes due to global climate trends. However, when considering the origin of bioluminescent bays, it is important to keep in mind that these systems resulted from the interaction of factors, such as, climatology, physiography, hydrology, geology, chemistry, and finally biology over periods of decades to hundreds of years, if not millennia. Any alteration of the above, due to anthropogenic causes or climate changes, may trigger ecosystem shifts that may cause unexpected or even irreversible effects.

The main potential stressors to bioluminescent systems due to climate changes are the increases in heavy precipitation, storms, and hurricanes. The expectation of increases in heavy precipitation and storms, lead to increases in runoff to these systems that can trigger increases in sediment and nutrient loadings affecting water quality due to changes in sedimentation (turbidity), productivity, and frequency and extension of salinity shifts. In

the case of Bahía Fosforescente, this problem might be compounded due to the decreased vegetation cover in the adjacent watershed. A possible scenario for bioluminescent bays is that the high nutrient loading from terrestrial runoff will lead to increases in diatom groups and possible decreases in bioluminescence. Much research is urgently needed in order to understand the impacts of global climate change on the phytoplankton composition of bioluminescent systems in Puerto Rico, with special emphasis on *Pyrodinium bahamense*.

MARINE MAMMALS

Introduction

The marine mammal fauna of the Wider Caribbean Region (WCR) is diverse, and marine mammals have significant ecological, aesthetic, and economic value to the countries and territories of the region. Regional success in managing and conserving marine mammals will ultimately depend on the countries' commitments to building capacity in order to implement a regional model by establishing conservation priorities, standards, and strategies for marine mammal conservation and education.

At least 32 species of marine mammals have been documented from the region—six species of baleen whales (Mysticeti), 24 species of toothed whales (Odontoceti), one sirenian (the West Indian manatee), and three pinnipeds (the Caribbean monk seal, the hooded seal, and the California sea lion). For many of these species, waters of the region serve as primary habitat for critical activities that include feeding, mating and calving. Although some species have been studied extensively elsewhere, data are scarce concerning the biology, life history, distribution and behavior of most cetacean (whale and dolphin) and manatee populations in the Caribbean Sea and Gulf of Mexico. The WCR is the one of only two regions in the world to have experienced the extinction of a marine mammal species (the Caribbean monk seal) in the past 250 years.

Regional marine mammals stressors

Fisheries Interactions

Marine mammals interact with active or abandoned fishing gear that could result in fatalities or accidents. This is something reported for all the Caribbean (Creswell, 2002; Romero et al., 2002). In some islands, like Barbados, when the incidental entanglement occurs the animal is not returned to the sea, but consumed or sold (Creswell, 2002). In Puerto Rico fisheries interactions with marine mammals have been reported for a variety of fishing gear. Humpback whales have been reported entangled with fish trap lines. Dolphin fatalities have been reported from gill net entanglement. Manatees have been caught accidentally on beach seine nets and fatalities have been reported due to infections caused by the abrasion and injuries of monofilament line entanglement for the extremities.

Pollution and Marine Mammals Health

Although evidence for links between chemical pollutants and the health of exposed marine mammals remains largely circumstantial, there is a growing concern that exposure to contaminants can increase susceptibility to disease and affect reproductive performance in marine mammals.

Hunting

Whaling has been an activity occurring in the Caribbean since the 1700's. In some areas it has developed artisanally and in others as an industry. The end of the Barbadian whale fishery is similar to that of Grenada's, Trinidad's, and Bequia's (Creswell 2002; Romero et al. 2002). Although the whaling industry at each place developed under different influences, used different equipment and methods, and operated in a different time period, each one was ultimately shut down due to overexploited whale populations (Creswell 2002; Romero et al. 2002). At present Barbados is under pressure to join the International Whaling Commission in order to promote commercial

whaling (Creswell 2002). Puerto Rico has never engaged in whaling activity.

Manatees throughout the Caribbean have been greatly impacted by hunting activities. Trinidad and Tobago are the only islands of the Lesser Antilles where manatees are still observed (Romero et al. 2002). They are locally extinct in Grenada and Guadeloupe. In many countries of Central America the populations has declined drastically. In Puerto Rico, hunting of manatees occurred until the mid-1990's.

Vessel Strikes

Marine mammals in the WCR are all susceptible to potential vessel strikes that could be fatal or leave the animal injured. Cruises, sailboats, motor boats and jet skis have been identified as causing these incidents. Puerto Rico has a report of a humpback whale injured by sailboat strike. Puerto Rico's manatees have been sighted with scars from boat propellers. Fatalities have been reported for manatees due to motor boat and jetski strikes.

Habitat Degradation

Although no study has documented the impacts of habitat degradation on marine mammals, it is logical to assume that there is a direct impact on a variety of species. In the case of manatees, which are coastal, the effects are more evident. Sedimentation, caused by a variety of activities, smothers seagrasses, their main food source. Manatees also seek calm areas for resting grounds, particularly used for calving. As these areas are developed the properties of a resting ground are lost.

Noise Pollution

Marine mammals are susceptible to noise pollution; beaked whales in particular. Military activities using naval sonar have been associated to mass mortalities of these whales. There is a report of one of these incidents for Puerto Rico. Manatees are also affected by noise pollution. The noise generated by boats, chains and dredging activities provoke manatees to leave preferred or secure habitat areas.

Status of Caribbean Marine Mammals

The following is an excerpt taken from Reeves (2005) which provides a summary status of marine mammals in the Caribbean region by major groups:

Pinnipeds

Although the West Indian monk seal (*Monachus tropicalis*) is considered to be extinct, there is evidence that hooded seals (*Cystophora cristata*) occasionally wander from their Subarctic and Arctic range to occur as vagrants in the Wider Caribbean Region.

Baleen Whales

It appears, on present evidence that only the Bryde's whale depends on the WCR for food resources. It is still unknown if they migrate seasonally into and out of the region. Two other species are considered seasonal migrants, the humpback whale (*Megaptera novaeangliae*) and the minke whale (*B. acutorostrata*). They come during the winter for breeding, although there is still uncertainty if this is true for the minke. The other balaenopterids that have been recorded – blue, fin, and sei (*B. musculus*, *B. physalus*, and *B. borealis*) – are probably “just visiting,” but the possibility cannot be ruled out that their visitations are more regular and frequent in unstudied or poorly studied parts of the region, or that the WCR is a significant portion of the normal range of one or more populations of these species. Similarly, the rare reports of North Atlantic right whales seem to suggest that they are, in some sense, “extralimital.” However, in view of recent occurrences of right whales in the region, this conclusion deserves careful reconsideration.

Toothed Cetaceans

In terms of science and conservation, research on two species or species groups of cetaceans in the Wider Caribbean Region has particular prominence globally: the sperm whale (*Physeter macrocephalus*) and the beaked whales

(Ziphiidae). Ongoing studies of sperm whales around Dominica by Hal Whitehead and his students from Dalhousie University promise to add important insights on the species' social structure and behavior, particularly when used in comparative analyses with their results from the eastern Pacific. Of more immediate applied importance is the diverse program of research on sperm whales in the northern Gulf of Mexico that includes satellite telemetry, photo-identification, monitoring of dive behavior and physiology, and controlled-exposure experimentation to assess the effects of underwater sound (e.g., Miller et al. 2004a, 2004b; Thode et al. 2002). This work's significance derives from global concern about the effects of acoustic disturbance on sperm (and other) whales, especially that from offshore oil and gas development.

Long-term studies of beaked whales have been undertaken in just two areas of the world. The Gulf off Nova Scotia, Canada (northern bottlenose whale, *Hyperoodon ampullatus*), and the Bahamas (Blainville's beaked whale, *Mesoplodon densirostris*). In the latter area, the work of Claridge and Balcomb (2001) was key in documenting the vulnerability of beaked whales exposed to military sonar under particular circumstances. Given the general rarity of opportunities for observational studies of beaked whales, and the high profile of the controversy surrounding the effects of high-intensity underwater sound on this group of whales, it is important that research effort in the Bahamas be maintained and, if possible, expanded.

Another point worth highlighting, as noted by Ward et al. (2001), concerns the habitat requirements of beaked whales. Contrary to the usual descriptions of various species' distributions as “cosmopolitan” or “worldwide” in deep offshore waters, it appears that their distributions are considerably more specialized and thus limited. The Bahamas studies provided the first good evidence of this for the mesoplodonts. Blainville's beaked whales generally occur only in depths between 200–1,000 m and near areas with particular bottom

topography. It should be noted in this context that similar analyses of habitat preferences of other odontocetes have been conducted in the northern Gulf of Mexico (e.g., Baumgartner et al. 2001). Thus, the Wider Caribbean Region has become a focal region of research on several species, including the beaked whales, the sperm whale, and several tropical to warm temperate delphinids.

A 2004 workshop (Reeves et al. 2004) ranked taxonomic uncertainty as high for killer whales (*Orcinus* sp.) and called for a global inventory of specimen material for that genus. It seems clear from the records summarized by Ward et al. (2001) that at least some of the killer whales in the WCR are mammal and sea turtle predators, but in the absence of rigorous analyses of morphological, dietary, and other types of data from the region, it remains impossible to judge whether more than one ecotype (and thus possibly eventually subspecies or species) is present. A regional inventory of sighting, stranding, and take records, perhaps followed by a directed effort to obtain and analyze biological materials from killer whales in specific parts of the Wider Caribbean Region (via biopsy), could be a significant contribution to ongoing global analyses. The same can be said of Blainville's beaked whales and Cuvier's beaked whales (*Ziphius cavirostris*), both of which the workshop described as "warranting special attention to resolve taxonomic uncertainty". Their vulnerability to underwater noise as well as entanglement in drift gillnets was noted, as was the fact that Dalebout (2002) found strong evidence of population structure in Cuvier's beaked whale, suggesting that there could be isolated regional populations. The apparently widespread and regular occurrence in the Wider Caribbean Region makes Cuvier's beaked whale a candidate for focused effort along the same lines as mentioned above for killer whales.

The subject of population structure of odontocetes within the Wider Caribbean Region has hardly begun to be addressed, but judging by findings elsewhere, considerable structure is likely present (e.g., island-associated near-shore populations and farther-ranging offshore populations). Given

the long history of exploitation of some near-shore species in some parts of the WCR (Caldwell and Caldwell 1975; Price 1985; Reeves 2002), this could mean that a number of populations have already been substantially depleted or even entirely eliminated. In the absence of even rudimentary survey data for most of the region (except U.S. waters of the northern Gulf of Mexico), uncertainty concerning population structure, abundance, and conservation status is the norm.

Outcomes and consequences of climate change on marine mammals

For the most part the literature, regarding climate change and marine mammals, focuses on marine mammals inhabiting the polar regions and indicates that arctic marine mammals are more likely to be affected (Tynan and DeMaster 1997, IPCC 2001, Harwood 2001, Clarke and Harris 2003). However, other literature indicates that the affect of climate change on the marine environment has the potential to have, and in some cases has already had, a considerable impact on marine ecosystems and species (Defra 2005). It is often difficult to judge the response of marine mammals to long-term environmental change because of the mismatch in scale between scientific research (months to decades, in localized areas) and marine mammal natural history (decades to centuries, often over large areas). The direct effects of climate change on marine mammals are from increasing temperatures and habitat degradation. They include changes in abundance, distribution, timing and range of migration, community structure, the presence and species composition of competitors and predators, prey availability and distribution, timing of breeding, reproductive success and, ultimately, survival (Defra 2005). The following provides some information on climate change outcomes as they relate to the Caribbean region.

Population Abundance and Distribution

Literature in this area is scarce; however, in general, information indicates that migratory marine species, by traveling large distances and being subject to a wide range of environmental

influences, are particularly likely to be affected by climate change at some point of their life cycles (CANARI 2008). While some species may increase in abundance or range, climate change will increase existing risk of extinction of some more vulnerable species (Defra 2005).

Food Supply

One of the greatest threats to marine mammals probably comes from changes in their food resources, as a result of climate change. Many prey species such as fish, cephalopods and plankton appear to rely on, and are influenced by, particular sets of environmental conditions (Harwood 2001). Any changes in the geographic distribution of these oceanographic conditions as a result of climate change will affect the abundance and distribution of prey species (Defra 2005). Notably, apart from species residing within the region, it appears that other long ranging migratory species may depend on the region for food supply. Reeves (2000) states that at least one species of baleen whale depends on the wider Caribbean region for food resources, namely the common Bryde's whale, *Balaenoptera cf. brydei*; however, whether it migrates seasonally into and out of the region remains to be determined (CANARI 2008).

Diseases

Changes in disease prevalence and, in turn, increased host morbidity or mortality may result from increases in host susceptibility, pathogenicity of the disease agent, or transmission of pathogens to hosts. A number of discrete or interacting factors can influence each of these processes, such as: nutrition, population density, host movement and distribution, host genetics, predation and fisheries bycatch, increased urbanization of the coast, contaminants, and stress (Reynolds III 2005). While information is scarce on specifics to how climate change affects marine mammal diseases it can be assumed that as climate change affects these processes, so will disease prevalence. In particular marine mammal stress from adverse oceanic conditions can challenge homeostatic processes. The subtle physiological changes involved in the stress response of marine

mammals are still poorly understood but are likely to decrease the immune response through a number of endocrine changes and direct effects on the lymphoid system (Reynolds III 2005). For instance, Wilson et al. (1999) found that epidermal lesions in bottlenose dolphins were more common in animals particularly stressed by low water temperatures and salinity. Information on diseases and marine mammals in the Caribbean is limited; however, information pertaining to other regions suggests that there is an increase in diseases affecting marine mammals and that this may be, in part, due to temperature changes (Marine Mammal Commission 2005).

Contaminants and Metabolism (Wells, 2010)

High summer metabolic rates and mortality rates suggest current thermal challenges, as water temperature approaches body temperature; this situation may be exacerbated through climate change. Thermal stresses may combine with toxicological stresses to increase mortality under warm water conditions. Lipids released from thinning blubber as waters warm can transport associated toxic environmental contaminants (e.g., PCBs, DDT and metabolites) to target organs or to organs where biotransformation can modify toxicity, leading to compromised immune function. Warmer waters are likely to support a variety of old and new pathogens, reduce dolphin host resistance, and/or increase the duration of exposure. Transfer of contaminants via lactation has been suggested as one cause of the increased mortality documented for first-born calves in the area. Taken together, these factors suggest that seasonal warming appears to lead to health challenges for Sarasota Bay bottlenose dolphins, perhaps approaching a tipping point, potentially leading to cascading declines in individual health. Information is needed to identify and detect signals of climate change, predict where and how impacts on marine mammals and their habitat are likely to occur, and prioritize pre-emptive management actions for providing these animals with as much capacity as possible to respond to climate change.

Knowledge Gaps and Research Needs

The cumulative effects of climate change stressors and multiple anthropogenic sources of environmental change on marine mammals are unknown, but each examined separately suggests that these animals must contend with an increasingly stressed ecosystem and will affect marine mammals negatively. More research is needed to determine to what extent. Addressing marine mammal responses to climate change requires research focused on predictive modelling of ecosystems, based on data from a suite of species selected for their life history characteristics. The current research that exists focuses almost exclusively on responses of marine mammals to non-climate change stressors, like boat strikes, noise pollution, etc. Information on long-term environmental changes, such as regime shifts and ENSO, are not well known and could help with understanding potential outcomes of climate change. Also, our understanding of diseases in marine mammals is poor compared to our knowledge of such processes in terrestrial animals. As a result, we do not know which diseases are normal components of a healthy marine ecosystem and which are novel and a consequence of anthropogenic factors. We also do not know if there is a real increase in diseases in marine mammals or how to control/prevent these diseases. Finally, there is an inability to properly assess effects of contaminants on marine mammals. The main reasons are the general lack of understanding of marine mammal health and physiology, the historic overreliance on extrapolation from unrelated species and unrelated tissues for toxicological assessments, and the logistical difficulty and hesitation to perform studies using capture-release and captive animals to relate contaminant exposure to effects. Furthermore, monitoring is required to determine whether management changes (such as restrictions to chemical use, changes in oil consumption or shipping, changes in disposal processes) result in decreased, unchanged, or increased burdens in tissues. Nevertheless this monitoring and studies related to effects of contaminants on marine mammals is critical for

management and conservation. In summary, if we are to measure responses to climate change we must understand marine mammal life histories, contaminant exposure, how to predict and prevent diseases, and how marine mammals respond to long-term environmental changes.

Summary of outcome and consequences of climate change on Marine Mammals

Marine mammals have significant ecological, aesthetic and economic value to the countries and territories of the wider Caribbean region, including Puerto Rico. At least 32 species of marine mammals have been documented from the region—six species of baleen whales (Mysticeti), 24 species of toothed whales (Odontoceti), one sirenian (the West Indian manatee), and three pinnipeds (the Caribbean monk seal, the hooded seal, and the California sea lion). For many of these species, waters of the region serve as primary habitat for critical activities that include feeding, mating and calving. Although some species have been studied extensively elsewhere, data are scarce concerning the biology, life history, distribution and behavior of most cetacean (whale and dolphin) and manatee populations in the Caribbean Sea and Gulf of Mexico. The Caribbean is the one of only two regions in the world to have experienced the extinction of a marine mammal species (the Caribbean monk seal) in the past 250 years.

Marine mammals suffer from many threats. In Puerto Rico fisheries interactions with marine mammals have been reported for a variety of fishing gear. Humpback whales have been reported entangled with fish trap lines. Dolphin fatalities have been reported from gill net entanglement. Manatees have been caught accidentally on beach seine nets and fatalities have been reported due to infections caused by the abrasion and injuries of monofilament line entanglement for the extremities. Pollution, hunting, vessel strikes, habitat degradation, and noise pollution also plague marine mammals around Puerto Rico.

Population abundance and distribution are expected to be affected by climate changes, specifically from increasing sea surface temperatures and ocean acidification, however more research is needed to determine which species ranges may expand or contract and how. Marine mammal food supplies (*i.e.*, fish, cephalopods like squid, and plankton) are directly affected by environmental conditions and as their food supplies are affected by climate change so too will marine mammals. It is anticipated that there will be more reports of disease in Puerto Rico's marine mammals as increasing sea surface temperatures increase the prevalence of disease. High summer metabolic rates and mortality rates suggest current thermal challenges, as water temperature approaches body temperature; this situation may be exacerbated in the future. Thermal stresses may combine with toxicological stresses to increase mortality under warm water

conditions. Lipids released from thinning blubber as waters warm can transport associated toxic environmental contaminants (e.g., PCBs, DDT, and metabolites) to target organs or to organs where biotransformation can modify toxicity, leading to compromised immune function. Warmer waters are likely to support a variety of old and new pathogens, reduce dolphin host resistance, and/or increase the duration of exposure. Transfer of contaminants via lactation has been suggested as one cause of the increased mortality documented for first-born calves in the area. Taken together, these factors suggest that seasonal warming appears to lead to health challenges. Information is needed to identify and detect signals of climate change, predict where and how impacts on marine mammals and their habitat are likely to occur, and prioritize pre-emptive management actions for providing these animals with as much capacity as possible to respond to climate change.



INTERSECTING ISSUES

In November 2010, the PRCCC founding members stressed the importance of also assessing the intersections between certain ecosystems, species, and key anticipated climate change outcomes and consequences. Changes in climate stressors will not affect Puerto Rico's ecosystems or species independently. Many systems are so connected that what happens in one may alter the structure and function of another. A good understanding of these interconnections can assist in planning our urban, agricultural, rural, and conservation areas appropriately to be able to adapt to a changing climate. Due to time limitations, however, a formal assessment of these intersecting issues was not possible. Throughout the report the PRCCC attempted to include many such issues; however, for example, the coupled nature of mangroves, seagrasses, and coral reefs, the dependence of commercially-important finfish on nursery habitats, or the interconnectedness of mountain and agricultural areas to coastal systems. Future PRCCC reports should prioritize the assessment of these types of intersections.

Looking at the Caribbean Natural Resources Institute 2008 report (CANARI 2008) on climate change and coastal and marine ecosystems, we can expand on the first theme. The high biodiversity found in Caribbean coral reefs is strongly influenced by the presence of adjacent mangrove forests and seagrass beds. These three ecosystems form strongly coupled habitat complexes, which are not completely understood, along the coastal seascape (Koch and Madden 2001; McKee et al. 2002; Mumby 2006). There is a continuum across these ecosystems in which complex nutrient exchanges define the spatial and temporal distribution of mangroves, seagrasses, and coral reefs, and negative impacts in one ecosystem can cascade across the coastal seascape, affecting other areas.

Some of the interactions across the seascape are as follows:

- **Nurseries:** Mangroves and seagrass beds are considered important juvenile habitats for a variety of fish and invertebrate species that

spend their adult life in coral reefs or offshore habitats (Ogden et al. 2005);

- **Foraging movements and migration:** Diurnal and nocturnal feeding migrations among habitats are a common feature of juvenile and some adult fish (Nagelkerken et al. 2000a, 2000b; Beets et al. 2003). As a result of these migrations, fish can function as vectors of organic material from seagrass beds to reefs, enhancing the growth rates of corals (Meyer et al. 1983);
- **Physical interactions:** Healthy coral reefs act like hydrodynamic barriers dissipating wave energy and creating low energy environments conducive to mangrove and seagrass colonization. At the land-sea boundary, coastal forests, mangroves, and seagrasses act as buffers, which intercept freshwater discharge, stabilize salinity, and trap and bind sediment (Ogden et al. 2005);
- **Exchange of particulate and dissolved organic matter:** Mass balance studies in a range of mangrove systems generally support the assertion that mangroves export organic matter in both particulate and dissolved forms (Lee 1995; Robertson and Alongi 1995).

The buffering capacity of coastal ecosystems is threatened by the projected rate of sea level rise under scenarios of global warming (Ogden et al. 2005). While healthy coral growth may keep pace with sea level rise, weakened reefs may be unable to grow sufficiently to enable them to continue their coastal protection function. These zones will become inundated and subjected to erosion by progressively larger waves. Seagrass and mangrove communities will be eroded and will become less effective buffers, releasing nutrients and sediment and further slowing coral reef growth rate and negatively impacting coral reef health.

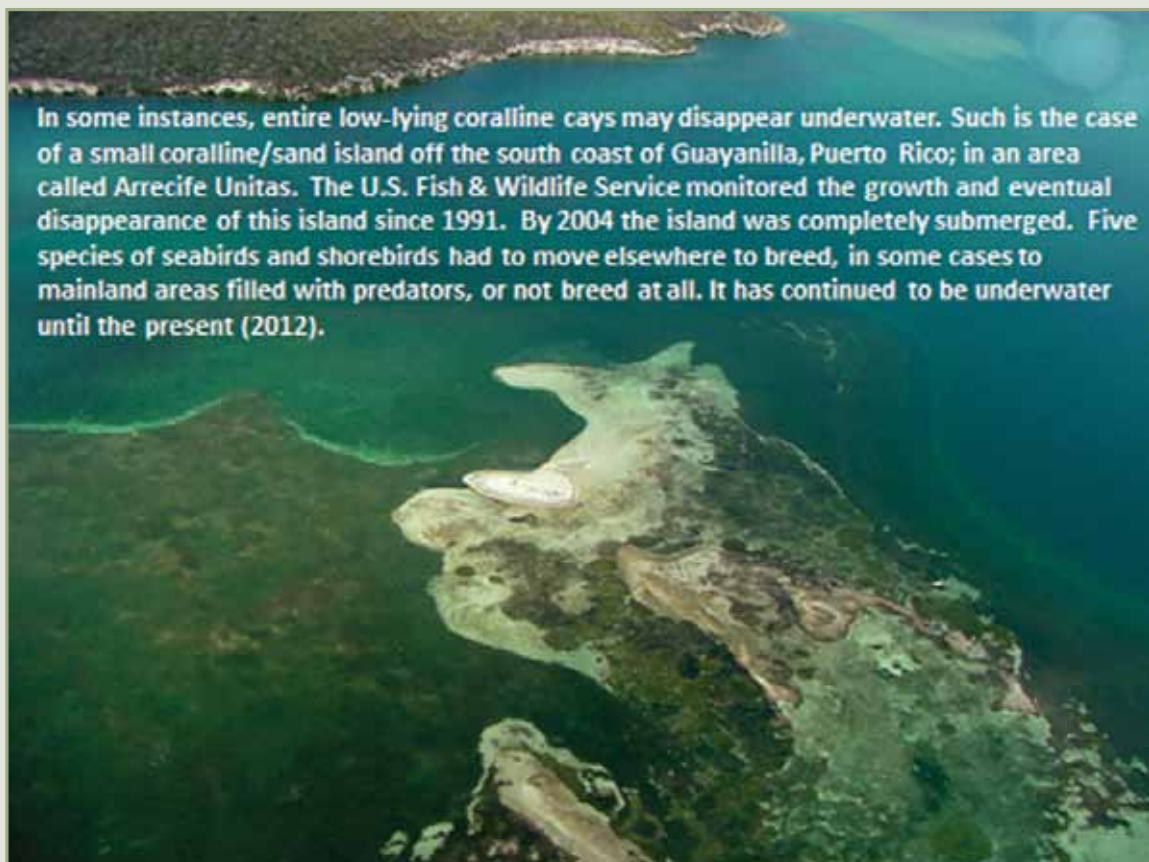
CONCLUSION

The Working Group 2 report highlights that the Puerto Rico Climate Change Council members and organizations are increasingly engaging in

research, monitoring, and observing initiatives to increase our understanding of climate change effects and support effective, informed natural resources management. This first-pass assessment lays the groundwork for future PRCCC reports to build upon and identifies areas where more research and expertise is needed.

The main effect of climate change on Puerto Rico's ecosystems and species will be synergistic in that already stressed systems will be exposed to additional stressors that push them over their limit of existence, resulting in widespread loss of habitat, unfavorable changes to structure and function, or diminished services to Puerto Rico's society. Some ecosystems and species will acclimate to changing environmental conditions better than others. While some species may potentially migrate to more favourable conditions in Puerto Rico (e.g., Colorado trees, swamp cyrilla), species already bumping up against the upper limits of their range may not be so fortunate, and could be diminished or lost from Puerto Rico altogether due to the lack of suitable environmental conditions (e.g., dolphinfish, yellowfin tuna). Others may not have

the ability to relocate and may become globally extinct, like the Coquí Duende, the Cricket Coquí, and the forest-dwelling Puerto Rican Upland Sphaero. On the other hand, new species or community assemblages could occur in Puerto Rico that may benefit society as they might provide new ecosystem services. More research is needed on potential future ecosystem states and the ability of future ecosystems to sustain human populations. Healthy ecosystems are our life support system, providing us with essential goods and services that would be extremely expensive or impossible to replace. Ecosystems purify air and water, and provide flood control. They supply us with marketable products and sequester carbon and build soils. They provide recreation, hunting and fishing, and wild places in which to enjoy nature for our spiritual and mental well-being. Puerto Rico's culture is greatly connected to the islands' ecosystems and species, perhaps to a greater extent than many other areas of the world. Human disruption of ecosystems, through climate change and other factors such as habitat destruction and pollution, can reduce ecosystems' ability to provide us with these valuable services.



In some instances, entire low-lying coralline cays may disappear underwater. Such is the case of a small coralline/sand island off the south coast of Guayanilla, Puerto Rico; in an area called Arrecife Unitas. The U.S. Fish & Wildlife Service monitored the growth and eventual disappearance of this island since 1991. By 2004 the island was completely submerged. Five species of seabirds and shorebirds had to move elsewhere to breed, in some cases to mainland areas filled with predators, or not breed at all. It has continued to be underwater until the present (2012).

WORKING GROUP 2 WORKS CITED

- (CANARI), C. N. R. I. 2008. The impacts of climate change on biodiversity in Caribbean islands: what we known, what we need to known, and building capacity for effective adaptation.
- (ETI), E. T. I. 2007. Valoración económica de los arrecifes de coral y ambientes asociados en el Este de Puerto Rico: Fajardo, Arrecifes La Cordillera, Vieques y Culebra. Informe final. Sometido al: Departamento de Recursos Naturales y Ambientales
- (NOAA), N. C. R. C. P. 2009. NOAA Coral Reef Conservation Program Goals & Objectives 2010-2015. NOAA, Silver Spring, MD.
- (UNEP), U. N. E. P. 2004. Eleventh Intergovernmental Meeting on the Action Plan for the Caribbean Environment Program and Eighth Meeting of the Contracting Parties to the Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region. UNEP, Caribbean Reefs@Risk, World Resources Institute, Montego Bay, Jamaica.
- ACKERMAN, R. A. 1997. The nest environment and the embryonic development of sea turtles. In : P.L. Lutz & J. A. Musick (Eds.). The biology of sea turtles. CRC Press, Boca Raton. pp. 83-106
- Adger, W.N. 2000. Social and Ecological Resilience: Are They Related? *Progress in Human Geography* 24, 347-364.
- Adolf, J. E., C. L. Yeager, M. E. Mallonee, W. D. Miller, and L. W. Harding. 2006. Environmental forcing of phytoplankton floral composition, biomass, and primary productivity in Chesapeake Bay, USA. *Estuarine, Coastal and Shelf Science* 67:108-122.
- Aguilar-Perera, J.A. (2004). Coastal habitat connectivity of reef fishes from southwestern Puerto Rico. Department of Marine Sciences, University of Puerto Rico, Mayaguez, Puerto Rico. Thesis.
- Aiken, K. 1993. Jamaica. In *Marine fishery resources of the Antilles: Lesser Antilles, Puerto Rico and Hispaniola, Jamaica, Cuba*. FAO Fisheries Technical Paper No. 326, Rome, 159-180.
- Allen, J.A., S.R. Pezeshki & J.L. Chambers. 1996. Interaction of flooding and salinity stress on baldcypress (*Taxodium distichum*). *Tree Physiology* 16:307-313.
- Allison et al. 2005. North sea fish distribution
- Anderson, D., P. Glibert, and J. Burkholder. 2002. Harmful algal blooms and eutrophication nutrient sources, composition, and consequences. *Estuaries* 25:704-726.
- Anthony, A., J. Atwood, P. August, C. Byron, S. Cobb, C. Foster, C. Fry, A. Gold, K. Hagos, L. Heffner, D. W. Kellogg, K. Lellis-Dibble, J. J. Opaluch, C. Oviatt, A. Pfeiffer-Herbert, N. Rohr, L. Smith, T. Smythe, J. Swift, and N. Vinhateiro. 2009. Coastal lagoons and climate change: Ecological and social ramifications in U.S. Atlantic and Gulf Coast ecosystems. *Ecology and Society* 14:8.
- Appeldoorn R., and Meyers, S. 1993. Puerto Rico and Hispaniola. In *Marine fishery resources of the Antilles: Lesser Antilles, Puerto Rico and Hispaniola, Jamaica, Cuba*. FAO Fisheries Technical Paper No. 326, Rome, 99-158.
- Appeldoorn, R., G.D. Dennis, and O. Monterossa-Lopez. 1987. Review of shared demersal resources of Puerto Rico and the Lesser Antilles region. In: R. Mahon (ed.), *Report and Proceedings of the Expert Consultation on Shared Fishery Resources of the Lesser Antilles Region*. FAO Fisheries Report 383:36-106.
- Armentano, T.V., Doren, R.F., Platt, W.J. and Mullins, T. 1995. Effects of Hurricane Andrew on coastal and interior forests of southern Florida: Overview and synthesis. *Journal of Coastal Research Special Issue* 2: 111-114
- Aronson RB and W.F. Precht. 1997. Stasis biological disturbance and community structure of a Holocene coral reef. *Paleobiology* 23:326-346
- Aronson RB, Precht WF. 2000. Herbivory and algal dynamics on the coral reef at Discovery Bay, Jamaica. *Limnol Oceanogr* 45:251-255
- Aronson RB, Precht WF. 2001. White-band diseases and the changing face of Caribbean coral reefs. *Hydrobiologia* 460:25-38

- Aronson, R. B., I. G. Macintyre, W. G. Precht, T. J. T. Murdoch, and C. M. Wapnick. 2002. The expanding scale of species turnover events on coral reefs in Belize. *Ecol. Monogr.* 72:233-249.
- ASEAN (2009), "People centered case study in Southeast Asia"
- Asian Wetland Symposium 2006
- Atema, J., M. J. Kingsford, and G. Gerlach. 2002. Larval reef fish could use odour for detection, retention and orientation to reefs. *Marine Ecology Progress Series* 241:151-160.
- Atlas, P. R. B. B. 2009. Puerto Rico Breeding Bird Atlas species index: Retrieved 7 July, 2012 from <http://www.aosbirds.org/prbba/SpeciesYSBL.html>.
- Bacon, P. R. 1989. Assessment of the economic impacts of Hurricane Gilbert on coastal and marine resources in Jamaica. Page 86 Unpublished MS.
- Bacon, P. R. 1991. The status of mangrove conservation in the CARICOM Islands of the Eastern Caribbean. Report to the Commission of the European Communities as part of the Tropical Forestry Action Plan for the Caribbean Region, 211 pp
- Bacon PR (1994) Template for evaluation of impacts of sea level rise on Caribbean coastal wetlands. *Ecol Eng* 3:171-186
- Bacon, P. 1995 Wetland Resource Rehabilitation for Sustainable Development in the Eastern Caribbean. In *Environment and Development in the Caribbean: Geographical Perspectives*, D. Barker and D.F.M. McGregor, eds. pp. 46-56. Kingston, Jamaica: University of West Indies Press
- Bacon, P. R. 2000. Redefining Tropical Coastal Wetlands, *Intercoast International Newsletter of Coastal Management* 37, Fall 2000
- Badola, R. and S.A. Hussain. 2005. Valuing ecosystem functions: an empirical study on the storm protection function of Bhitarkanika mangrove ecosystem, India. *Environmental Conservation* 32(1): 85-92
- Baelde P. 1990. Differences in the structure of fish assemblages in *Thalassia testudinum* beds in Guadeloupe, French West Indies, and their ecological significance. *Marine Biology* 105: 163-173
- Bahena, H., C. Campos, L. Carrera-Parra, N. E. González, R. Herrera, M. Maas, J. Ruiz, and S. I. Salazar-Vallejo. 2000. Impacto del huracán Mitch en el Caribe y el Mexicano (octubre de 1998). *Cienc. Desarr. México* 26:20-27.
- Baisre, J. 1993. Cuba. In *Marine fishery resources of the Antilles: Lesser Antilles, Puerto Rico and Hispaniola, Jamaica, Cuba*. FAO Fisheries Technical Paper No. 326, Rome, 181-235.
- Baisre, J. A. 2000. Chronicle of Cuban marine fisheries (1935-1995). Trend analysis and fisheries potential. FAO Fish. Tech. Pap., 394, 26 p.
- Baisre, J. A. 2004. La pesca marítima en Cuba. Editorial Científico-Técnica. La Habana, 372 p
- Baker, A. C., 2003. Flexibility and specificity in coral-algal symbiosis: diversity, ecology, and biogeography of *Symbiodinium*. *Annual Review of Ecology, Evolution, and Systematics* 34: 661-689.
- Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. *Science* 247: 198-201.
- Ball, M.C. and G.D. Farquhar. 1984. Photosynthetic and Stomatal Responses of the Grey Mangrove, *Avicennia marina*, to Transient Salinity Conditions. *Plant Physiology* 74(1): 7-11.
- Ball, M.C., M.J Cocharane and H.M. Rawson. 1997. Growth and water use of the mangroves *Rhizophora apiculata* and *R. stylosa* in response to salinity and humidity under ambient and elevated concentrations of atmospheric CO₂. *Plant Cell and Environment* 20: 1158-1166.
- Ballantine, D. L., R. S. Appeldoorn, P. Yoshioka, E. Weil, R. Armstrong, J. R. García, E. Otero, F. Pagán, C. Sherman, E. A. Hernández-Delgado, A. Bruckner, and C. Lilyestrom. 2008. Biology and ecology of Puerto Ricans coral reefs. Page 803 in B. M. Riegl and R. E. Dodge, editors. *Coral Reefs of the World, Vol. I. Coral reefs of the USA*. Springer-Science, Business Media B.V.
- Banus, M. 1983. The effect of thermal pollution on red mangrove seeding, small trees and on mangrove reforestation. In: *Coral Reefs, Seagrass Beds and Mangroves: Their Interaction in the Coastal Zones of the Caribbean*, ed. J.C. Ogden and E.H. Gladfelter, p. 114-127.
- Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C. & Silliman, B. R. The value of estuarine and

- coastal ecosystem services. *Ecol. Monogr.* 81, 169–193 (2011).
- Barreto, M. 2010. Final Report: A geomorphic assessment at selected beach sites using imagery analysis (1936-2007) and beach profiling techniques (2009-2010): as a tool to define coastal indicators for management applications. Department of Natural and Environmental Resources, Puerto Rico Coastal Zone Management Program San Juan, PR.
- Barrientos, K.; Ramirez-Gallego, Diez, C.E.; van Dam, R.P. Metabolic warming in hawksbill turtles at Mona Island, Puerto Rico. In press, Proceedings 31'st Annual Symposium on Sea Turtle Biology and Conservation, 2011.
- Barton, M., and Barton, A.C..1987. Effects of salinity on oxygen consumption of *Cyprinodon variegatus*. *Copeia* 1987, 230-232.
- Bassim, K. M., P.W. Sammarco, and T. L. Snell. 2002. Effects of temperature on success of (self and non-self) fertilization and embryogenesis in *Diploria strigosa* (Cnidaria, Scleractinia). *Mar. Biol.* 140: 479-488.
- Bassim, K., and P. Sammarco. 2003. Effects of temperature and ammonium on larval development and survivorship in a scleractinian coral (*Diploria strigosa*). *Mar. Biol.* 142: 241-252.
- Bauer, R. T. 1985a. Diel and seasonal variation in species composition and abundance of Caridean shrimps (Crustacea, Decapoda) from seagrass meadows on the north coast of Puerto Rico. *Bulletin of Marine Science* 36:150-162.
- Bauer, R. T. 1985b. Hermit crab fauna from seagrass meadows in Puerto Rico: Species composition, diel and season variation in abundance. *Journal of Crustacean Biology* 5:249-257.
- Bauer, R. T. 1985c. Penaeod Shrimp fauna from tropical seagrass meadows: Species composition, diurnal and seasonal variation in abundance. *Proc. Biol. Soc. Wash.* 98:177-190.
- Bauer, L.J., C. Menza, K.A. Foley, and M.S. Kendall. 2008. An Ecological Characterization of the Marine Resources of Vieques, Puerto Rico. Part I: Historical Data Synthesis. NOAA Technical Memorandum NOS NCCOS 86. Silver Spring, MD. 121 pp.[online http://www.ccma.nos.noaa.gov/publications/Vieques_characterization_final.pdf]
- Baumgartner, M.F., K.D. Mullin and L.N. May, T.D. Leming. 2001. Cetacean habitats in the northern Gulf of Mexico. *Fisheries Bulletin* 99:219-239.
- Beard, K.H., A.K. Eschtruth, K.A. Vogt, D.J. Vogt & F.N. Scatena. 2003. The effects of the frog *Eleutherodactylus coqui* on invertebrates and ecosystem processes at two scales in the Luquillo Experimental Forest, Puerto Rico. *Journal of Tropical Ecology* 19:607–617.
- Beck, M.W., K.L. Heck Jr. K.W. Able, D.L. Childers and 9 others. 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates. *Bioscience* 51: 633-641.
- Beets, J., L. Muehlstein, K. Haught, and H. Schmitges. 2003. Habitat connectivity in coastal environments: patterns and movements of Caribbean coral reef fishes with emphasis on Bluestriped Grunt, *Haemulon sciurus*. *Gulf and Caribbean Research* 14(2): 29-42.
- Bellwood, D. R., T. P. Hughes, C. Folke, and M. Nyström. 2004. Confronting the coral reef crisis. *Nature* 429:827-833.
- Berrios, J.M., J.K. Gonzalez Azar, I. Diaz Rodriguez. 1985(Digital Format 2005): Fish population studies of the seagrass beds and coral reefs of Cayo Berberia and Cayo Ratones, P.R..Department of Natural Resources, Scientific Research Area, Marine Resources Division. NOAA/RSMAS Report.
- Bessat, F. and Buigues, D. 2001. Two centuries of variation in coral growth in a massive *Porites* colony from Moorea (French Polynesia): a response of ocean-atmosphere variability from south central Pacific. *Palaeogeography, Palaeoclimatology, Palaeoecology* 175: 381-392.
- Beuchat, C.A., F.H. Pough & M.M. Stewart. 1984. Response to simultaneous dehydration and thermal stress in three species of Puerto Rican frogs. *Journal of Comparative Physiology* 154:579–585.
- Bird, E. C. F. 1985. *Coastline Changes*. Wiley and Sons, New York.
- Bird, E. C. F. 1987. The Modern Prevalence of Beach Erosion *Marine Pollution Bulletin* 18:151-157.
- Bjorndal, K. A. 1997. Foraging ecology and nutrition of sea turtles. Pages 199-231 in P. L. Lutz and J. A.

Musick, editors. The Biology of Sea Turtles. CRC Press, Boca Raton, FL.

- Blaustein, A.R., S.C. Walls, B.A. Bancroft, J.J. Lawler, C.L. Searle & S.S. Gervasi. 2010. Direct and indirect effects of climate change on amphibian populations. *Diversity* 2:281–313.
- Boesch, D.F., and Turner, R.E. (1984) Dependence of fishery species on salt marshes: The role of food and refuge. *Estuaries* 7, 460–468.
- Bohnsack, J. A. 1993. The impacts of fishing on coral reefs. Pages 96–200 in R. Ginsburg, editor. *Proceedings of the Colloquium on Global Aspects of Coral Reefs: health, hazards and history*. Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, FL.
- Bonkosky, M., E. A. Hernández-Delgado, B. Sandoz, I. E. Robledo, J. Norat-Ramírez, and H. Mattei. 2009. Detection of spatial fluctuations of non-point source fecal pollution in coral reef surrounding waters in southwestern Puerto Rico using PCR-based assays. *Marine Pollution Bulletin* 58:45–54.
- Boorman, J. 1989. *Culicoides* (Diptera: Ceratopogonidae) of Arabian Peninsula with notes on their medical and veterinary importance. *Fauna of Saudi Arabia*, 10 (1989), pp. 160–224
- Bortone, S. A. 2006. Recommendations on establishing a research strategy in the Gulf of Mexico to assess the effects of hurricanes on coastal ecosystems. *Estuaries and Coasts* 29:1062–1066.
- Bouchon, C., Bouchon-Navarro, Y., Louis, M., and Laborel, J. 1987. Influences of the degradation of coral assemblages on the fish communities of Martinique (French West Indies) KB. *Proc. Gulf. Caribb. Fish. Inst.*, 38: 452–469.
- Bouchon, C., Y. Bouchon-Navarro, D. Imbert, and M. Louis. 1991. The effect of Hurricane Hugo on the coastal environment of Guadeloupe Island (FWT). *Ann. Inst. Oceanogr., Paris, Nouv. Ser.* 67:5–33.
- Brander, K.M., Blom, G., Borges, M.F. et al. 2004 (2003). Changes in fish distribution in the eastern North Atlantic: are we seeing a coherent response to changing temperature? *ICES Marine Science Symposium* 219: 261–270.
- Brander, K. 2009. Impacts of climate change on fisheries. *Journal of Marine Systems* 79:3–4.
- Brautigam, A. and K.L. Eckert. 2006. *Turning the Tide: Exploitation, Trade and Management of Marine Turtles in the Lesser Antilles, Central America, Colombia and Venezuela*. TRAFFIC International. Cambridge, UK. 548 pp.
- Brinson, M.M., R.R. Christian, and L.K. Blum. 1995. Multiple states in the sea-level induced transition from terrestrial forest to estuary. *Estuaries* 18: 648–659.
- Brown, B.E. 1997. Coral bleaching: causes and consequences. *Coral Reefs*, 16: S129–S138.
- Bruckner, A. W., and R. J. Bruckner. 1997. Outbreak of coral disease in Puerto Rico. *Coral Reefs* 16:260.
- Bruckner, A. W., and R. J. Bruckner. 2006. Consequences of yellow band disease (YBD) on *Montastraea annularis* (species complex) populations on remote reefs off Mona Island, Puerto Rico. *Dis. Aquat. Orgs.* 69:67–73.
- Bruckner, A. W., and R. L. Hill. 2009. Ten years of change to coral communities off Mona and Desecheo Islands, Puerto Rico, from disease and bleaching. *Dis. Aquat. Orgs.* 87:19–31.
- Bruun, P. 1962. Sea level rise as a cause of shore erosion. *Journal of Waterways and Harbours Division ASCE* 88:117–130.
- Bryant, D. L., L. Burke, J. McManus, and M. Spalding. 1998. *Reefs at risk: a map-based indicator of threat to the world's coral reefs*. World Resources Institute, Washington, D.C.
- Buddemeier, R. W., J. A. Kleypas, and R. Aronson. 2004. *Coral Reefs and Global Climate Change. Potential Contributions of Climate Change to Stresses on Coral Reef Ecosystems*, Arlington, VA.
- Burke, L., and J. Maidens. 2004. *Reefs at risk in the Caribbean*. World Resources Institute, Washington, D.C.
- Burkholder, P. R., L. M. Burke, and L. R. Almodóvar. 1967. Carbon assimilation of marine flagellate blooms in neritic waters of southern Puerto Rico. *Bulletin of Marine Science* 17:1–15.
- Burkholder, P. R., and L. M. Burkholder. 1958. Studies on B vitamins in relation to productivity on the Bahía Fosforescente, Puerto Rico. *Bulletin of Marine Science Gulf and Caribbean* 8:203–223.
- Burrowes, P.A., R.L. Joglar & D.E. Green. 2004. Potential causes for amphibian declines in Puerto Rico. *Herpetologica* 60:141–154.

- Burrowes, P.A., A.V. Longo & C.A. Rodríguez. 2008a. Potential fitness cost of *Batrachochytrium dendrobatidis* in *Eleutherodactylus coqui*, and comments on environment-related risk of infection. *Herpetotropicos* 4:51–57.
- Burrowes, P.A., A.V. Longo, R.L. Joglar & A.A. Cunningham. 2008b. Geographic distribution of *Batrachochytrium dendrobatidis* in Puerto Rico. *Herpetological Review* 39:321–324.
- Bush, D. M., R. M. T. Webb, J. González Liboy, L. Hyman, and W. J. Neal. 1995. *Living with the Puerto Rico Shore*. Duke University Press, Durham, North Carolina and London.
- Bush, D.M., W.J. Neal, and C.W. Jackson. 2009. Summary of Puerto Rico's Vulnerability To Coastal Hazards: Risk, Mitigation, And Management With Examples (in) Kelley, Joseph T., Orrin H. Pilkey, and J. Andrew G. Cooper (editors), *America's Most Vulnerable Coastal Communities*, Geological Society of America Special Paper 460, p. 149-165.
- Buyukates, Y., and D. Roelke. 2005. Influences of pulsed inflows and nutrient loading on zooplankton and phytoplankton community structure and biomass in microcosm experiments using estuarine assemblages. *Hydrobiology* 548:233-249.
- Bythell J.C., E. Gladfelter, and M. Bythell. 1993. Chronic and catastrophic natural mortality of three common Caribbean corals. *Coral Reefs* 12:143–152
- Cadi, A., V. Delmas, A.C. Prévot-Julliard, P. Joly, C. Pieau & M. Girondot. 2004. Successful reproduction of the introduced slider turtle (*Trachemys scripta elegans*) in the South of France. *Aquatic Conservation: Marine and Freshwater Ecosystem* 14:237–246.
- Cahoon, D., D. Reed, and J. Day. 1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. *Marine Geology* 128: 1–9
- Cahoon, D.R., P. Hensel, J. Rybczyk, K.L. McKee, C.E. Proffitt, and B.C. Perez. 2003. Mass tree mortality leads to mangrove peat collapse at Bay Islands, Honduras after Hurricane Mitch. *Journal of Ecology* 91: 1093-1105.
- Cahoon, D.R. and J.C. Lynch. 1997. Vertical accretion and shallow subsidence in a mangrove forest of southwestern Florida, U.S.A. *Mangroves and Salt Marshes* 1: 173-186.
- Caldeira, K., and M.E. Wickett (2003) Anthropogenic carbon and ocean pH. *Nature*, 425, 365.
- Caldwell, D.K. and Caldwell, M.C. 1975. Dolphin and small whale fisheries of the Caribbean and West Indies: occurrence, history and catch statistics – with special reference to the Lesser Antillean island of St Vincent. *Journal of the Fisheries Research Board of Canada* 32:1105-1110
- Cambers, G. 1996. Hurricane impact on beaches in the eastern Caribbean islands, 1989-1995.
- Cambers, G. 1997. Beach changes in the eastern Caribbean islands: hurricane impacts and implications for climate change. *Journal of Coastal Research*:29-47.
- Cambers, G. 1998. *Coping with beach erosion* UNESCO Publishing.
- Cambers, G. 2005. Caribbean islands coastal ecology and geomorphology. Pages 221-226 in M. L. Schwartz, editor. *Encyclopedia of coastal science*. Springer Publishing.
- Capella, J. 2010. Sea Level Rise analysis for the Caribbean Coastal Ocean Observing System and the Puerto Rico Climate Change Council. Unpublished.
- Cary, C. & M.A. Alexander. 2003. Climate change and amphibian declines: is there a link? *Diversity and Distributions* 9:111–121.
- Carr, J. A., P. D'Odorico, K. J. McGlathery, and P. L. Wiberg. 2012. Stability and resilience of seagrass meadows to seasonal and interannual dynamics and environmental stress. *Journal of Geophysical Research* 117.
- Carrubba, L., E. Otero, N. Jimenez, and J. Bauza. 2003. Using GIS to quantify propeller scarring in seagrass beds of La Parguera and Guanica Natural reserves, Puerto Rico. 31st AMLC Scientific Meeting, Port of Spain, Trinidad.
- Carter, C. M., A. H. Ross, D. R. Schiel, C. Howard-Williams, and B. Hayden. 2005. In situ microcosm experiment on the influence of nitrate and light on phytoplankton community composition. *J. Exp. Mar. Biol. Ecol.* 326:1-13.
- Carter, R. W. G. 1991. Near-future sea level impacts on coastal dune landscapes. *Landscape Ecology* 6:29-

- Carter, R. W. G. 1998. Coastal Environments. Academic Press, London.
- Causey, B., J. Delaney, E. Diaz, D. Dodge, J. Garcia, J. Higgins, B. Keller, W. Jaap, C. Matos, G. Schmahl, C. Rogers, M. Miller, and D. Turgeon. 2002. Status of Coral Reefs in the U.S. Caribbean and Gulf of Mexico: Florida, Texas, Puerto Rico, U.S. Virgin Islands, Navassa. Pages 251-276 in C. R. Wilkinson, editor. Status of coral reefs of the world: 2002. GCRMN Report. Australian Institute of Marine Science, Townsville, Australia.
- Cedeño-Maldonado, D. J. 2008. Spectral properties and population dynamics of the harmful dinoflagellate *Cochlodinium polykrikoides* (Margelef) in Southwestern Puerto Rico. University of Puerto Rico, Mayagüez, Puerto Rico.
- Center for Integrative Environmental Research (CIER). 2007. The US Economic Impacts of Climate Change and the Costs of Inaction. College Park, MD, Center for Integrative Environmental Research, University of Maryland.
- Charman, D. 2002. Peatlands and environmental change. J. Wiley & Sons, London and New York.
- Chen, C. P., and B. Y. Chen. 1992. Effects of high temperature on larval development and metamorphosis of *Arachnoides placenta* (Echinodermata: Echinoidea). *Marine Biology* 112:445-449.
- Cheung, W., V. Lam, J. L. Sarmiento, K. Kearney, R. Watson, D. Zeller, and D. Pauly. 2010. Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology* 16:24-35.
- Chinea, J. D. 1980. The forest vegetation of the Limestone Hills of Northern Puerto Rico. Cornell University Graduate School New York.
- Christiansen C. and D. Bowman D. 1986. Sea-level changes, coastal dune building and sand drift, NW Jutland, Denmark. *Geografisk Tidsskrift* 86:28-31
- Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr & P. Whetton, 2007: Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Church, J., J. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M. Nhuan, D. Qin, P. Woodworth. 2001. Chapter 11. Changes in Sea Level. Pp. 639-693 IN Houghton, J., Y. Ding, D. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell, C. Johnson, eds. *Climate Change 2001: The Scientific Basis*. Published for the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, 881 pp.
- Church, J.A., N.J. White, R. Coleman, K. Lambeck & J.X. Mitrovica. 2004. Estimates of the regional distribution of sea level rise over the 1950-2000 period. *Journal of Climate* 17:2609-2625.
- Cintrón, G., Lugo, A.E., Pool, D.J., Morris, G., 1978. Mangroves of arid environments in Puerto Rico and adjacent islands. *Biotropica* 10, 110-121.
- Clarke A, Harris CM (2003) Polar marine ecosystems: major threats and future change. *Environ Conserv* 30:1-25
- Clarke, A. and Johnston, N. M. (1999). Scaling of metabolic rate with body mass and temperature in teleost fish. *J. Anim. Ecol.* 68, 893-905.
- Claridge, D.E. and K.C. Balcomb. 2001. Occurrence and distribution of beaked whales in The Bahamas. Poster presented at the Beaked Whale Workshop, 14th Biennial Conference on the Biology of Marine Mammals, Vancouver, Canada, November 2001.
- Claro, R., Baisre, J.A., Lindeman, K.C., and García-Arteaga, J.P. 2001. Cuban fisheries: historical trends and current status. In Claro, R., Lindeman, K.C., Parenti, L.R., (Eds.) *Ecology of the Marine Fishes of Cuba*. Smithsonian Institution Press, Washington and London, 194-218.
- Cintrón, G. 1969. Seasonal fluctuations in a tropical bay. University of Puerto Rico, Mayagüez, Puerto Rico.

- Cintrón, G., W. S. Maddux, and P. R. Burkholder. 1970. Some consequences of brine pollution in the Bahía Fosforescente, Puerto Rico. *Limnology and Oceanography* 15:246-249.
- Clark, A., and N. M. Johnston. 1999. Scaling of metabolic rate with body mass and temperature in teleost fish. *Journal of Animal Ecology* 68:893-905.
- Ciudadanos del Karso. (2010). Ciudadanos del Karso. Retrieved 10/1/2010, from <http://cdk-pr.org/>
- Claro, R., Cantelar, K., Pina Amargós, F., García-Arteaga, and J.P. 2007. Cambios en las comunidades de peces de los arrecifes coralinos del Archipiélago Sabana-Camagüey, Cuba. *Biología Tropical* 55 (1).
- Claro, R., García-Arteaga, J.P., Gobert, B., Cantelar Ramos, K., Valle Gómez, S.V., Pina-Amargós, F. 2004. Situación actual de los recursos pesqueros del archipiélago Sabana-Camagüey, Cuba. *Bol. Invest. Mar. Cost.* 33, 41-57.
- Cloern, J. E., and A. D. Jassby. 2010. Patterns and scales of phytoplankton variability in estuarine and coastal ecosystems. *Estuaries and Coasts* 33.
- Clough BF, Andrews TJ, Cowan JR. 1982. Physiological processes in mangroves. In: Clough BF, ed. *Mangrove ecosystems in Australia: structure, function and management*. Canberra, ACT, Australia: Australian National University Press, 194-210.
- Coates, T., A. Brampton, and G. Motyka. 2000. A guide to managing coastal erosion in beach/dune systems. HR Wallingford and the Scottish Natural Heritage, Edinburgh, UK.
- Coker, R. E., and J. G. González. 1960. Limnetic copepod populations of Bahía Fosforescente and adjacent waters of Puerto Rico. *J. Elisha Mitchell Scient. Soc.* 76:8-28.
- Coleman, J.M., Huh, O.K., Braud Jr., D. (2008) Wetland loss in world deltas. *Journal of Coastal Research*. 24(1A), 1-14
- Coles, R., L. McKenzie, S. Campbell, J. Mellors, M. Waycott, and L. Goggin. 2004. Seagrasses in Queensland waters. Page 6 in C. R. R. Centre, editor.
- Coles, S. L., and P. L. Jokiel. 1992. Effects of salinity on coral reefs. Pages 147-166 in D. W. Connell and D. W. Hawker, editors. *Pollution in Tropical Aquatic System*. CRC Press, Boca Raton, Ann Arbor.
- Cooper TF, De 'Ath G, Fabricius KE, Lough JM. 2008. Declining coral calcification in massive Porites in two nearshore regions of the northern Great Barrier Reef. *Glob. Chang. Biol.* 14:529-38
- Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, and S. Naeem. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387:253-260.
- Cowardin, L. M., V. Carter, F. C. Golet, E. T. LaRoe. 1979. Classification of wetlands and deepwater habitats of the United States. U. S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. Jamestown, ND: Northern Prairie Wildlife Research Center Home Page. <http://www.npwrc.usgs.gov/resource/1998/classwet/classwet.htm> (Version 04DEC98).
- Creed, J.C., R.C. Phillips & B.I. Van Tussenbroek. 2003. The seagrasses of the Caribbean, p. 234-242. In E.P. Green & F.T. Short. *World Atlas of Seagrasses: Present Status and Future Conservation*. University of California, Berkeley, USA.
- Creswell, J.E., 2002. The exploitative history and present status of marine mammals in Barbados, W.I., *Macalester Environmental Review* (28 May 2002)
- Cróquer, A., and E. Weil. 2009a. Changes in Caribbean coral disease prevalence after the 2005 bleaching event. *Dis. Aquat. Orgs.* 83:33-43.
- Cróquer, A., and E. Weil. 2009b. Spatial variability in distribution and prevalence of Caribbean scleractinian coral and octocoral diseases. II. General-level analysis. *Dis. Aquat. Orgs.* 83:209-222.
- Dahdouh-Guebas, F., Jayatissa, L.P., Di Nitto, D., Bosire, J.O., Lo Seen, D and Koedam, N. 2005. Current biology, Vol. 15, No 12 pp443-447.
- Dahdouh-Guebas, F. 2006. "Mangrove forests and tsunami protection", In: "McGray Hil Yearbok of Science and Technology", McGraw-Hill Professional, New York, USA, pp. 187-191.
- Dalebout, M. L., J. G. Mead, C. Scott Baker, A. N. Baker and A. L. van Helden. (2002). A new species of beaked whale *Mesoplodon perrini* sp. n. (Cetacea: Ziphiidae) discovered through phylogenetic analyses of mitochondrial DNA sequences. *Marine Mammal Science* 18:577-608.

- Dam Roy, S and Krishnan, P (2005). "Mangrove stands of Andaman vis-avis tsunami." *Current Science* Vol 89 No. 11, pp. 1800-1804.
- Das, S. and J.R. Vincent. 2008. Mangroves protected villages and reduced death toll during Indian super cyclone *Sustainability Science*
- Das, S., and R. Bellamy. 2007. Mangroves-A Natural Defense against Cyclones, South Asian Network for Development and Environmental Economics (SANDEE) Policy Brief 24-07.
- De'ath, G., J.M. Lough, and K.E. Fabricius, 2009: Declining Coral Calcification on the Great Barrier Reef. *Science*, 323, 116-119.
- Delannoy, C. A. (1997). "Status of the Broad-Winged Hawk and Sharp-Shinned Hawk in Puerto Rico." *Caribbean Journal of Science* 33: 21-33.
- Daufresne, M., K. Lengfellner, and U. Sommer. 2009. Global warming benefits the small in aquatic ecosystems. *Proceedings of the National Academy of Sciences* 106:788-793.
- Day, J. W., R. R. Christian, D. M. Boesch, A. Yáñez-Arancibia, J. Morris, R. R. Twilley, L. Naylor, L. Schaffner, and C. Stevenson. 2008. Consequences of climate change on the ecogeomorphology of coastal wetlands. *Estuaries and Coasts* 31:477-491.
- (DEFRA) Department for Environment, Food and Rural Affairs. 2005. Charting progress: An integrated assessment of the State of the UK Seas. Defra, London, 120 pp.
- Dennis, G D., D. Hensley, P. L. Colin, and J. J. Kimmel. 2004. New Records of Marine Fishes from the Puerto Rican Plateau. *Caribb. J. Sci.* 40(1):70-87
- Derner, J.D., Schuman, G.E., 2007. Carbon sequestration and rangelands: a synthesis of land management and precipitation effects. *Journal of Soil and Water Conservation* 62, 77-85.
- Diaz-Pulido, G., and McCook, L. J. (2002). The fate of bleached corals: patterns and dynamics of algal recruitment. *Marine Ecology Progress Series* 232, 115-128. doi:10.3354/MEPS232115
- Diaz-Pulido G, McCook LJ, Dove S, Berkelmans R, Roff G, et al. (2009) Doom and Boom on a Resilient Reef: Climate Change, Algal Overgrowth and Coral Recovery. *PLoS ONE* 4(4): e5239. doi:10.1371/journal.pone.0005239
- Dixson, D. L., P. L. Munday, and G. P. Jones. 2010. Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues. *Ecology Letters* 13:68-75.
- Dmiél, R. 1972. Effect on activity and temperature on metabolism and water loss in snakes. *American Journal of Physiology* 223:510-516.
- Donaldson, E.M. (1990) Reproductive indices as measures of the effects of environmental stressors. *Am. Fish. Soc. Symp.* 8, 145-166.
- Donelson, J. M., P. L. Munday, M. I. McCormick, N. W. Pankhurst, and P. M. Pankhurst. 2010. Effects of elevated water temperature and food availability on the reproductive performance of coral reef reef. *Marine Ecology Progress Series* 401:233-243.
- Doney, S., V. Fabry, R. Feely, and J. A. Kleypas. 2009. Ocean acidification: The other CO2 problem. *Annual Review of Marine Science* 1:169-192.
- Drexler, J.Z. and K.C. Ewel. 2001. Effect of the 1997-1998 ENSO-related drought on hydrology and salinity in a Micronesian wetland complex. *Estuaries* 24: 347-356.
- Duarte, C.M and C.L. Chiscano. 1999. Seagrass biomass and production: A reassessment. *Aquatic Botany* 65: 159-174.
- Duellman, W.E. & L. Trueb. 1994. *Biology of Amphibians*, second edition. The Johns Hopkins University Press, Baltimore, Maryland.
- Duellman, W.E. 1999. The West Indies and Middle America: contrasting origins and diversity. In Crother, B. I., ed. *Caribbean Amphibians and Reptiles*. Academic Press, Hartcourt Brace and Company, San Diego, California, U.S.A., pp. 357-369.
- Duffy, J.E. and J.J. Stachowicz. 2006. Why biodiversity is important to oceanography: potential roles of genetic, species, and trophic diversity in pelagic ecosystem processes. *Marine Ecology Progress Series* 311:179-189.
- Eakin, C. M., J. A. Morgan, T. B. Smith, G. Liu, L. Alvarez-Filip, B. Baca, C. Bouchon, M. Brandt, A. Bruckner, A. Cameron, L. Carr, M. Chiappone, M. James, C. Crabbe, O. Day, E. de la Guardia-Llanso, D. DiResta,

- D. Gilliam, R. Ginsburg, S. Gore, H. Guzmán, E. A. Hernández-Delgado, E. Husain, C. Jeffrey, R. Jones, E. Jordán-Dahlgren, P. Kramer, J. Lang, D. Lirman, J. Mallela, C. Manfrino, J. P. Maréchal, J. Mihaly, J. Miller, E. Mueller, E. Muller, M. Noordeloos, H. Oxenford, D. Ponce-Taylor, N. Quinn, K. Ritchie, S. Rodríguez, A. Rodríguez-Ramírez, S. Romano, J. Samhuri, G. Schmahl, S. Steiner, M. Taylor, S. Walsh, E. Weil, and E. Williams. 2010. Caribbean corals in crisis: Record thermal stress, bleaching and mortality in 2005. *PLoS ONE* 5.
- Edmunds, P.J. 2004. Juvenile coral population dynamics track rising seawater temperature on a Caribbean reef. *Mar. Ecol. Progr. Ser.* 269:111-119.
- Ellison, A. M., E. J. Farnsworth, and R. R. Twilley. 1996. Facultative mutualism between red mangroves and root-fouling sponges in Belizean mangal. *Ecology* 77: 2431-2444.
- Ellison JC (2000) How South Pacific mangroves may respond to predicted climate change and sea level rise. In: *Climate Change in the South Pacific: Impacts and Responses in Australia, New Zealand and Small Islands States*. Kluwer Academic Publishers, Dordrecht.
- Ellison JC (2004) Vulnerability of Fiji's mangroves and associated coral reefs to climate change. Review for the World Wildlife Fund. Launceston, Australia, University of Tasmania.
- Ellison, J.C. 2005. Impacts on mangrove ecosystems. *The Great Greenhouse Gamble: A conference on the Impacts of Climate Change on Biodiversity and Natural Resource Management: Conference Proceedings*, Sydney, NSW, EJ.
- Epstein PR, Sherman BH, Siegfried ES, Langston A, Prasad S, McKay B (eds) (1998) *Marine ecosystems: emerging diseases as indicators of change: health of the oceans from Labrador to Venezuela*. Year of the Ocean Special Report. The Center for Health and the Global Environment, Harvard Medical School, Boston, MA
- Erdman and Grana 2007. Coastal fishes in Puerto Rico
- Erftemeijer, P.L., B. Riegl, B.W. Hoeksema, P.A. Todd. 2012. Environmental impacts of dredging and other sediment disturbances on corals: a review. *Marine Pollution Bulletin* 64(9): 1737-65
- (ETI) Estudios Técnicos Inc. 2007. Valoración económica de los arrecifes de coral y ambientes asociados en el Este de Puerto Rico: Fajardo, Arrecifes La Cordillera, Vieques y Culebra. Informe final. Sometido al: Departamento de Recursos Naturales y Ambientales 27 de diciembre de 2007.
- Ewel, J. J., and J. L. Whitmore. 1973. The Ecological Life Zones of Puerto Rico and then Virgin Islands. in U. S. F. Service, editor. U.S. Department of Agriculture.
- Fabry, V., B. Seibel, R. Feely, and J. Orr. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. *ICES Journal of Marine Science* 65(3):414-432.
- Falkowski, P. G., R. T. Barber, and V. Smetacek. 1998. Biogeochemical Controls and Feedbacks on Ocean Primary Production. *Science* 281:200.
- Farrell, A. P. 1997. Effects of temperature on cardiovascular performance. Pages 135-158 in C. Wood and D. McDonald, editors. *Global Warming: Implications for Freshwater and Marine Fish*, Society for Experimental Biology Seminar Series 61. Cambridge University Press, Cambridge, UK.
- Feagin, R.A., N. Mukherjee, K. Shanker, A.H. Baird, J. Cinner, A.M. Kerr, N. Koedam, A. Sridhar, R. Arthur, L.P. Jayatissa, D. L. Seen, M. Menon, S. Rodriguez, Md. Shamsuddoha and F. Dahdough-Guebas. 2009. Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters. *Conservation Letters* 3(1): 1-11.
- Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, V.J. Fabry, F.J. Millero. 2004. Impact of anthropogenic CO₂ on the CaCO₃ system in the oceans. *Science (New York, N.Y.)* 305 (5682) p. 362-6
- Ferguson, M.W.J. & T. Joanen. 1982. Temperature of egg incubation determines sex in *Alligator mississippiensis*. *Nature* 296:850-853.
- Ferguson, M.W.J. & T. Joanen. 1983. Temperature Dependent Sex Determination in *Alligator mississippiensis*. *J. Zool. Lend.* 200: 143-177.
- Field, C.D. 1995. Journey amongst mangrove. *International Society for Mangrove Ecosystems*, Okinawa, Japan.
- Fish, M. R., I. M. Cote, J. A. Gill, A. P. Jones, S. Renshoff, and A. Watkinson. 2005. Predicting the impact of

- sea level rise on Caribbean sea turtles nesting habitat. *Conservation Biology* 19:482-491.
- Fitt, W.K., Brown, B.E., Warner, M.E and Dunne R.P. 2001. Coral bleaching: interpretation of thermal tolerance limits and thermal thresholds in tropical corals. *Coral Reefs*, 20, 51-65.
- Fosberg, F. R. (1971), "Mangroves verses tidal waves", *Biological Conservation*, 4: 38-39
- Foster, P. 2001. The potential negative impacts of global climate change on tropical montane cloud forests. *Earth-Science Reviews* 55:73-106.
- Gagliano, M., M. I. McCormick, and M. G. Meekan. 2007. Survival against the odds: Ontogenetic changes in selective pressure mediate growth-mortality trade-offs in a marine fish. *Proceedings of the Royal Society* 274.
- Galgano, F. A., S. P. Leatherman, and B. C. Douglas. 2004. Inlets Dominate U.S. East Coast Shoreline Change. *Journal of Coastal Research*.
- Gao, X. and J. Xu. 2002. Impact of Rizhao coastal area exploitation on inter-tidal habitats and zoobenthic communities. *Studia Marina Sinica*. 44:61-65.
- Garcia-Rios, C.I., 2001. Praderas de hierbas marinas. <<http://cuhttpwww.upr.clu.edu/~cgarcia/ecologiacostanera/Clase/Tha-001/THALASIA.98.htm>>. Accessed on April 2007.
- García-Sais, J. R., R. S. Appeldoorn, A. Bruckner, C. Caldow, J.D. Christensen, C. Lilyestrom, M.E. Monaco, J. Sabater, E. Williams, E. Diaz. 2003. The State of Coral Reef Ecosystems of the Commonwealth of Puerto Rico. NOAA [Online: http://ccma.nos.noaa.gov/ecosystems/coralreef/coral_report_2005/PR_Ch5_C.pdf]
- García-Sais, J. R., R. S. Appeldoorn, T. Batista, L. Bauer, A. Bruckner, C. Caldow, L. M. Carruba, J. Corredor, E. Díaz, C. Lilyestrom, G. García-Moliner, E. Hernández-Delgado, C. Menza, J. Morell, A. Pait, J. Sabater, E. Weil, E. Williams, and S. Williams. 2008. The state of coral reef ecosystems in Puerto Rico. Page 569 in J. E. Waddell and A. M. Clarke, editors. *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008*. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team, Silver Spring, MD.
- Gardner, L. R., I. M. Côté, J. A. Gill, A. Grant, and A. R. Watkinson. 2005. Hurricanes and Caribbean coral reefs: Impacts, recovery patterns, and role in long-term decline. *Ecology* 86:174-184.
- Gardner, T. A., I. M. Côté, J. A. Gill, A. Grant, and A. R. Watkinson. 2003. Long-term region-wide declines in Caribbean corals. *Science* 301:958-960.
- Garrison, V. H., E. A. Shinn, W. T. Foreman, D. W. Griffin, C. W. Holmes, C. A. Kellogg, M. S. Majewski, L. L. Richardson, K. B. Ritchie, and G. W. Smith. 2003. African and Asian dust: from desert soils to coral reefs. *BioScience* 53:469-480.
- Geiser D.M., J.I. Pitt, J.W. Taylor. 1998. Cryptic speciation and recombination in the aflatoxin-producing fungus *Aspergillus flavus*. *Proceedings of the National Academy of Sciences, USA*, 95, 388-393.
- GEOHAB. 2001. Global Ecology and Oceanography of Harmful Algal Blooms, Science Plan. P. Glibert and G. Pitcher (eds.), SCOR and IOC, Baltimore and Paris, 86 pp.
- GEOHAB 2005. Global Ecology and Oceanography of Harmful Algal Blooms, GEOHAB Core Research Project: HABs in Upwelling Systems. G. Pitcher, T.Moita, V. Trainer, R. Kudela, P. Figueiras, T. Probyn (Eds.) IOC and SCOR, Paris and Baltimore.82 pp.
- Gerlach, G., J. Atema, M. J. Kingsford, K. Black, and V. Miller-Sims. 2007. Smelling home can prevent dispersal of reef fish larvae. *Proceedings of the National Academy of Sciences of the United States of America* 104:858-863.
- Gibbons, J.W., D.E. Scott, T.J. Ryan, K.A. Buhlmann, T.D. Tuberville, B.S. Metts, J.L. Greene, T. Mills, Y. Leiden, S. Poppy & C.T. Winne. 2000. The global decline of reptiles, déjà vu amphibians. *BioScience* 50:653-666.
- Gilbes-Santaella, F. 2003. Comparative study of the conditions in La Parguera and Puerto Mosquito: the dangers of sedimentation and development pressure.
- Gill, T. 1931. *Tropical forests of the Caribbean*. Baltimore, MD: The Resad-Taylor Co. 318 p.
- Gilman, E., H. Van Lavieren, J. Ellison, V. Jungblut, L. Wilson, F. Areki, G. Brighthouse, J. Bungitak, E. Dus, M. Henry, I. Sauni Jr., M. Kilman, E. Matthews, N. Teariki-Ruatu, S. Tukia, K. Yuknavage. 2006.

- Pacific Island Mangroves in a Changing Climate and Rising Sea. UNEP Regional Seas Reports and Studies No. 179. United Nations Environment Programme, Regional Seas Programme, Nairobi, KENYA. Gilman, E., J. Ellison & R. Coleman. 2007. Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position. *Environmental Monitoring and Assessment* 124:105–130.
- Gladfelter EH, Monahan RK, Gladfelter WB (1978) Growth rates of five reef-building corals in the northeastern Caribbean. *Bull Mar Sci* 28: 728-734 Glynn, P. W. 1988. El Niño-Southern Oscillation 1982-1983: Nearshore population, community, and ecosystem responses. *Annual Review of Ecology and Systematics* 19:309-345.
- Glynn, P.W. 1993. Coral-reef bleaching – ecological perspectives. *Coral Reefs*, 12, 1-17.
- Glynn PW. 1996. Coral reef bleaching: facts, hypotheses and implications. *Global Change Biology* 2:495-509.
- Glynn, P. W., L. R. Almodovar, and J. G. Gonzalez. 1964. Effects of hurricane Edith on marine life in La Parguera, Puerto Rico. *Caribbean Journal of Science* 4:335-345.
- Glynn, P.W. 2000. El Niño-Southern Oscillation mass mortalities of reef corals: a model of high temperature marine extinctions? In: *Carbonate Platform Systems: Components and Interactions*, edited by E. Insalaco, P.W. Skelton, and T.J. Palmer. Geological Society of London, Special Publications 178: 117-133.
- Glynn, P.W., Mate, J.L., Baker, A.C. and Calderon, M.O. 2001. Coral bleaching and mortality in Panama and Ecuador during the 1997-1998 El Niño Southern Oscillation event: spatial/temporal patterns and comparisons with the 1982-1983 event. *Bulletin of Marine Science* 69: 79-109
- Goenaga, C., and M. Canals. 1979. Relación de mortandad masiva de *Millepora complanata* con alta pluviosidad y escorrentía del Río Fajardo en Cayo Ahogado, Fajardo. Sexto simposio de los Recursos Naturales Departamento de Recursos Naturales y Ambientales, San Juan, PR.
- Goenaga, C., and G. Cintrón. 1979. Inventory of Puerto Rican coral reefs. Department of Natural and Environmental Resources, San Juan, PR.
- Goenaga, C., V. P. Vicente, and R. A. Armstrong. 1989. Bleaching induced mortalities in reef corals from La Parguera, Puerto Rico: A precursor of change in the community structure of coral reefs? *Caribbean Journal of Science* 25:59-65.
- Goenaga, C. 1990. Efecto de huracanes sobre los arrecifes de coral en Puerto Rico. Ponencia ante la Conferencia de Huracanes, junio 7 de 1990, Departamento de Recursos Naturales y Ambientales, San Juan, PR 16 pp.
- Goh, B. P. L., and C. S. Lee. 2010. A study of the effect of sediment accumulation on the settlement of coral larvae using conditioned tiles. Page 5 in *Proceedings of the 11th International Coral Reef Symposium, Session 24*.
- Gold, K. 1965. A note on the distribution of luminescent dinoflagellates and water constituents in Phosphorescent Bay, Puerto Rico. *Ocean* 1:77-80.
- Goenaga, C. 1986. Los arrecifes costaneros en Puerto Rico: Estado actual e implicaciones sociales. *Bol. Cien. Sur.* 13(2):78-91.
- Goenaga, C. 1988. The distribution and growth of *Montastrea annularis* (Ellis and Solander) in Puerto Rican inshore
- Goenaga C, 1990. Efecto de huracanes sobre los arrecifes de coral en Puerto Rico. Ponencia ante la Conferencia de Huracanes, junio 7 de 1990, Departamento de Recursos Naturales, San Juan, P.R. 16 pp.
- Goenaga, C. 1991. The state of coral reefs in the wider Caribbean. *Interciencia* 16:12-20.
- Goenaga, C. and R. H. Boulon. 1992. The State of Puerto Rican and U.S. Virgin Islands Corals: An Aid to Managers. Report submitted to Caribbean Fisheries Management Council, Hato Rey, P.R. 66 pp.
- Liboy, J. G. 2005 (Year of Digitization). An Examination of the Present Condition of Seagrass Meadows in La Parguera, Puerto Rico. Online [Access Date September 10 2012]: <http://www.aoml.noaa.gov/general/lib/CREWS/Cleo/PuertoRico/prpdfs/liboy-seagrass.pdf>

- Goudriaan, J., 1993. Interaction of ocean and biosphere in their transient responses to increasing atmospheric CO₂. *Vegetatio* 104/105, 329±337.
- Gould, W. A., G. González, and G. Carrero Rivera. 2006. Structure and composition of vegetation along an elevational gradient in Puerto Rico. *Journal of Vegetation Science* 17:653-664.
- Gould, W. A., G. Gonzalez, A. T. Hudak, T. N. Hollingsworth, and J. Hollingsworth. 2008b. Forest Structure and Downed Woody Debris in Boreal, Temperate, and Tropical Forest Fragments. *Ambio* 37:577-587.
- Gould WA, Alarcón C, Fevold B, Jiménez ME, Martinuzzi S, Potts G, Quiñones M, Solórzano M, Ventosa E. 2008a. The Puerto Rico Gap Analysis Project. Volume 1: Land cover, vertebrate species distributions, and land stewardship. Gen. Tech. Rep. IITF-GTR-39. Río Piedras, PR: U.S. Department of Agriculture, Forest Service, International Institute of Tropical Forestry. 165 p.
- Gould WA.; González G, Carrero Rivera G. 2006. Structure and composition of vegetation along an elevational gradient in Puerto Rico. *Journal of Vegetation Science*. 17: 653-664.
- Gunderson, A.R. & M. Leal. 2012. Geographic variation in vulnerability to climate warming in a tropical Caribbean lizard. *Functional Ecology* DOI: 10.1111/j.1365-2435.2012.01987.x
- Green and Short 2003. Seagrasses and where they grow
- Greenway, M. 1995. Trophic relationships of macrofauna within a Jamaica seagrass meadow and the role of the echinoid *Lythechinus variegatus* (Lamarck). *Bulletin of Marine Science* 56:719-736.
- Griffith, D., M. V. Pizzini, and C. G. Quijano. 2007. Overview Vol. I in *Entangled Communities: Socioeconomic Profiles of Fishers, Their Communities and Their Responses to Marine Protective Measures in Puerto Rico*. J. J. Agar and B. Stoffle, eds. Miami, FL: NOAA Technical Memorandum NMFS-SEFSC-556.
- *Haines, H., W. C. Kleese, 1977. Effect of warm water temperature on a herpesvirus infection of sea turtles. 15:756-759. Hallegraeff, G., J. Beardall, S. Brett, M. Doblin, W. Hosja, M. de Salas, and P. Thompson. 2009. Phytoplankton in E. S. Poloczanska, A. J. Hobday, and A. J. Richardson, editors. *A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009*.
- Harley, C. D., H. A. Randall, K. M. Hultgren, B. G. Miner, C. J. Sorte, C. S. Thornber, L. F. Rodriguez, L. Tomanek, and S. L. Williams. 2006. The impacts of climate change in coastal marine systems. *Ecology Letters* 9:228-241.
- Harlin, M.M., Thorne-Miller, B., Boothroyd, J., 1982. Seagrass-sediment dynamics of a flood-tidal delta in Rhode Island (USDA). *Aquatic Botany* 14, 127-138.
- Harmelin-Vivien, M. L. 1994. The effects of storms and cyclones on coral reefs: a review. *Journal of Coastal Resources Special Issue No. 12*:211-231.
- Harmelin-Vivien, M. L., and P. Laboute. 1986. Catastrophic impact of hurricanes on atoll outer reef slopes in the Tuamotu (French Polynesia). *Coral Reefs* 5.
- Harty, C. 2004. Planning strategies for mangrove and saltmarsh changes in Southeast Australia. *Coastal Management* 32: 405-415. Harvell CD, Kim K, Burkholder JM, Colwell RR, Epstein PR, Grimes DJ, Hofmann EE, Lipp EK, Osterhaus ADME, Overstreet RM, Porter JW, Smith GW, Vasta GR (1999) Emerging marine diseases: climate links and anthropogenic factors. *Science* 285:1505-1510
- Harvell, C. D., C. E. Mitchell, J. R. Ward, S. Altizer, A. P. Dobson, R. S. Ostfield, and M. D. Samuel. 2002. Climate warming and disease risks for terrestrial and marine biota. *Science* 296:2158-2162.
- Harwood J. (2001) Marine mammals and their environment in the twenty-first century. *Journal of Mammalogy* 82, 630-640 Hassan, R., R. Scholes, N. Ash. 2005. *Millennium Ecosystem Assessment*. Island Press, Washington, DC.
- Hastings, J. W. 1983. Chemistry and control of luminescence in marine organisms. *Bulletin of Marine Science* 33:818-828.
- Hawkins, J. P., and C. M. Roberts. 2004. Effects of artisanal fishing on Caribbean coral reefs. *Conservation Biology* 18:215-226.
- Hays, G. C., A. J. Richardson, and C. Robinson. 2005. Climate change and marine plankton. *Trends in Ecology & Evolution* 20:337-344.

- Hemminga, M., and C. M. Duarte. 2000. *Seagrass Ecology: An Introduction*. Cambridge University Press, Cambridge, U.K.
- Hernández-Becerril, D.U. 1995. Planktonic diatoms from the Gulf of California and coasts off Baja California: the genera *Rhizosolenia*, *Proboscia*, *Pseudosolenia*, and former *Rhizosolenia* species. *Diatom Res.*, 10: 251-267
- Hernández-Delgado, E. A. 1992. Coral reef status of northeastern and eastern Puerto Rican waters: Recommendations for long-term monitoring, restoration and a coral reef management plan. Submitted to the Caribbean Fishery Management Council, Hato Ray, Puerto Rico.
- Hernández-Delgado, E.A. 2000. Effects of anthropogenic stress gradients in the structure of coral reef fish and epibenthic communities. Ph.D. Dissertation, Dept. Biology, University of Puerto Rico, San Juan, P.R. 330 pp.
- Hernández-Delgado, E.A., L. Alicea-Rodriguez, C.G. Toledo-Hernandez, and A.M. Sabat. 2000. Baseline characterization of coral reef epibenthic and fish communities within the proposed Culebra Island Marine Fishery Reserve, Puerto Rico. *Proceedings of the Gulf Caribbean Fisheries Institute*. 51: 537-556.
- Hernández Delgado, E.A., & L. Alicea Rodríguez. 1993. Estado ecológico de los arrecifes de coral en la costa este de Puerto Rico: I. Bahía Demajagua, Fajardo, y Playa Candelero, Humacao. *Memorias del XII Simposio de la Fauna y Flora del Caribe*, 30 de abril de 1993, Depto. Biología, Recinto Universitario de Humacao, Humacao, P.R. 2-23.
- Hernandez-Delgado, E.A. and A.M. Sabat. 2000. Ecological status of essential fish habitats through and anthropogenic environmental stress gradient in Puerto Rican coral reefs. *Proceedings of the Gulf and Caribbean Fisheries Institute*. Creswell, R. L. (ed.), 51: 457-470.
- Hernández-Delgado, E. A. 2005. Historia natural, caracterización, distribución y estado actual de los arrecifes de coral Puerto Rico. 281-356. Page 563 in R. L. Joglar, editor. *Biodiversidad de Puerto Rico: Vertebrados Terrestres y Ecosistemas*. Serie Historia Natural. Editorial Instituto de Cultura Puertorriqueña, San Juan, PR.
- Hernández-Delgado, E. A., A. Alvarado, R. Laureano, K. Flynn, and S. Griffin. 2011. Seawall Construction Activities Cause a Localized Mass Mortality of Threatened Elkhorn Coral (*Acropora palmata*) at Vega Baja, Puerto Rico. *Proceedings of the Gulf Caribbean Fisheries Institute* 63:511.
- Hernández-Delgado, E. A., C. E. Ramos-Scharrón, C. Guerrero, M. A. Lucking, R. Laureano, P. A. Méndez-Lázaro, and J. O. Meléndez-Díaz. 2012. Long-term impacts of tourism and urban development in tropical coastal habitats in a changing climate: Lessons learned from Puerto Rico. Pages 357-398 in M. Kasimoglu, editor. *Visions from Global Tourism Industry- Creating and Sustaining Competitive Strategies*. Intech Publications.
- Hernández-Delgado, E. A., S.E.Suleiman-Ramos, M.A. Lucking, R. Laureano, J. Fonseca, P. Alejandro, I. Olivo, A. Archilla, S. Griffin, P. Rodriguez. 2012. Low-tech community-based management tools for coral reef adaptation to climate change: Case studies from Puerto Rico. Poster. *Adaptation Futures*. 2012 International Conference on Climate Adaptation 29-31 May 2012.
- Hernández-Delgado, E. A., and B. Sandoz-Vera. 2011. Impactos antropogénicos en los arrecifes de coral. 62-72. . Page 255 in J. Seguinot-Barbosa, editor. *Islas en Extinción: Impactos Ambientales en las Islas de Puerto Rico*. Ediciones SM, Cataño, PR.
- Hernández-Delgado, E. A., B. Sandoz, M. Bonkosky, H. Mattei, and J. Norat. 2010. Impacts of nonpoint source sewage pollution in elkhorn coral, *Acropora palmara* (Lamarck), assemblages of the southwestern Puerto Rico shelf. Pages 747-751 in *Proceedings of the 11th International Coral Reefs Symposium*.
- Hernández-Pacheco, R., E. A. Hernández-Delgado, and A. M. Sabat. 2011. Demographics of bleaching in the Caribbean reef-building coral *Montastraea annularis*. *Ecosphere* 2:1-13.
- Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research* 50:839-866.
- Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, P. F. Sale,

A. J. Edwards, K. Caldeira, N. Knowlton, C. M. Eakin, R. Iglesias-Prieto, N. Muthiga, R. H. Bradbury, A. Dubi, and M. E. Hatzioios. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318:1737-1742.

Hoegh-Guldberg, O., and B. Salvat. 1995. Periodic mass-bleaching and elevated sea temperatures: bleaching of outer reef slope communities in Moorea, French Polynesia. *Marine Ecology Progress Series* 121:181-190.

Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine & Freshwater Research* 50: 839-66.

Hoegh-Guldberg, O. et al. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318: 1737-1742.

Hoegh-Guldberg, O. and Bruno, JF. 2010. The Impact of Climate Change on the World's Marine Ecosystems. *Science* 328: 1523 – 1528

Hoey AS, Bellwood DR (2009) Limited functional redundancy in a high diversity system: single species dominates key ecological process on coral reefs. *Ecosystems* 12:1316–1328

Holbrook, S. J., R. J. Schmitt, and J. S. Stephens Jr. 1997. Changes in an assemblage of temperate reef fish associated with a climate shift. *Ecological Applications* 7:1299-1310.

Howard, R.J. & I.A. Mendelssohn. 1999. Salinity as a constraint on growth of oligohaline marsh macrophytes. II. Salt pulses and recovery potential. *American Journal of Botany* 86:795–806.

Houde, E. 1989. Comparative growth, mortality, and energetics of marine fish larvae: Temperature and implied latitudinal effects. *Fishery Bulletin US* 87:471-495.

Huertas, I. E., M. Rouco, V. López-Rodas, and E. Costas. 2011. Warming will affect phytoplankton differently: evidence through a mechanistic approach. *Proc. R. Soc. B*.

Hughes, A.R. and J.J. Stachowicz. 2004. Genetic diversity enhances the resistance of a seagrass ecosystem to disturbance. *Proceedings of the National Academy of Sciences* 101:8998-9002
 Hughes, A. R., and J. J. Stachowicz. 2011. Seagrass genotypic diversity increases disturbance response via complementarity and dominance *Journal of Ecology* 99:1365-2745.

Hughes, A. R., J. J. Stachowicz, and G. D. Tilman. 2004. Genetic diversity enhances the resistance of a sea grass ecosystem to disturbance. *Proceedings of the National Academy of Sciences of the United States of America* 101:8998-9002.

Hughes, T. P. 1994. Catastrophes, phase shifts and large-scale degradation of a Caribbean coral reef. *Science* 265:1547-1551.

Hughes, T. P., A. H. Baird, D. R. Bellwood, M. Card, S. R. Connolly, C. Folke, R. Grosberg, O. Hoegh-Guldberg, J. B. Jackson, J. Kleypas, J. M. Lough, P. Marshall, M. Nystrom, S. R. Palumbi, J. M. Pandolfi, B. Rosen, and J. Roughgarden. 2003. Climate change, human impacts, and the resilience of coral reefs. *Science* 301:929-933.

Hunt Von Herbing, I. 2002. Effects of temperature on larval fish swimming performance: The importance of physics. *Journal of Fish Biology* 61:865-876.

Hunte, W. 1987. Summary of available database on oceanic pelagic fisheries in the Lesser Antilles. In: Mahon, R., (Ed.) Report and proceedings of the expert consultation on shared fishery resources of the Lesser Antilles. FAO Fish. Rep. 383, 125-176. ISBN: 92-5-102577-0

Hutchings, P. and Saenger, P. 1987. *Ecology of Mangroves*. Queensland University Press.

IPCC 2007: impacts, adaptation and vulnerability. In: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 23–78.

Interior, U. S. D. o. 1986. The bioluminescent bays of Puerto Rico: A plan for their preservation (IUCN) International Union for Conservation of Nature. N.D. Invasive Species. [online] Available at: <http://www.iucn.org/about/union/secretariat/offices/iucnmed/iucn_med_programme/species/invasive_species/> [Accessed 16 April 2012]. IUCN. 2012. The IUCN Red List of Threatened Species: Amphibians: Geographic Patterns. In IUCN, editor.

Jackson, J.B.C..1997. Reefs since Columbus. *Coral Reefs* 16(Suppl):S23–S32

- Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury R, Cooke R, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ, Warner R (2001) Historical overfishing and the recent collapse of coastal ecosystems. *Science* 293:629–638.
- Jacobson, E.R. 1993. Implications of infectious diseases for captive propagation and introduction programs of threatened/endangered reptiles. *Journal of Zoo and Wildlife Medicine* 24:245–255.
- James, K.R., Hart, B.T., 1993. Effect of salinity on four freshwater macrophytes. *Aust. J. Mar. Freshwater Res.* 44, 769–777.
- Jameson, S. C., J. M. McManus, and M. D. Spalding. 1995. State of the reefs: regional and global perspectives. U.S. Department of State, Washington, D.C.
- Janzen, F.J. 1994. Climate change and temperature-dependent sex determination in reptiles. *Proceedings of the National Academy of Sciences, U.S.A.* 91:7487–7490.
- JBNERR. 2010. Jobos Bay National Estuarine Research Reserve Management Plan 2010-2015. The Puerto Rico Department of Natural and Environmental Resources.
- Jeffrey, C.F.G., P.W. Mueller, M.S. Kendall, K. Buja, K. Edwards, S.D. Hile, and L. Carrubba. 2010. Biogeographic Characterization of Essential Fish Habitats Affected by Human Activities in the Coastal Zone of Puerto Rico. NOAA Technical Memorandum NOS NCCOS 115. Silver Spring, MD. 31 pp.[online:http://ccma.nos.noaa.gov/ecosystems/coralreef/vieques/vieques_part_ii.pdf]
- Jenkins, G.P. and P.A. Hamer. 2001. Spatial variation in the use of seagrass and un-vegetated habitats by post-settlement King George whiting (*Percoidei: Sillaginidae*) in relation to meiofaunal distribution and macrophyte structure. *Marine Ecology Progress Series* 224: 219–229.
- Jiménez, J.A., A.E. Lugo, and G. Cintrón. 1985. Tree mortality in mangrove forests. *Biotropica* 17: 177–185.
- Jobling, M. 1997. Temperature and growth: Modulation of growth rate via temperature change. Pages 223–254 in C. M. Wood and D. G. McDonald, editors. *Global Warming: Implications for Freshwater and Marine Fish*, Society for Experimental Biology Seminar Series 61. Cambridge University Press, Cambridge, UK.
- Johnson, J.E. and Marshall, P.A. (eds.) 2007. *Climate Change and the Great Barrier Reef*. Great Barrier Reef Marine Park Authority and Australian Greenhouse Office, Australia.
- Jokiel, P. L., K. S. Rodgers, I. B. Kuffner, A. J. Andersson, E. F. Cox, and F. T. Mackenzie. 2008. Ocean acidification and calcifying reef organisms: A mesocosm investigation. *Coral Reefs* 27:473–483.
- Jones, G. P., M. I. McCormick, M. Srinivasan, and J. V. Eagle. 2004. Coral decline threatens fish biodiversity in marine reserves. *PNAS* 101:8251–8253.
- Kathiresan, K. 2000. Studies on Pichavaram mangroves, southeast India. *Hydrobiologia*, 430, 185–205
- Kendall, Matthew S.; Katherine A. Eschelbach. 2006. Spatial analysis of the benthic habitats within the limited-use zones around Vieques, Puerto Rico. *Bulletin of Marine Science*, 79(2): 389–400, 2006.
- Kennedy, V.S., R.R. Twilley, J.A. Kleypas, J.H.Cowan, Jr., S.R. Hare. 2002. *Coastal and Marine Ecosystems and Global Climate Change. Potential Effects on U.S. Resources*. Prepared for the Pew Center on Global Climate Change.
- Kim, K. and Harvell, C.D. 2001. Aspergillois of sea fan corals: disease dynamics in the Florida Keys, USA. In: Porter KG, Porter J (eds) *Linkages among ecosystems in the Florida Hydroscape*. CRC Press, Boca Raton, FL: 813–823 pp.
- Kingsford, M. J., J. M. Leis, A. Shanks, K. C. Lindeman, and e. al. 2002. Sensory environments, larval abilities and local self-recruitment. *Bulletin of Marine Science* 70:309–340.
- Kleypas, J. A., R. W. Buddemeier, D. Archer, J. P. Gattuso, C. Langdon, and B. N. Opdyke. 1999. Geochemical consequences of increased atmospheric CO₂ on coral reefs. *Science* 284:118–120.
- Kleypas, J.A., and C. Langdon. 2006. Coral reefs and changing seawater chemistry. Pp. 73–110 in *Coral Reefs and Climate Change: Science and Management*. J.T. Phinney, W. Skirving, J. Kleypas, and O. Hoegh-Guldberg, eds, American Geophysical Union, Washington, DC
- Kleypas, J. A., R. A. Feely, V. J. Fabry, O. Langdon, C. L. Sabine, and L. L. Robbins. 2006. Impacts of Ocean

Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research, report of a workshop held 18-20 April 2005. NSF, NOAA, USGS, St. Petersburg, FL.

- Kleypas, J.A., and C. Langdon. 2006. Coral reefs and changing seawater chemistry. Pp. 73–110 in *Coral Reefs and Climate Change: Science and Management*. J.T. Phinney, W. Skirving, J. Kleypas, and O. Hoegh-Guldberg, eds, American Geophysical Union, Washington, DC
- Knowlton, N. 2001. The future of coral reefs. *Proceedings of the National Academy of Sciences, U.S.A.* 98:5419-5425.
- Kjerfve, B., K.E. Magill, J.W. Porter, J.D. Woodley. 1986. Hindcasting of hurricane characteristics and observed storm damage on a fringing reef. Jamaica, West Indies. *J. mar. Res.* 44: 119-148.
- Kuffner, I. B., A. J. Andersson, P. L. Jokiel, K. S. Rodgers, and F. T. Mackenzie. 2008. Decreased abundance of crustose coralline algae due to ocean acidification. *Nature Geoscience* 54:548-559.
- Langdon, C. 2003. Review of experimental evidence for effects of CO₂ on calcification of reef builders. *Proceedings of the 9th International Coral Reef Symposium*. Bali, Indonesia, 23-27 October 2000, Vol. 2: 1091-1098.
- Larsen, M. C., and R. M. T. Webb. 2009. Potential effects of runoff, fluvial sediment, and nutrient discharges on the coral reefs of Puerto Rico. *Journal of Coastal Research* 25:189-208.
- Lassen, M. K., K. D. Nielsen, K. Richardson, K. Garde, and L. Schlüter. 2010. The effects of temperature increases on a temperate phytoplankton community - a mesocosm climate change scenario. *Journal of Experimental Marine Biology and Ecology* 383:79-88.
- Lessios, H. A. (1988). Population dynamics of *Diadema antillarum* (Echinodermata: Echinoidea) following mass mortality in Panamá. *Marine Biology* 99: 515-526.
- Ley, J. A., C. C. McIvor, and C. L. Montague. 1999. Fishes in mangrove prop-root habitats of Northeastern Florida Bay: distinct assemblages across an estuarine Gradient. *Est. Coast. Shelf Sci.* 48: 701-723.
- Lillywhite, H.B. 1987. Temperature, Energetics, and Physiological Ecology. In Seigel, A., J.T. Collins & S.S. Novak, eds. *Snakes: ecology and evolutionary biology*. MacMillan Publ. Co., New York, pp 396-421.
- Ling, S. D., C. R. Johnson, K. Ridgway, A. J. Hobday, and M. Haddon. 2009. Climate-driven range extension of a sea urchin: Inferring future trends by analysis of recent population dynamics. *Global Change Biology* 15:719-731.
- Lionard, M., S. Roy, M. Tremblay-Létourneau, and A. Ferreyra. 2012. Combined effects of increased UV-B and temperature on the pigment-determined marine phytoplankton community of the St. Lawrence Estuary. *Marine Ecology Progress Series* 445:219-234.
- Lirman, D. and W.P. Cropper. 2003. The influence of salinity on seagrass growth, survivorship, and distribution within Biscayne Bay, Florida: field, experimental, and modeling studies. *Estuaries*, 26:131-141
- Little, E.L., Jr., Wadsworth, F.H. (1964): Common trees of Puerto Rico and the Virgin Islands. *Agriculture Handbook No. 249*, U.S. Department of Agriculture, Forest Service.
- Lloret, J., and A. Marín-Guirao. 2008. In coastal lagoon eutrophication likely to be aggravated by global climate change? *Estuarine, Coastal and Shelf Science* 78:403-412.
- Lomas, M. W., and E. M. Glibert. 2000. Comparisons of nitrate uptake, storage and reduction in marine diatoms and flagellates. *Journal of Phycology* 36:903-913.
- Losos, J.B., T.W. Schoener & D.A. Spiller. 2003. Effect of immersion in seawater on egg survival in the lizard *Anolis sagrei*. *Oecologia* 137:360–362.
- Lough JM, Barnes DJ. 1997. Several centuries of variation in skeletal extension, density and calcification in massive *Porites* colonies from the Great Barrier Reef: a proxy for seawater temperature and a background of variability against which to identify unnatural change. *J. Exp. Mar. Biol. Ecol.* 211:29–67
- Lough, J.M. and Barnes, D.J. 2000. Environmental controls on growth of the massive coral *Porites*. *Journal of Experimental Marine Biology and Ecology* 245: 225-243.
- Lough, J.M. 2001. Unprecedented thermal stress to coral reefs? *Geophysical Research Letters*, 27, 3901-

3904.

- Loya, Y. 1976. Effects of water turbidity and sedimentation on the community structure of Puerto Rican corals. *Bull. Mar. Sci.* 26(4):450-466.
- Lugo, A. E. 2000. Effects and outcomes of Caribbean hurricanes in a climate change scenario. *The Science of the Total Environment* 262:243-251.
- Lugo, A.E. 2005a. The ecosystems of the Luquillo Mountains. *Acta Cientifica*. 19(1-3): 3-6
- Lugo, A. E. 2005. "Los bosques." In *Biodiversidad de Puerto Rico. Vertebrados terrestres y ecosistemas*. Ed. R. L. Joglar. San Juan, PR: Editorial del Instituto de Cultura Puertorriqueña. 2005. pp. 395-548.
- Lugo, A. E., and L. M. Castro. 2001. Puerto Rican Karst - A Vital Resource. in U. S. F. Service, editor.
- Lugo, A.E., and G. Cintron. 1975. The mangroves of Puerto Rico and their management. In; G. Walsh, S. Snedaker, and H. Teas (Eds.). *Proceedings of the International Symposium on Biology and Management of Mangroves*, pp. 825-846. Inst. Food Agr. Sci., Univ. of Florida, Gainesville. 846 pp.
- Lugo, A. E., C. S. Rogers, and S. W. Nixon. 2000. Hurricanes, coral reefs and rainforests: Resistance, ruin and recovery in the Caribbean. *Ambio* 29:106-114.
- Lugo, A. E., AND E. HELMER. 2004. Emerging forests on abandoned land: Puerto Rico's new forests. *For. Ecol. Manage.* 190: 145-161.
- Lugo, A.E., and S.C. Snedaker. 1974. The ecology of mangroves. *Ann. Rev. Ecology and Systematics* 5: 39-64.
- Luthi, D., M. Floch, B. Bereiter, T. Blunier, and e. al. 2008. High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature* 435:379-382.
- Lybolt, M., D. Neil, J. Zhao, Y. Feng, K. F. Yu, and J. Pandolfi. 2011. Instability in a marginal coral reef: the shift from natural variability to a human-dominated seascape. *Frontiers in Ecology and the Environment* 9:154-160.
- Mahon, R. (Ed.). 1987. Report and proceedings of the expert consultation on shared fishery resources of the Lesser Antilles. FAO. Fish. Rep. 383, 278 pp
- Mahon, R. 1993. Lesser Antilles. In *marine fishery resources of the Antilles: Lesser Antilles, Puerto Rico and Hispaniola, Jamaica, Cuba*. FAO Fisheries Technical Paper No. 326, Rome, 235 p.
- Mann, M.E., Bradley, R.S. and Hughes, M.K. 2000. Long-term variability in the El Niño Southern Oscillation and associated teleconnections. In Diaz, H.F. and Markgraf, V. (Eds.) *El Niño and the Southern Oscillation: Multiscale Variability and its Impacts on Natural Ecosystems and Society*. Cambridge University Press, Cambridge, UK., 357-412.
- Margalef, R. 1961. Hidrografía y fitoplancton de un área marina de la costa meridional de Puerto Rico. *Investigación Pesquera* 18:33-96.
- Margalef R. 1978. Life-forms of phytoplankton as survival alternatives in an unstable environment. *Oceanol Acta* 1:493-509
- Margalef, R., and G. Gonzalez. 1958. Densification of phytoplankton in the vicinity of a shallow coast subjected to intense evaporation. Pages 14-15 in 2nd meeting of the Association of Island Marine Laboratories.
- Marić, D., R. Krause, J. Godrijan, N. Supić, T. Djakovic, and R. Precali. In press. Phytoplankton response to climatic and anthropogenic influences in the north-eastern Adriatic during the last four decades. *Estuarine, Coastal and Shelf Science*.
- Martin, S., R. Rodolfo-Metalpa, E. Ransome, S. Rowley, M. C. Buia, J. P. Gattuso, and J. Hall-Spencer. 2008. Effects of naturally acidified seawater on seagrass calcareous epibionts. *Biology Letters* 4:689-692.
- Martinuzzi, S., W. A. Gould, O. M. Ramos González, and B. Edwards. 2007. Development of a landforms model for Puerto Rico and its application for land cover change analysis. *Caribbean Journal of Science* 43:161-171.
- Martinuzzi, S., Gould, W.A., Lugo, A.E. and Medina, E. 2009. Conversion and recovery of Puerto Rican mangroves: 200 years of change. *Forest Ecology and Management* 257: 75-84
- Martinuzzi, S., Medina, W. A. Gould, and A. E. Lugo. 2009. Conversion and recovery of Puerto Rican

mangroves: 200 years of change. *Forest Ecology and Management* 257:75-84.

- Massel, S.R., Furukawa, K. and R.M. Brinkman, 1999, Surface wave propagation in mangrove forests, *Fluid Dynamic Research* 24 p.219-249
- Maul, G. A. 1993. Implications of future climate on the ecosystems and socio-economic structure in the marine and coastal regions of the Intra-Americas Sea. in G. A. Maul, editor. *Climatic change in the Intra-Americas Sea implications of future climate on the ecosystems and socio-economic structure in the marine and coastal regions of the Caribbean Sea, Gulf of Mexico, Bahamas, and the northeast coast of South America*. E. Arnold, London.
- McCain, C.M. & R.K. Colwell. 2011. Assessing the threat to montane biodiversity from discordant shifts in temperature and precipitation in a changing climate. *Ecology Letters* 14:1236–1245.
- McCallum, M.L., J.L. McCallum, & S.E. Trauth. 2009. Predicted climate change may spark box turtle declines. *Amphibia-Reptilia* 20:259–264.
- McClanahan, T., N. Polunin, and T. Done. 2002. Ecological states and the resilience of coral reefs. *Conservation Ecology* 6:18.
- McCoy, M. 1996. The seasonal, freshwater march at Palo Verde National Park. Pages 133-137 in A.J. Hails (ed), *Wetlands, Biodiversity and the Ramsar Convention: The Role of the Convention on Wetlands in the Conservation and Wise Use of Biodiversity*. Gland, Switzerland: Ramsar Convention Bureau.
- McKee, K.L., Cahoon, D.R. & Feller, I.C. 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecology and Biogeography*, 16, 545–556
- McKee, K.L. & McGinnis, T.E. (2002) Hurricane Mitch: effects on mangrove soil characteristics and root contributions to soil stabilization. USGS Open File Report OFR-02-178 (<http://www.nwrc.usgs.gov/hurricane/mitch/mckee%20rpt100702.pdf>).
- Mckenzie, F. and M. Benton. 1972. Biological inventory of the waters and keys of north-east Puerto Rico. Final report submitted to the Division of Natural Resources, Department of Public Works, San Juan, P.R. 90 pp.
- McLeod, E. and R.V. Salm. 2006. *Managing Mangroves for Resilience to Climate Change*. IUCN, Gland, Switzerland. 64p.
- McManus, J. M., L. A. B. Meñez, K. N. K. Reyes, S. G. Vergara, and M. C. Alban. 2000. Coral reef fishing and coral-algal phase shifts: implications for global reef status. *ICES Journal of Marine Science* 57:572-578.
- Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver & Z.-C. Zhao, 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Meesters, E.H., Bak, R.P.M., Westmacott, S., Ridgley, M., Dollar, S. 1998. A fuzzy logic model to predict coral reef development under nutrient and sediment stress. *Conservation Biol.* 12: 957-965
- Melkania, U., V. Singh, B. Bohra. 2007. Ecosystem diversity and carbon sequestration: challenges and a way out for ushering in a sustainable future. National conference.
- Meulen, van der, F. 1990. European dunes: Consequences of climate change and sealevel rise. In: Bakker, T.W., Jungerius, P.D. & Klijn, J.A. (eds.) *Dunes of the European coasts*. Catena Suppl. 18: 209-223
- Meyer, J.L., E.T. Schultz & G. Helfman. 1983. Fish schools: an asset to corals. *Science* 220: 1047-1049.
- Meylan, A., B. Schroeder, and A. Mosier. 1995. Sea turtle nesting activity in the State of Florida 1979-1992. Florida Marine Research Publications Number 52; St. Petersburg, Florida
- Micheli, F and B.S. Halpern. 2005. Low functional redundancy in coastal marine assemblages. *Ecol Lett* 8:391–400
- Michener, W. K., E. R. Blood, K. L. Bildstein, M. M. Brinson, and L. R. Gardner. 1997. Climate change, hurricanes and tropical storms, and rising sea level in coastal wetlands. *Ecological Applications* 7:770-801.
- Millennium Ecosystem Assessment. 2005. *Ecosystems and human well-being: synthesis*. Washington,

- DC: Island Press. ISBN 1-59726-040-1. Miller R.J., A.J. Adams, N.B. Ogden, J.C. Ogden, and J.P. Ebersole. 2003. *Diadema antillarum* 17 years after mass mortality: is recovery beginning on St. Croix? *Coral Reefs* 22:181-187.
- Miller, P.J.O., M. Johnson, and Tyack. P.L. 2004a. Sperm whale behavior indicates the use of echolocation click buzzes "creaks" in prey capture. *Biol. Lett.* 271: 2239-2247.
- Miller, P.J.O., M.P. Johnson, P.L. Tyack, E.A. Terray. 2004b. Swimming gaits, passive drag, and buoyancy of diving sperm whales (*Physeter macrocephalus*). *J. Exp. Biol.* 207: 1953-1967.
- Miller, J., R. Waara, E. Muller, and C. Rogers. 2006. Coral bleaching and disease combine to cause extensive mortality on reefs in U.S. Virgin Islands. *Coral Reefs* 25:418.
- Miller, G. L., A.E. Lugo, & International Institute of Tropical Forestry. 2009. Guide to the ecological systems of Puerto Rico. San Juan, P.R.: U.S. Dept. of Agriculture, Forest Service, International Institute of Tropical Forestry.
- Miller, J., E. Muller, C. Rogers, R. Waara, A. Atkinson, K. R. T. Whelan, M. Patterson, and B. Witcher. 2009. Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the U.S. Virgin Islands. *Coral Reefs* 28:925-937.
- Mimura, N., L. Nurse, R.F. McLean, J. Agard, L. Briguglio, P. Lefale, R. Payet and G. Sem, 2007: Small islands. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 687-716.
- Miranda-Azeiteiro, U., and J. C. Marques. 2003. Introducing "plankton responses to environmental variability". *Acta Oecologica* 24.
- Mitra, S., R. Wassmann, and P.L.G. Vlek. 2005. An appraisal of global wetland area and its organic carbon stock. *Current Science* 88 (1).
- Mitsch, W.J. & J.G. Gosselink. 2007. *Wetlands*, 4th Ed. John Wiley & Sons, Inc.
- Moore, L. J., B. T. Benumof, and G. B. Griggs. 1999. Coastal Erosion Hazards in Santa Cruz and San Diego Counties, California. *Journal of Coastal Research* 28:121-139.
- Moore, S. K., V. L. Trainer, N. J. Manuta, M. S. Parker, E. A. Laws, L. C. Backer, and L. E. Fleming. 2008. Impacts of climate variability and future climate change on harmful algal blooms and human health. *Environmental Health* 7:S4.
- Moran, X. A., A. Lopez-Urrutia, A. Calvo-Diaz, and W. K. W. Li. 2010. Increasing importance of small phytoplankton in a warmer ocean. *Global Change Biology* 16:1137-1144.
- Morelock, J. 1978 *Shoreline of Puerto Rico*. Coastal Zone Management Program, Department of Natural Resources, Commonwealth of Puerto Rico
- Morelock, J. 1984. Coastal Erosion in Puerto Rico. *Shore and Beach*: 18-27
- Morelock, J. and Barreto, M., 2003, An update of coastal erosion in Puerto Rico: *Shore and Beach*, v.71 n.1, p 7-12.
- Morris, I. 1981. The physiological ecology of phytoplankton. Page 625 in I. Morris, editor. *Studies in ecology*, v. 7. University of California Press, Berkeley and New York.
- Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. *Ecology* 83(10): 2869-2877.
- Morton, R. A., and K. K. McKenna. 1999. Analysis and Projection of Erosion Hazard Areas in Brazoria and Galveston Counties, Texas. *Journal of Coastal Research* 28:106-120.
- Moyle, PB and Cech, JJ (2004) *Fishes, An Introduction to Ichthyology*. 5th Ed, Benjamin Cummings. ISBN 978-0-13-100847-2
- Mrosovsky, N. 1988. Pivotal temperatures for loggerhead turtles (*Caretta caretta*) from northern and southern nesting beaches. *Can. J. Zool.* 66: 661 - 669.
- Mrosovsky, N. Kame. S. Diez, C.E., van Dam, R.P. 2009. Methods of estimating natural sex ratios of sea turtles from incubation temperatures and laboratory data. *Endangered Species Res.* 8: 147-155 pp.
- Muehlstein, L.K. 1989. Perspectives on the wasting disease of eelgrass *Zostera marina*. *Diseases of Aquatic Organisms* 7: 1-21.
- Muehlstein, L. K. & Beets, J. 1989. Seagrass Declines and Their Impacts on Fisheries. *Proceedings of the 42nd Gulf and Caribbean Fisheries Institute* Ocho Rios, Jamaica,

55-65 pp.

- Mumby, P.J. 2006. Connectivity of reef fish between mangroves and coral reefs: Algorithms for the design of marine reserves at seascape scales. *Biological Conservation* 128: 215-222.
- Munday, P. L., G. P. Jones, M. S. Pratchett, and A. Williams. 2008. Climate change and the future for coral reef fish. *Fish and Fisheries* 9:261-285.
- Munday, P. L., D. L. Dixon, J. M. Donelson, G. P. Jones, M. S. Pratchett, G. V. Devitsina, and K. B. Døving. 2009a. Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proceedings of the National Academy of Sciences of the United States of America* 106:1848-1852.
- Munday, P. L., J. M. Leis, J. M. Lough, C. B. Paris, M. J. Kingsford, M. L. Berumen, and J. Lambrechts. 2009b. Climate change and coral reef connectivity. *Coral Reefs* 28:379-395.
- Munro, J.L. 1983. Caribbean coral reef fisheries. Studies review 7. International Center for Living Aquatic Resource Management (ICLARM), Manila, Philippines.
- Murray, J.D. 2002. Temperature-Dependent Sex Determination (TSD): Crocodilian Survivorship. In *Mathematical Biology: I. An Introduction*, 3rd Ed. Springer-Verlag Berlin Heidelberg, pp. 119-145.
- Musick, J. A., and C. J. Limpus. 1997. Habitat utilization and migration in juvenile sea turtles. Pages 137-163 in P. L. Lutz and J. A. Musick, editors. *The Biology of Sea Turtles*. CRC Press, Boca Raton, FL.
- Nagelkerken I, M. Dorenbosch, WCEP Verberk, E. Cocheret de la Moriniere, G. van der Velde. 2000a. Day-night shifts of fishes between shallow-water biotopes of a Caribbean bay, with emphasis on the nocturnal feeding of Haemulidae and Lutjanidae. *Mar Ecol. Prog. Ser.* 194: 55-64.
- Nagelkerken, I., M. Dorenbosch, WCEP, Verberk, E. Cocheret de la Moriniere, G. van der Velde. 2000b. Importance of shallow-water biotopes of a Caribbean bay for juvenile coral reef fishes: patterns in biotope association, community structure and spatial distribution. *Mar. Ecol. Prog. Ser.* 202: 175-192.
- Nagelkerken, I., S. Kleijnen, T. Klop, R. van den Brand, E. Cocheret de la Morinière, and G. van der Velde. 2001. Dependence of Caribbean reef fishes on mangroves and seagrass beds as nursery habitats: a comparison of fish faunas between bays with and without mangroves/seagrass beds. *Marine Ecology Progress Series* 214:225-235.
- Nagelkerken I, Roberts CM, van der Velde G, Dorenbosch M, van Riel MC, Cocheret de la Morinière E, Nienhuis PH. 2002. How important are mangroves and seagrass beds for coral-reef fish? The nursery hypothesis tested on an island scale. *Marine Ecology Progress Series* 244: 299-305
- Naidoo, G. 1983. Effects of flooding on leaf water potential and stomatal resistance in *Bruguiera gymnorhiza* (L.) Lam. *New Phytol* 93:369-376.
- Narayan, S., Suzuki, T., Stive, M.J.F., Verhagen, H.J., Ursem, W.N.J. and Ranasinghe, R. 2010. On the effectiveness of mangroves in attenuating cyclone-induced waves. *Proceedings of the International Conference on Coastal Engineering* 32 (no page numbers).
- Nicholls, R.J. 2004. Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. *Global Environmental Change (A Human Policy Dimension)* 14:69-86.
- Nilsson, G. E., N. Crawley, I. G. Lunde, and P. L. Munday. 2009. Elevated temperature reduces the respiratory scope of coral reef fish. *Global Change Biology* 15:1405-1412.
- Ning, Z.H., R.E. Turner, T. Doyle and K.K. Abdollahi. 2003. Integrated Assessment of the Climate Change Impacts on the Gulf Coast Region. Gulf Coast Climate Change Assessment Council (GCRCC) and Louisiana State University (LSU) Graphic Services.
- Nozawa, Y. and P.L. Harrison. 2007. Effects of elevated temperature on larval settlement and post-settlement survival in scleractinian corals, *Acropora solitaryensis* and *Favites chinensis*, *Marine Biology*, 152:1181-1185
- Nyström M. 2006. Redundancy and response diversity of functional groups: implications for the resilience of coral reefs. *Ambio* 35(1): 30-5.
- Ogden, J.C., S.M. Davis, T. K. Barnes, K.J. Jacobs, J. H. Gentile. 2005. Total system conceptual ecological model. *Wetlands* 25(4): 955-979.

- Opitz, S. 1996. Trophic Interactions in Caribbean Coral Reefs. ICLARM Technical Report 43. International Center for Living Aquatic Resources Management, Makati City, Philippines. 341 pp. Orth, R. J. e. a. 2007. A global crisis for seagrass ecosystems. *BioScience* 56:987-996.
- Otero, E., and L. Carrubba. 2007. Characterization of Mechanical Damage to Seagrass Beds in La Cordillera Reefs Natural Reserve. Final Report for the Department of Natural and Environmental resources, Task CRI-10 Conservation and Management of Puerto Rico's Coral Reefs, Award No. NA04NOS4190112.
- Otero, E., and L. Carrubba. 2008. Characterization of Mechanical Damage to Seagrass Beds at Highly Visited Areas of Culebra, Puerto Rico. Final Report for the Department of Natural and Environmental Resources, Task CRI-10 Puerto Rico Coral Reefs and Recreational Overuse Strategy.
- Paddack, M. J., J. D. Reynolds, C. Aguilar, R. S. Appeldoorn, J. Beets, E. W. Burkett, P. M. Chittaro, K. Clarke, R. Esteves, A. C. Fonseca, G. E. Forrester, A. M. Friedlander, J. García-Sais, G. González-Sansón, L. K. B. Jordan, D. B. McClellan, M. W. Miller, P. P. Molloy, P. J. Mumby, I. Nagelkerken, M. Nemeth, R. Navas-Camacho, J. Pitt, N. V. C. Polunin, M. C. Reyes-Nivia, D. R. Robertson, A. Rodríguez-Ramírez, E. Salas, S. R. Smith, R. E. Spieler, M. A. Steele, I. D. Williams, C. L. Wormald, A. R. Watkinson, and I. M. Côté. 2009. Recent region-wide declines in Caribbean reef fish abundance. *Current Biology* 19:590-595.
- Paerl, H. W. 1995. Coastal eutrophication in relation to atmospheric nitrogen deposition: current perspectives. *Ophelia* 41:237-259.
- Parker, R. O., and R. L. Dixon. 1998. Changes in a north Carolina reef fish community after 15 years of intense fishing - Global warming implications. *Transactions of the American Fisheries Society* 127:908-920.
- Parmesan C. and G. Yohe. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421, 37-42.
- Parrish, J.D. 1989. Fish communities of interacting shallow-water habitats in tropical oceanic regions. *Mar. Ecol. Prog. Ser.* 58: 143-160.
- Patterson KL, Porter JW, Ritchie KB, Polson SW, Mueller E, Peters EC, Santavy DL, Smith GW (2002) The etiology of white pox a lethal disease of the Caribbean elkhorn coral *Acropora palmata*. *Proc Natl Acad Sci USA* 99:8725-8730
- Pauley, D., V. Christensen, S. Guénette, T. J. Pitcher, U. R. Sumaila, C. J. Walters, R. Watson, and D. Zeller. 2002. Toward sustainability in world fisheries. *Nature* 418:689-695.
- Pearce, F. 1996. Living sea walls keep floods at bay. *New Scientist* 150, 7.
- Pearch, R. W., and O. Bjorkman. 1983. Physiological effects. Pages 65-105 in E. R. Lemon, editor. *Carbon Dioxide and Plants: The Response of Plants to Rising Levels of Atmospheric CO₂* Westview Press, Boulder, Colorado.
- Perry, A. L., P. J. Low, J. R. Ellis, and J. D. Reynolds. 2005. Climate change and distribution shifts in marine fish. *Science* 308:1912-1915.
- Perry, C. T., S. G. Smithers, S. E. Palmer, P. Larcombe, and K. G. Johnson. 2008. 1200 year paleoecological record of coral community development from the terrigenous inner shelf of the Great Barrier Reef. *Geology* 36:691-694.
- Perry, C. T., S. G. Smithers, and K. G. Johnson. 2009. Long-term coral community records from Luggar Shoal on the terrigenous inner-shelf of the central Great Barrier Reef, Australia. *Coral Reefs* 28:941-948.
- Pianka, E.R. 1986. *Ecology and Natural History of Desert Lizards*. Princeton University Press, Princeton, U.S.A.
- Podestá, G.P. and Glynn, P.W. 2001. The 1997-98 El Niño event in Panama and Galapagos: an update of thermal stress indices relative to coral bleaching. *Bulletin of Marine Science* 69: 43-59.
- Pörtner, H.O., B. Berdal, R. Blust, O. Brix, A. Colosimo, B. De Wachter, A. Giuliani, T. Johansen, T. Fischer, R. Knust, G. Lannig, G. Naevdal, A. Nedenes, G. Nyhammer, F.J. Sartoris, I. Serendero, P. Sirabella, S. Thorkildsen, and M. Zakhartsev. 2001. Climate induced temperature effects on growth performance, fecundity and recruitment in marine fish: developing a hypothesis for cause and effect relationships in Atlantic cod (*Gadus morhua*) and common eelpout (*Zoarces viviparus*).

Cont. Shelf Res. 21, 1975-1997.

- Pörtner, H., M. Langenbuch, and A. Reipschläger. 2004. Biological impact of elevated ocean CO₂ concentrations: Lessons from animal physiology and earth history. *Journal of Oceanography* 60:705-718.
- Pörtner, H. O., and A. P. Farrell. 2008. Physiology and climate change. *Science* 322:690-692.
- Pough, F.H., T. Taigen, M. Stewart & P. Brussard. 1983. Behavioral modification of evaporative water loss by a Puerto Rican frog. *Ecology* 64:244-252.
- Pounds, J. A., M. P. L. Fogden, and J. H. Campbell. 1999. Biological response to climate change on a tropical mountain. *Nature* 398:611-615.
- Pounds, J.A., M.R. Bustamante, L.A. Coloma, J.A. Consuegra, M.P.L. Fogden, P.N. Foster, E. La Marca, K.L. Masters, A. Merino-Viteri, R. Puschendorf, S.R. Ron, G. Sánchez- Azofeifa, C.J. Still & B.E. Young. 2006. Widespread amphibian extinctions from epidemic disease driven by global warming. *Nature* 439:143-144.
- Prakash, A., and M. A. Rashid. 1968. Influence of humic substances on the growth of marine fitoplankton: dinoflagellates. *Limnology and Oceanography* 13:598-606.
- Pratchett, M. S., P. L. Munday, S. K. Wilson, N. J. Graham, J. E. Cinner, D. R. Bellwood, G. P. Jones, N. V. C. Polunin, and T. R. McClanahan. 2008. Effects of climate-induced coral bleaching on coral-reef fishes - ecological and economic consequences. *Oceanography and Marine Biology: an annual review* 46:251-296.
- Pratchett, M. S., S. K. Wilson, and A. H. Baird. 2006. Declines in the abundance of Chaetodon butterflyfishes following extensive coral depletion. *Journal of Fish Biology* 69:1269-1280.
- (PRCZMP) Puerto Rico Coastal Zone Management Program. 2009. Program Revision
- Price, W.S. 1985. Whaling in the Caribbean: historical perspective and update. *Reports of the International Whaling Commission* 25:413-420
- Prospero, J. M., and P. J. Lamb. 2003. African droughts and dust transport to the Caribbean: climate change implications. *Science* 302:1024-1027.
- Przeslawski, R., A. R. Davis, and K. Benkendorff. 2005. Synergistic effects associated with climate change and the development of rocky shore molluscs. *Global Change Biology* 2005:515-522.
- Psuty, N. 1990. Fore dune mobility and stability, Fire Island, New York. Pages 159-176 in K. Nordstrom, N. Psuty, and R. W. G. Carter, editors. *Coastal dunes: Form and Process*. John Wiley, Chichester.
- Osti, R., S. Tanaka, T. Tokioka. 2009. The importance of mangrove forest in tsunami disaster mitigation. *Disasters* 33(2): 22.
- Ramesh, R. and S. Ramachandran. 1999. Coastal zone management: Issues and initiatives in small south Asian nations. In: *Perspectives on integrated coastal zone management*, Solomons W, Turner R.K., de Lacerda, L.D. and Ramachandran S. (eds.) Springer, Germany. pp. 239-254.
- Ramos-Scharrón, C. E. 2012. Effectiveness of drainage improvements in reducing sediment production rates from an unpaved road. *Journal of Soil and Water Conservation* 67:87-100.
- Ramos-Scharrón, C. E., J. M. Amador, and E. A. Hernández-Delgado. 2012. An interdisciplinary Erosion Mitigation Approach for Coral Reef Protection - A Case Study from the Eastern Caribbean. Pages 127-160 in A. Cruzado, editor. *Marine Ecosystems*. Intech Publishing.
- Raven, J. A., D. I. Walker, A. M. Johnston, L. Handley, and J. Kubler. 1995. Implications of ¹³C natural abundance measurements for photosynthetic performance by marine macrophytes in their natural environment. *Marine Ecology Progress Series* 123:193-205.
- Reading, C.J., L.M. Luiselli, G.C. Akani, X. Bonnet, G. Amori, J.M. Ballouard, E. Filippi, G. Naulleau, D. Pearson & L. Rugiero. 2010. Are snake populations in widespread decline? *Biology Letters*, doi:10.1098/rsbl.2010.0373 (published online).
- Reagan, D. P. 1996a. The role of amphibians and reptiles in a West Indian rain forest food web. In Powell, R. & R.W. Henderson, eds. *Contributions to West Indian Herpetology: A Tribute to Albert Schwartz*. Contributions to Herpetology, volume 12, Society for the Study of Amphibians and Reptiles, Ithaca, New York, U.S.A., pp. 217-227
- Reagan, D.P. 1996b. Anoline lizards. In D.P. Reagan, D.P. & R.W. Waide, eds. *The Food Web of a Tropical*

- Rain Forest. University of Chicago Press, Chicago, Illinois, U.S.A., pp. 321–345.
- Reed, D.J. 1995. The response of coastal marshes to sea-level rise: survival or submergence? *Earth Surface Processes and Landforms* 20:39-48.
- Reefbase. 2012. "Coral Bleaching Dataset," online at <http://www.reefbase.org> (downloaded 26 December 2012).
- Reeves, R.R. 2000. The value of sanctuaries, parks and reserves (Protected areas) as tools for conserving marine mammals. Final report to the Marine Mammal Commission. Bethesda, Maryland, USA.
- Reeves, R., B. Stewart, P. Clapham, J. Powell. 2002. National Audobon Society Guide to Marine Mammals of the World. New York: Alfred A. Knopf.
- Reeves, R.R., Perrin, W.F., Taylor, B.L., Baker, C.S. and Mesnick, S.L. (eds.). 2004. Report of the Workshop on Shortcomings of Cetacean Taxonomy in Relation to Needs of Conservation and Management, April 30 – May 2, 2004, La Jolla, California. NOAA Technical Memorandum NMFS-SWFSC-363.
- Reid, J.B., P.G.H. Evans, S.P. Northridge. 2003. Atlas of Cetacean Distribution in North-West European Waters Joint Nature Conservation Committee, Peterborough, UK: 76 pp. <<http://www.jncc.gov.uk/page-2713>>
- Reynolds, C. S. 1984. Phytoplankton periodicity: The interactions of form, function and environmental variability. *Freshwater Biology* 14:111-142.
- Richards-Zawacki, C.L. 2010. Thermoregulatory behaviour affects prevalence of chytrid fungal infection in a wild population of Panamanian golden frogs. *Proceedings of the Royal Society B* 277 (1681): 519-528.
- Richardson LL (1998) Coral diseases: what is really known? *Trends Ecol Evol* 13:438–443
- Richardson LL, Goldberg WM, Carlton RG, Halas JC (1998a) Coral disease outbreak in the Florida Keys: plague type II. *Rev Biol Trop* 46:187–198
- Richardson LL, Goldberg WM, Kuta KG, Aronson RB, Smith GW, Ritchie KB, Halas JC, Feingold JS, Miller SL (1998b) Florida's mystery coral killer identified. *Nature* 392:557–558
- Richardson L.L. and R. Aronson. 2002. Infectious diseases of reef corals. *Proceedings of the 9th International Coral Reef Symposium* 1: 1225–1230.
- Rijnsdorp, A. D., M.A. Peck, G.H. Englehard, C. Mo'llmann, and J.K. Pinnegar. 2009. Resolving the effect of climate change on fish populations. *ICES Journal of Marine Science*, 66: 1570–1583.
- Rivera, L. W., and T. M. Aide. 1998. Forest recovery in the karst region of Puerto Rico. *Forest Ecology and Management* 108:63-75.
- Rivera-Monroy, V. H., de Mutsert, K., Twilley, R. R., Castaneda-Moya, E., Romigh, M. M., and Davis, S. E. (2007). Patterns of nutrient exchange in a riverine mangrove forest in the Shark River Estuary, Florida, USA. *Hydrobiologia*, 17, 169–178.
- Rios-López, N. 2008. Effects of increased salinity on tadpoles of two anurans from a Caribbean Coastal Wetland in relation to their natural abundance. *Amphibia-Reptilia* (29): 7–13.
- Rios-López, N. and T. M. Aide. 2007. Herpetofaunal dynamics during secondary succession. *Herpetologica*, 63: 35–50.
- Rios-López, N. and T. M. Aide. 2007. Herpetofaunal dynamics during secondary succession. *Herpetologica*, 63: 35–50.
- Rodríguez-Robles, J. A., T. Jezkova, and M. Leal. 2008. Genetic structuring in the threatened "Lagartijo del Bosque Seco" (*Anolis cooki*) from Puerto Rico. *Molecular Phylogenetics and Evolution* 46: 503-514
- Roberts, C. M. 1995. Effects of fishing on the ecosystem structure of coral reefs. *Conservation Biology* 9:988-995.
- Roberts, C. M. 1997. Connectivity and management of Caribbean coral reefs. *Science* 278:1454-1457.
- Roessig, J.M., C.M Woodley, J.J. Cech, Jr. and L.J Hansen. 2004. Effects of global climate change on marine and estuarine fishes and fisheries. *Reviews in Fish Biology and Fisheries* 14: 251-275.
- Rogers, C. S., T. H. Suchanek, and F. A. Pecora. 1982. Effects of hurricanes David and Frederic (1979) on shallow *Acropora palmata* reef communities: St. Croix, U.S. Virgin Islands. *Bulletin of Marine Science* 32:532-548.

- Rogers, C.S. 1985. Degradation of Caribbean and western Atlantic coral reefs, and decline of associated fisheries. *Proceedings 5th International Coral Reef Symposium*.
- Rogers, C. S. 1990. Responses of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress Series*. 62: 185-202.
- Rogowitz, G.L. 1996. Evaluation of thermal acclimation and altitudinal variation of metabolism in a Neotropical lizard, *Anolis gundlachi*. *Copeia*, 1996: 535-542.
- Romero, A., R. Baker and J. E. Creswell. 2002. Environmental history of marine mammal exploitation in Trinidad and Tobago, W.I., and its ecological impact. *Environment and History* 8: 255-274.
- Root, T.L., Price, J.T., Hall, K.R., Schneider, S.H., Rosenzweig, C. and J. A. Pounds. 2003. Fingerprints of global warming on wild animals and plants. *Nature*, 421, 57-60.
- Rosenberg E, Ben-Haim Y (2002) Microbial diseases of corals and global warming. *Environ Microbiol* 4(6):318-326
- Ross MS, Obrien JJ, Sternberg LD (1994) Sea-level rise and the reduction in pine forests in the Florida Keys. *Ecol Appl* 4:144-156
- Roth, L.C. 1997. Implications of periodic hurricane disturbance for the sustainable management of Caribbean mangroves. B. Kjerfve, L.D. Lacerda, and E.H.S. Diop, editors. *Mangrove ecosystem studies in Latin America and Africa*. UNESCO, Paris France.
- Rothschild B. J. Cambridge, MA, USA: Harvard University Press; 1986. *Dynamics of Marine Fish Populations*. 1995.
- Roughgarden, J., *Anolis Lizards of the Caribbean: Ecology, Evolution, and Plate Tectonics*. Oxford University Press, Oxford UK
- Ruiz, G.M., Hines, A.H., and Posey, M.H. (1993) Shallow water as a refuge habitat for fishes and crustaceans in non-vegetated estuaries: An example from Chesapeake Bay. *Mar. Ecol. Prog. Ser.* 99, 1-16.
- Ruiz-Ramos, D. V., E. A. Hernández-Delgado, and N. Schizas. 2011. Population status of the long-spine sea urchin, *Diadema antillarum* Philippi, in Puerto Rico 20 years after a mass mortality event. *Bulletin of Marine Science* 87:113-127.
- Saenger, P. & J.H. Moverley. 1985, 'Vegetative phenology of mangroves along the Queensland coastline', in MG Ridpath & LK Corbett (eds), *Ecology of the wet-dry tropics : proceedings of a joint symposium with the Australian Mammal Society in association with the Darwin Institute of Technology*, vol. 13, Darwin, NT, 15-17 May 1983, Blackwell Scientific Book Distributors, Melbourne, Vic., pp. 257-265.
- Salazar-Vallejo, S. I. 2002. Huracanes y biodiversidad costera tropical. *Rev. Biol. Trop.* 50:415-428.
- San Juan, A. E., and J. G. González. 2000. Distribution of nutrients in the Phosphorescent Bay at La Parguera, on the southwest coast of Puerto Rico. Pages 451-456 in *Proceedings of the 51st annual Gulf and Caribbean Fisheries Institute*
- (SCDNR) South Carolina Department of Natural Resources and National Oceanic and Atmospheric Administration, Coastal Services Center. 2000. Characterization of the Ashepoo-Combahee-Edisto (ACE) Basin, South Carolina. CD-ROM. SC Marine Resources Center Special Scientific Report Number 17. NOAA/CSC/20010-CD. Charleston, SC: NOAA Coastal Services Center.
- Schofield P.J. 2009. Geographic extent and chronology of the invasion of non-native lionfish (*Pterois volitans* [Linnaeus 1758] and *P. miles* [Bennett 1828]) in the Western North Atlantic and Caribbean Sea. *Aquatic Invasions* 4: 473-479 doi:10.3391/ai.2009.4.3.5
- Schot, P. P. 1999. Wetlands. Pages 62-85 in B. Nath, P. Compton, D. Devuyst, and L. Hens, editors. *Environmental Management in Practice: Vol. 3*. Routledge, London and New York.
- Schreiber, E.A. 2002. Climate and weather effects on seabirds. In: Schreiber, E.A. & Burger, J. (Eds.). *Biology of marine birds*. Boca Raton, Florida: CRC Press. pp. 179-215.
- Schreiber EA, Burger J (eds) (2002) *Biology of marine birds*. CRC Press LLC, Boca Raton, FL.
- Schreiber, E.A. and D.S. Lee. 2000. Status and Conservation of West Indian Seabirds. 2000. *Waterbirds: The International Journal of Waterbird Biology* 23(2): 298-302.
- Secretariat of the Convention on Biological Diversity (2010) *Global Biodiversity Outlook 3*. Montreal. 94 pp.
- Seixas, C. E. 1988. Patrones de distribución espacial y sucesión temporal en poblaciones de dinoflagelados de la Bahía Fosforescente, Puerto Rico. University of Puerto Rico, Mayagüez, Puerto Rico.
- Seliger, H. H., J. H. Carpenter, M. Loftus, W. H. Biggley, and W. D. McElroy. 1971. Bioluminescence and

- phytoplankton sucessions in Bahía Fosforscente, Puerto Rico. *Limnology and Oceanography* 16:608-622.
- Shine, R. 1991. *Australian Snakes, a Natural History*. Ithaca, New York: Cornell University Press.
- Shinn, E. A., G. W. Smith, J. M. Prospero, P. Betzer, M. L. Hayes, V. Garrison, and R. T. Barber. 2000. African dust and the demise of Caribbean coral reefs. *Geophysical Research Letters* 27:3029-3032.
- Shirayama, Y. and H. Thornton. 2005. Effect of increased atmospheric CO₂ on shallow water marine benthos. *Journal of Geophysical Research* 110(c9).
- Short, F.T. and Burdick, D.M., 1996. Quantifying eelgrass habitat loss in relation to housing development and nitrogen loading in Waquoit Bay, Massachusetts. *Estuaries* 19, 730-739.
- Short, F.T. and Wyllie-Echeverria, S. 1996. Natural and human-induced disturbance of seagrasses. *Environmental Conservation* 23: 17-27
- Short, F. T., and H. A. Neckles. 1998. The effects of global climate change on seagrasses. *Aquatic Botany* 63:169-196.
- Sierra-Beltrán, A.P., La Barbera, R., Cortés-Altamirano and Gaviria, F. 2004. Presentación. En: Proliferaciones de algas nocivas en el Caribe. *Rev. Biología Tropical* 52 (Supl. 1), X1-X11.
- Sinclair, M. 1988. *Marine Populations: An Essay on Population Regulation and Speciation*. Washington Sea Grant Program, University of Washington Press, Seattle, Washington, USA. 252 pp
- Skoczylas, R. 1970. Influence of temperature on gastric digestion in the grass snake, *Natrix natrix*. *L. Comp. Biochem. Physiol.* 33: 793-804.
- Smart, M. D., D. Rada, D. Nielsen, and T. Claflin. 1985. The effect of commercial and recreational traffic on the resuspension of sediments in a tropical estuary. *Hydrobiology* 126:263-274.
- Smayda, T. J. 1970. Growth potencial bioassays of water masses using diatom cultures: Phosporescent Bay (Puerto Rico) and Caribbean Waters. *Helgoländer wiss. Meeresunters* 20:172-194.
- Smayda, T. J. 1997. Harmful algal blooms: Their ecolophysiology and general relevance to phytoplankton blooms in the sea. *Limnology and Oceanography* 42:1137-1153.
- Smetacek, V., and J. E. Cloern. 2008. On Phytoplankton trends. *Science* 319:1346-1348.
- Snedaker, S., 1993. Impact on mangroves. In: Maul, G.A. (Ed.), *Climate Change in the Intra-American Seas: Implications of Future Climate Change on the Ecosystems and Socio-economic Structure of the Marine and Coastal Regimes of the Caribbean Sea, Gulf of Mexico, Bahamas and N. E. Coast of South America*. Edward Arnold, London, pp. 282–305.
- Smith, R.B., R. A. Seigel, K.R. Smith. 1998. Occurrence of Upper Respiratory Tract Disease in Gopher Tortoise Populations in Florida and Mississippi. *Journal of Herpetology* 32(3): 426-430.
- Spalding, M. D. (1997). *The Global distribution and Status of Mangrove Ecosystems*. Intercoast Network: Mangrove Edition.
- Spalding M., M. Kainuma & L. Collins. 2010. *World Atlas of Mangroves*. Earthscan Publications, London. 319pp.
- Soler-Figueroa, B. M. 2006. Comparación temporal y espacial de factores bióticos y abióticos en la Bahía Bioluminiscente en La Parguera y Puerto Mosquito en Vieques. University of Puerto Rico, Mayagüez, PR.
- Soler-Figueroa, B. M., and E. Otero. 2011. Daily, spatial and seasonal variability of *Pyrodinium bahamense* and *Ceratium furca* at Bahía Fosforescente, La Parguera, Puerto Rico. ASLO Aquatic Sciences Meeting, San Juan, PR.
- Souter, D., and O. Linden. 2000. The health and future of coral reef systems. *Ocean and Coastal Management* 43:657-688.
- Spalding, M., Kainuma, M., Collins, L. (2010) *World atlas of mangroves*. ITTO, ISME, FAO, UNEP-WCMC, UNESCO-MAB and UNU-INWEH. Earthscan UK, USA.
- Spatharis, S., G. Tsirtsis, D. B. Danielidis, T. Do Chi, and D. Mouillot. 2007. Effects of pulsed nutrient inputs on phytoplankton assemblage structure and blooms in an enclosed coastal area. *Estuarine, Coastal and Shelf Science* 73:807-815.
- Sponaugle, S., K. Grorud-Colvert, and D. Pinkard. 2006. Temperature-mediated variation in early life history traits and recruitment success of the coral reef fish *Thalassoma bifasciatum* in the Florida Keys. *Marine Ecology Progress Series* 308:1-15.

- Stahle, D.W., Cleaveland, M.K., Therrell, M.D., Gay, D.A., D'Arrigo, R.D., Krusic, P.J., Cook, E.R., Allan, R.J., Cole, J.E., Dunbar, R.B., Moore, M.D., Stokes, M.A., Burns, B.T., Villanueva-Diaz, J. and Thompson L.G. 1998. Experimental dendroclimatic reconstruction of the Southern Oscillation. *Bulletin of the American Meteorological Society*, 79, 2137-2152.
- Staudinger, Michelle D., Nancy B. Grimm, Amanda Staudt, Shawn L. Carter, F. Stuart Chapin III, Peter Kareiva, Mary Ruckelshaus, Bruce A. Stein. 2012. Impacts of Climate Change on Biodiversity, Ecosystems, and Ecosystem Services: Technical Input to the 2013 National Climate Assessment. Cooperative Report to the 2013 National Climate Assessment. 296 p. Available at: <http://assessment.globalchange.gov>
- Steneck, R. S. 1994. Is herbivore loss more damaging to reefs than hurricanes? Case studies from two Caribbean reef systems (1978-1988). Pages 220-226 in R. N. C. Ginsburg, editor. *Proceedings of the Colloquium on Global Aspects of Coral Reefs, Health, Hazards and History*. Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, FL.
- Stenseth, N. C., and A. Mysterud. 2002. Climate, changing phenology, and other life history traits: nonlinearity and match-mismatch to the environment. *Proceedings of the National Academy of Sciences* 99:13379-13381.
- Stewart, M. M. 1995. Climate driven population fluctuations in rain forest frogs. *Journal of Herpetology* 29:437-446.
- Stewart, M.M. and L.L. Woolbright. 1996. Amphibians. Pp. 273-320. In Reagan, D.P. and R.B. Waide (Eds.), *The Food Web of a Tropical Rain Forest*. University of Chicago Press, Chicago, Illinois.
- Stoddart, D. R. 1985. Hurricane effects on coral reefs. Pages 349-350 in *Proceedings of the 5th International Coral Reef Symposium*.
- Svenson, R. L. J., E. Johansson, and P. Aberg. 2006. Competing species in a changing climate: effects of recruitment disturbances on two interacting barnacle species. *Journal of Animal Ecology* 75:765-776.
- SWoT (Status of the World's Sea Turtles) 2006. Ed. Mast, R. Available at www.seaturtlestatus.org
- Syvitski, J.P.M., Kettner, A. J., Overeem, I., Hutton, E. W., Hannon, M. T., Brakenridge, G. R., Day, J., Vorosmarty, C., Saito, Y., Giosan, L., and Nicholls, R.J. (2009) Sinking deltas due to human activities. *Nature Geoscience*. 2, 681-686.
- Tanzil JTI, Brown BE, Tudhope AW, Dunne RP (2009) Decline in skeletal growth of the coral *Porites lutea* from the Andaman Sea, South Thailand between 1984 and 2005. *Coral Reefs* (on line first doi 10.1007/s00338-008-0457-5
- Te, F. T. 1997. Turbidity and its effect on corals: A model using the extinction coefficient (K) of photosynthetic active radiance (PAR). Pages 1899-1904 in *Proceedings of the 8th International Coral Reef Symposium*.
- Thayer, G.W., D.R. Colby, W.F. Hettler, Jr. 1987. Utilization of the red mangrove prop root habitat by fishes in south Florida. *Mar Ecol Prog Ser* 35: 5-38
- Thieler, E. R., and Danforth, W. W. 1993. Historical shoreline changes in Puerto Rico, 1901-1987: U.S. Geological Survey Open-File Report No. 93-574, 267 p., 39 plates. Thieler, E.R., and Danforth, W.W. 1994. Historical shoreline mapping (II): Application of the Digital Shoreline Mapping and Analysis Systems (DSMS/DSAS) to shoreline change mapping in Puerto Rico. *Journal of Coastal Research*, v. 10, no. 3, p. 600-620
- Thieler, R. E., R. W. Rodriguez, and E. A. Himmelsstoss. 2007. Historical Shoreline Changes at Rincón, Puerto Rico 1936-2006. U.S. Department of the Interior's U.S. Geological Survey.
- Thode, A., Mellinger, D. K., Stienessen, S., Martinez, A., and Mullin, K. 2002. Depth-dependent acoustic features of diving sperm whales *Physeter macrocephalus* in the Gulf of Mexico. *J. Acoust. Soc. Am.* 112, 308-321.
- Thomas C. D., A. Cameron, R.E. Green, M. Bakkenes, L.J. Beaumont, Y.C. Collingham, B.F.N. Erasmus, M. Ferreira de Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A.S. van Jaarsveld, G.F. Midgley, L. Miles, M.A. Ortega-Huerta, A. Townsend Peterson, O.L. Phillips and S.E. Williams. 2004 Extinction risk from climate change. *Nature* 427, 145-148. doi:10.1038/nature02121
- Thomas, C.A. and S. Dabo. 2005. Determining the correlation between sea surface

- temperature [sic], chlorophyll concentration, QuikSCAT wind data and the presence of *Caretta caretta* and *Chelonia mydas* in the mid-Atlantic. Report prepared for the Undergraduate Research Experience in Ocean and Marine Science Program. Elizabeth City, North Carolina: Elizabeth City State University Thomas, T., and B. Devine. 2005. Island Peak to Coral Reef: A Field Guide to the Plant and Marine Communities of the Virgin Islands. The University of the Virgin Islands.
- Thorhaug, A., Miller, B., Jupp, B., Booker, F. 1985. Effects of a variety of impacts on seagrass restoration in Jamaica, Marine Pollution Bulletin, 16(9): 355-360
- Titus, J.G. and V. Narayanan. 1995. The Probability of Sea Level Rise. U.S. Environmental Protection Agency. Washington, DC: 186 pp. EPA 230-R95-008
- Torres Rodríguez, M., 1994. Plan de manejo para los manglares de Puerto Rico. Estado Libre Asociado de Puerto Rico. Departamento de Recursos Naturales y Ambientales, San Juan, PR
- Townsend, D. S., and M. M. Stewart. 1985. Direct development in *Eleutherodactylus coqui* (Anura: Leptodactylidae): A staging table. Copeia 1985(2):423-436.
- Trotz, U.O. 2009. Climate Change Impacts in the Caribbean. Presentation to the United Nations Climate Change Conference, COP 15. Bella Center, Copenhagen, Denmark. Monday, December 14th, 2009. [https://seors.unfccc.int/seors/attachments/get_attachment?code=HG7W47KLU6P47R9QHHKQIL4530OZKDQ0]
- Tucker, J.K., C.R. Dolan, J.T. Lamer and E.A. Dustman. 2008. Climatic Warming, Sex Ratios, and Red-Eared Sliders (*Trachemys scripta elegans*) in Illinois. Chelonian Conservation and Biology 7(1): 60-69.
- Turner, R. E. 2003. Coastal ecosystems of the Gulf of Mexico and climate change. in Z. H. Ning, R. E. Turner, T. Doyle, and K. K. Abdollahi, editors. Integrated assessment of the climate change impacts on the Gulf Coast region. Gulf Coast Climate Change Assessment Council and Louisiana State University Graphic Services, Washington, D.C.
- Twilley, R.R. 1997. Mangrove wetlands. In Southern Forested Wetlands: Ecology and Management. M. Messina and W. Connor (eds.). CRC Press, Boca Raton, FL, pp. 445-473 Twilley, R.R., E. Barron, H.L. Gholz, M.A. Harwell, R.L. Miller, D.J. Reed, J.B. Rose, E. Siemann, R.G. Wetzel, and R.J. Zimmerman. 2001. Confronting Climate Change in the Gulf Coast Region: Prospects for Sustaining Our Ecological Heritage. Union of Concerned Scientists, Cambridge, MA and Ecological Society of America, Washington, DC.
- Tynan, Cynthia T. and Douglas P. DeMaster, 1997. Observations and Predictions of Arctic Climate Change: Potential Effects on Marine Mammals. Arctic. Vol. 50: 308-322. Upadhyay, V., Ranjan, R., Singh, J., 2002. Human-mangrove conflicts: The way out. Curr Sci India 83, 1328-1336. [UNEP] United Nations Environment Programme. 1994. Assessment and monitoring of climatic change impacts on mangrove ecosystems. UNEP Regional Seas Reports and Studies. Report no. 154.
- UNEP-Millennium Ecosystem Assessment 2004/2005. Ecosystems and human well-being: current state and trends: findings of the Condition and Trends Working Group / edited by Rashid Hassan, Robert Scholes, Neville Ash. Island Press. ISBN 1-55963-228-3
- UNEP/GPA. 2006. The state of the marine environment: regional assessments. UNEP/GPA, The Hague.
- UNESCO. 1992. Coastal systems studies and sustainable development. Proceedings of the COMAR Interregional Scientific Conference, UNESCO, Paris, 21-25 May, 1991. UNESCO, Paris. 276 pp. Unsworth, R.K.J., C.J. Collier, G.M. Henderson and L.J. McKenzie. 2012. Tropical seagrass meadows modify seawater carbon chemistry: implications for coral reefs impacted by ocean acidification. Environmental Research Letters 7(2): 024026
- Valeiras, E. 2007. Extracción de arena de el área de planificación especial de Isabela. Programa de Manejo de la Zona Costanera: Los primeros 25 años. Pp. 8-9
- Valenzuela, N. 2004. Evolution and maintenance of temperature-dependent sex determination. Pp. 131-147. In Valenzuela, N. and V. Lance, Eds. Temperature Dependent Sex Determination in Vertebrates. Smithsonian Books. Washington D.C. Valle-Esquivel, M., M. Shviani, D. Matos-Caraballo, and D. J. Die. 2011. Coastal fisheries of Puerto Rico. Pages 285-313 in S. Salas, R. Chuenpagdee, A. Charles, and J. C. Seijo, editors. Coastal fisheries of Latin America and the Caribbean. FAO Fisheries and

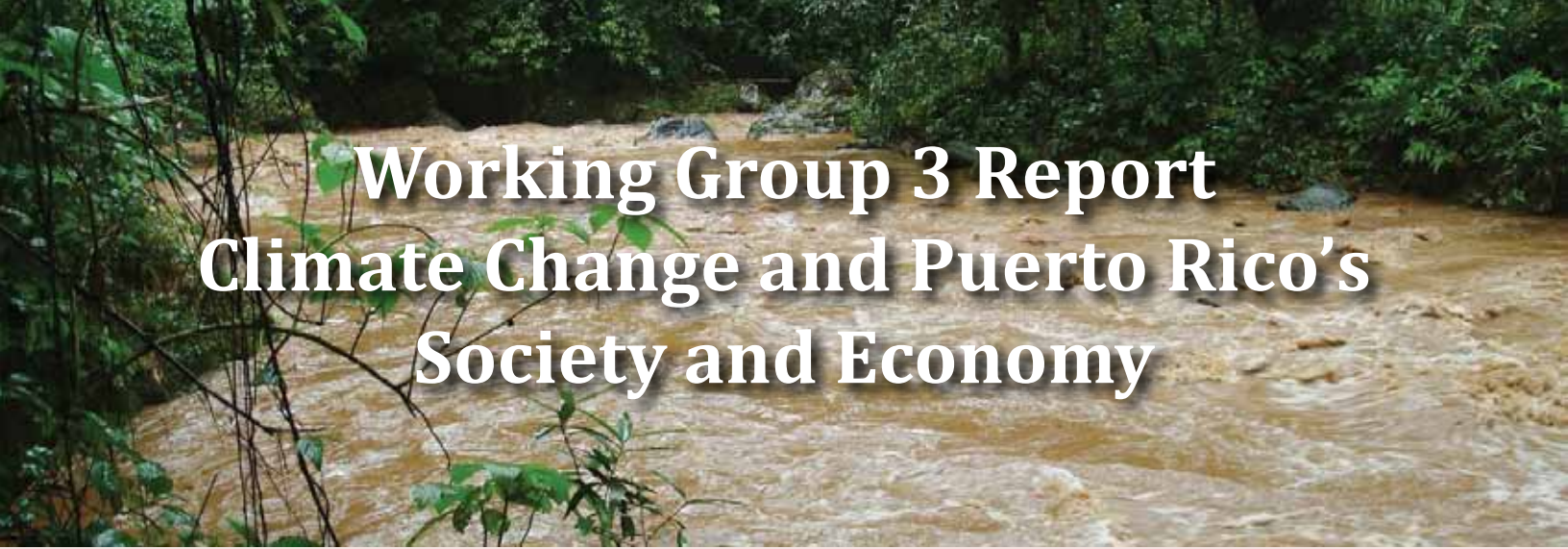
Aquaculture Technical Paper No. 544. FAO Rome.

- Van der Molen, M. K. 2002. Meteorological impacts of land use change in the maritime tropics. Ph.D. thesis, VU University Amsterdam, Amsterdam, the Netherlands.
- Van der Molen, M.K., A.J. Dolman, M.J. Waterloo, and L.A. Bruijnzeel. 2006. Climate is affected more by maritime than by continental land use change: a multiple-scale analysis. *Global and Planetary Change* 54: 128-149.
- Vannucci, Marta. 1997. Supporting Appropriate Mangrove Management. Intercoast Network International Newsletter of Coastal Management. Special Edition #1, March 1997. http://www.crc.uri.edu/download/1997_SE1_CRC_MangroveEdition.pdf
- van Woosik, R. 1991. Immediate impact of the January 1991 floods on the coral assemblages of the Keppel Islands. Great Barrier Reef Marine Park Authority Research Publication No. 23:30.
- Vargas-Ángel, B., E. C. Peters, E. Kramarsky-Winter, D. S. Gilliam, and R. E. Dodge. 2007. Cellular reactions to sedimentation and temperature stress in the Caribbean coral *Montastraea cavernosa*. *Journal of Invertebrate Pathology* 95:140-145.
- Ventosa-Febles, E. A., M. Camacho Rodríguez, J. L. Chabert Llompert, J. Sustache Sustache, and D. Dávila Casanova. 2005. Puerto Rico Critical Wildlife Areas. Department of Natural and Environmental Resources, San Juan, PR.
- Veron, J. E., O. Hoegh-Guldberg, T. M. Lenton, J. M. Lough, D. O. Obura, P. Pearce-Kelly, C. R. Sheppard, M. Spalding, M. G. Stafford-Smith, and A. D. Rogers. 2009. The coral reef crisis: the critical importance of <350 ppm CO₂. *Marine Pollution Bulletin* 58:1428-1436.
- Vicente, V. P. 1992. Resource Category 1 Designation: The Seagrass Beds of Culebra Island, Puerto Rico. in U. S. F. a. W. S. Ecological Services, editor., Boquerón, Puerto Rico.
- Vicente, V.P. and C. Goenaga. 1984. Mass mortalities of the sea urchin *Diadema antillarum* (Philippi) in Puerto Rico. *CEER-- M-195:1-30*.
- Vicente, V. P., L. R. Almodovar, J. A. Rivera, and D. Corales. 1980. An ecological evaluation of the seagrasses in Guayanilla Bay. *Science-Ciencia, Boletín Científico del Sur* 7:91-103.
- Vicente, V. P., and J. A. Rivera. 1982. Depth limits of the seagrasses *Thalassia testudinum* (Konig) in Jobos and Guayanilla bays, Puerto Rico. *Caribbean Journal of Science* 17:73-79.
- Vicente, V. P. 1992. A summary of ecological information on the seagrass beds of Puerto Rico. In E. Seliger (ed.). *Coastal Plant Communities of Latin America*, Academic Press, New York, New York. Pgs. 123-133.
- Vilella, F. J., and R. González. 2009. Geographic distribution of the Puerto Rican Nightjar: a patch occupancy approach. Final report, Cooperative Agreement 011406-001. USGS Cooperative Research Unit, Mississippi State University, Mississippi State, Mississippi.
- Vitt, L.J and J.P. Caldwell. 2009. *Herpetology (Third Edition): An Introductory Biology of Amphibians and Reptiles*. ISBN: 978-0-12-374346-6
- Vivaldi, J. L., and C. Paniagua Valverde. 1986. Las Lagunas de Puerto Rico. Volume IX, Compendio Enciclopédico de los Recursos Naturales de Puerto Rico. Departamento de Recursos Naturales San Juan, PR.
- Wadsworth, Frank H. 1950. Notes on the climax forests of Puerto Rico and their destruction and conservation prior to 1950. *Caribbean Forester*. 11: 38-47.
- Wainwright, P. C. 1994. Functional morphology as a tool in ecological research. In: *Ecological Morphology: Integrative Organismal Biology*. eds, P. C. Wainwright and S. M. Reilly. Chicago, Univ. Chicago Press. pp 42-59.
- Wake, D.B. 1991. Declining amphibian populations. *Science* 253: 860.
- Walker, L. A. 1997. Populations dynamics of dinoflagellates in two bioluminescent bays: Bahía Fosforescente and Puerto Mosquito, Vieques. University of Puerto Rico, Mayagüez, PR.
- Walters, B.B. 2004. Local management of mangrove forests: Effective conservation or efficient resource exploitation? *Human Ecology* 32:177-195.
- Ward, N., Moscrop, A. and Carlson, C. 2001. Elements for the development of a marine mammal action plan for the Wider Caribbean: a review of marine mammal distribution.

- Warrick, R.A. 1988. Carbon Dioxide, Climatic Change and Agriculture. *The Geographical Journal* 154 (2): pp. 221-233
- Waycott, M., Duarte, C. M., Carruthers, T. J. B., Orth, R. J., Dennison, W. C., Olyarnik, S., Calladine, A. Fourqurean, J. W., Heck, Jr., K. L., Hughes, A., R., Kendrick, G. A., Kenworthy, W. J., Short, F. T., and Williams, S. L. (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences*, 106 (doi:10.1073.pnas.0905620106)
- Webber, H. H., and H. V. Thurman. 1991. *Marine Biology*, 2nd edition. Harper Collins Publishers, New York, New York.
- Weber, M., D. de Beer, C. Lott, L. Polerecky, K. Kohls, R. M. M. Abed, T. G. Ferdelman, and K. E. Fabricius. 2012. Mechanisms of damage to corals exposed to sedimentation. *Proceedings of the National Academy of Sciences*.
- Weil, E. 2004. Coral reef diseases in the wider Caribbean, 69-104. Page 488 in E. Rosenberg and Y. Loya, editors. *Coral Health and Disease*. Springer-Verlag, Berlin, Germany.
- Weil, E., and A. Cróquer. 2009. Spatial variability in distribution and prevalence of Caribbean scleractinian coral and octocoral diseases. I. Community-level analysis. *Dis. Aquat. Orgs.* 83:195-208.
- Weil, E., A. Cróquer, and I. Urreiztieta. 2009. Yellow band disease compromises reproductive output of the Caribbean reef-building coral *Montastraea faveolata* (Anthozoa, Scleractinia). *Dis. Aquat. Orgs.* 87:45-55.
- Weil, E., E. A. Hernández-Delgado, A. W. Bruckner, A. L. Ortiz, M. Nemeth, and H. Ruiz. 2003. Distribution and status of Acroporid (Scleractinia) populations in Puerto Rico. 71-98. Page 199 in A. W. Bruckner, editor. *Proceedings of the Caribbean Acropora Workshop: Potential Application of the U.S. Endangered Species Act as a Conservation Strategy*. NOAA Tech. Memorandum NMFS-OPR-24, Silver Spring, MD.
- Weil, E., and C. S. Rogers. 2011. Coral reef diseases in the Atlantic-Caribbean, 465-491. Page 552 in Z. Dubinsky and N. Stambler, editors. *Coral Reefs: An Ecosystem in Transition*. Springer-Verlag, Dordrecht, Germany.
- Weir-Brush, J.R., V.H. Garrison, G.W. Smith, and E.A. Shinn. 2004. The relationship between gorgonian coral (Cnidaria: Gorgonacea) diseases and African dust storms. *Aerobiologia* 20: 119-126.
- Weiss, J. L., Overpeck, J. T., & Strauss, B. (2011). Implications of recent sea level rise science for low-elevation areas in coastal cities of the conterminous USA. *Climatic Change*, , 1-11.
- WEIMERSKIRCH, H. (2002) Seabird demography and its relationship with the marine environment. In *Biology of Marine Birds* (eds E.A. Schreiber & J. Burger), pp. 115–135. CRC Press, Boca Raton, USA.
- Wells, S., C. Ravilous, E. Corcoran. 2006. In the Front Line: Shoreline Protection and Other Ecosystem Services from Mangroves and Coral Reefs. United Nations Environment Programme World Conservation Monitoring Centre, Cambridge, UK, 33 pp.
- Wells, K.D. 2007. *The Ecology and Behavior of Amphibians*. University of Chicago Press, Chicago, IL.
- Wells R.S., V. Tornero, A. Borrell, A. Aguilar, T.K. Rowles, H.L. Rhinehart, S. Hofmann, W.M. Jarman, A.A. Hohn, and J.C. Sweeney. 2005. Integrating life-history and reproductive success data to examine potential relationships with organochlorine compounds for bottlenose dolphins (*Tursiops truncatus*) in Sarasota Bay, Florida. *Sci Total Environ* 349: 106-119.
- Widdicombe, C. E., D. Eloire, D. Harbour, R. P. Harris, and P. J. Somerfield. 2010. Long-term phytoplankton community dynamics in the western English Channel. *Journal of Plankton Research* 32:643-655.
- Wilkinson, C. 2000. *Status of Coral Reefs of the World: 2000*. Australian Institute of Marine Science.
- Wilkinson, C., Souter, D. (2008). *Status of Caribbean coral reefs after bleaching and hurricanes in 2005*. Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre, Townsville, 152 p. (ISSN 1447 6185)
- Williams, E. H., Jr., and L. Bunkley-Williams. 1988. Bleaching of Caribbean coral reef symbionts in 1987-1988. *Proceedings of the 6th International Coral Reef Symposium* 3:313-318.
- Williams, K., Pinzon, Z., Stumpf, R. and Raabe, E. 1999. Sea-level rise and coastal forests on the Gulf of Mexico. Department of the Interior, U.S. Geological Survey, Centre for Coastal Geology, St.

Petersburg, Report 99-441, 99 127.

- Williams, E. H., Jr., and L. Bunkley-Williams. 1990. The world-wide coral reef bleaching cycle and related sources of coral mortality. *Atoll. Research Bulletin* 335:1-71.
- Williams, E. H., Jr., C. Goenaga, and V. Vicente. 1987. Mass bleachings on Atlantic coral reefs. *Science* 238:877-878.
- Williams, K., Z. Pinzon, R. Stumpf, and E. Raabe. 1999. Sea-level rise and coastal forests on the Gulf of Mexico. in D. o. t. Interior, editor. U.S. Geological Survey, Centre for Coastal Geology.
- Wilson B, H. Arnold, G. Bearzi, C.M. Fortuna, R. Gaspar, S. Ingram, C. Liret, S. Pribanić, et al. 1999. Epidermal diseases in bottlenose dolphins: Impacts of natural and anthropogenic factors. *Proceedings of the Royal Society of London* 266:1077–1083. doi: 10.1098/rspb.1999.0746.
- Winder, M., and D. E. Schindler. 2004. Climate change uncouples trophic interactions in an aquatic ecosystem. *Ecology* 85:2100-2106.
- Woodroffe, C.D. and Grindrod, J. 1991. Mangrove biogeography: the role of Quaternary environmental and sea-level change. *J. Biogeogr.* 18:479-492.
- Wood, C.M. and D.G. McDonald. 1997. *Global Warming: Implications for Freshwater and Marine Fish*. Cambridge Univ. Press, Cambridge
- Woolbright, L.L. 1991. The impact of Hurricane Hugo on forest frogs in Puerto Rico. *Biotropica* 23: 462-467.
- Woolbright, L.L. 1996. Disturbance influences long-term population patterns in the Puerto Rican frog, *Eleutherodactylus coqui* (Anura: Leptodactylidae). *Biotropica* 28: 493-501.
- Wootton, J.T., C. A. Pfister, and J.D. Forester. 2008. Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset. *PNAS* 105(48):18848-18853.
- Wu, W., C. Hall, and L. Zhang. 2006. Predicting the temporal and spatial probability of orographic cloud cover in the Luquillo experimental forest in Puerto Rico using generalized linear (mixed) models. *Ecological Modelling*, 192, 473–498.
- Wulf, K. 2001. Recovery of Soufrière after Hurricane Lenny. *MPA News* 3:2.
- Zimmerman, J. T. F. 1981. The flushing of well-mixed tidal lagoons and its seasonal fluctuation. in P. Lasserre and H. Postma, editors. *Coastal lagoon research, present and future: Proceedings of a seminar*. UNESCO Technical Papers in Marine Science 32. . United Nations Educational, Scientific and Cultural Organization, Paris, France.
- Zimmerman, R. C., D. G. Kohrs, D. L. Steller, and R. S. Alberte. 1995. Sucrose partitioning in *Zostera marina* L. in relation to photosynthesis and the daily light-dark cycle. *Plant Physiology* 108:1665-1671.
- Zitello, A.G., D.R. Whitall, A. Dieppa, J.D. Christensen, M.E. Monaco, and S.O. Rohmann. 2008. Characterizing Jobos Bay, Puerto Rico: A Watershed Modeling Analysis and Monitoring Plan. NOAA Technical Memorandum NOS NCCOS 76, NOAA Silver Spring, MD. 81pp [online: <http://ccma.nos.noaa.gov/publications/CEAPHiRes.pdf>]



Working Group 3 Report Climate Change and Puerto Rico's Society and Economy

Editors:

Kasey R. Jacobs¹ and Ernesto L. Diaz¹

Contributing Authors (In Alphabetical Order):

Lisamarie Carrubba², Juan A. Castañer³, Ruperto Chaparro⁴, Wanda L. Crespo Acevedo³, Ernesto Diaz¹, Raimundo Espinoza⁵, Soledad Gaztambide⁶, Kasey R. Jacobs¹, Roberto Moyano³, Víctor Nieto⁸, Susan Pacheco^{10,11}, Antares Ramos⁹, Pedro Santa⁸, Raúl Santiago Bartolomei³, Raul Santini Rivera¹, Jose Seguinot Barbosa¹², Jose Juan Terrasa¹³

Acknowledgments:

This report is a product of the project *Puerto Rico Coastal Adaptation Project* carried out by the Puerto Rico Coastal Zone Management Program and funded by NOAA's OCRM through Section 309 of the Coastal Zone Management Act. A special thanks to EPA, DNER, NOAA, USFWS, USGS, and IITF for sponsoring the November 2011 conference *Climate Change in the Caribbean: Puerto Rico and the U.S. Virgin Islands* where many key discussions occurred as well as the Puerto Rico Tourism Company, the Puerto Rico Conservation Trust and The Nature Conservancy for their support of conference activities and throughout the development of this report. We would like to thank you Carla Loubriel for assistance with editing earlier versions of the report. We also thank the Social and Environmental Research Institute, the South Carolina Sea Grant Consortium, and the University of South Carolina for their development and training of the VCAPS diagrams and process that was used to facilitate WG 3 meeting discussions and the writing process.

¹Puerto Rico Coastal Zone Management Program at the Department of Natural and Environmental Resources

² NOAA Marine Fisheries Service

³Estudios Técnicos, Inc.

⁴Puerto Rico Sea Grant College Program

⁵The Nature Conservancy

⁶The Conservation Trust of Puerto Rico

⁷University of Puerto Rico School of Architecture

⁸AA.E.I.O.U

⁹NOAA Ocean and Coastal Resource Management

¹⁰ The Climate Reality Project – Puerto Rico

¹¹University of Texas

¹² University of Puerto Rico Medical Sciences Campus

¹³The Puerto Rico Tourism Company, Division of Planning

TABLE OF CONTENTS

OVERVIEW OF PUERTO RICO'S EXISTING VULNERABILITIES.....	253
WORKING GROUP 3 REPORT ORGANIZATION.....	157
CLIMATE CHANGE AND PUERTO RICO'S SOCIETY AND ECONOMY (BY SECTOR).....	260
CRITICAL INFRASTRUCTURE	260
ENERGY.....	261
COMMUNICATIONS	261
TRANSPORTATION	262
PORTS	263
WASTE MANAGEMENT AND RECYCLING.....	264
THE INDUSTRIAL LANDSCAPE AND BROWNFIELDS	264
BUILDINGS	264
HISTORIC AND CULTURAL SITES.....	267
WATER RESOURCES.....	269
BOX: POSSIBLY IMPACTS OF CLIMATE CHANGE ON PUERTO RICO'S AGRICULTURAL	
WATER RESOURCES BY ERIC W. HARMSSEN	276
WASTE WATER AND STORM WATER.....	278
DAMS, LEVEES AND FLOOD CONTROL.....	279
BOX: CLIMATE CHANGE AND HEALTH IMPACTS IN PUERTO RICO.....	280
ECONOMIC DEVELOPMENT	283
A BRIEF OVERVIEW OF PUERTO RICO'S ECONOMY.....	283
PUERTO RICO'S ECONOMY AND CLIMATE CHANGE	284
REAL GROWTH OF PUERTO RICO'S ECONOMY	287
MANUFACTURING.....	288
BOX: FILM AND ENTERTAINMENT INDUSTRY	290
TOURISM	291
OUTDOOR RECREATION	295
FINANCE.....	297
BOX: WHERE WILL FUTURE COASTAL DISASTERS OCCUR?	298
ECONOMIC STUDIES	300
RESULTS FROM RISK ASSESSMENT WORKSHOPS.....	301
RISK MATRIX FOR SOCIETAL ASSETS OF PUERTO RICO.....	301
BOX: THE PSYCHO-SPIRITUAL VALUE OF NATURE CONSERVATION IN THE FACE	
OF CLIMATE CHANGE.....	305
CONCLUSION	307
WORKS CITED	308

Overview of Puerto Rico's Existing Vulnerabilities

The Commonwealth of Puerto Rico consists of 78 municipalities; 44 are coastal or insular. As of April 1, 2010 Puerto Rico's population was 3,725,789, or 82,821 less than in April 2000. This is the first time since the Federal Census has been conducted in Puerto Rico that the Puerto Rican population decreased from one decade to another. The analysis conducted by the Puerto Rico Coastal Zone Management Program using the 2010 Census data shows that 56% of the population (2,317,189 people) live in the coastal municipalities. Puerto Rico has an area of 9,497 km² (3,508 mi²) and a population density of almost 449 inhabitants per km² (449 inhabitants per ~0.4mi²). According to the United Nations Demographic Yearbook, this represents one of the highest population densities in the World. Average life expectancy is 78.5 years and 94.1% of the population is literate; Puerto Rico would rank high in terms of the United Nation's Human Development Index. However, there are other relevant socioeconomic conditions that may affect Puerto Rico's capacity to cope and adapt to potential non-climate and climate stressors.

Puerto Rico's population reflects high levels of vulnerability to hazards. The most vulnerable are those who are economically disadvantaged, less prepared, and under social inequitable conditions, such as insufficient infrastructure and services. Puerto Rico has a growing elderly population.

¹ United Nations, Department of Economics and Social Affairs, United Nations Statistic Division. Demographic Year Book. (Table No.3, Population by sex, annual rate of population increase, surface area and density). Retrieved from <http://unstats.un.org/unsd/demographic/products/dyb/dyb2009-2010.htm>.

In 2010, 15% of the population was 65 years or more, versus 11.2% reported in 2000. According to the 2010 Census, 56.3% of the population lives below the poverty line. Per capita income in 2010 was \$10,392, significantly lower than the \$26,059 reported for the mainland United States. The highest educational level attained by 57% of

- 56% of the population lives in coastal municipalities
- 52% of population are female
- 25% of the population are under 18 years of age
- Unemployment rate: 14.9% (as of March 2012)
- 56.3% of the population lives below the poverty line
- Median household income: \$18,692
- Per capita income: \$10,392 (2010).
- 94.1% of the population is literate

the population ranges from not having completed a degree to a high school diploma. Data from the Puerto Rico Department of Labor and Human Resources reveals that unemployment occurs amongst people with all levels of education, especially among those employees who does not have a high school diploma, but also among those with an Associate's Degree; while the unemployment rates for those with a college education or a higher degree are lower than the Puerto Rico average. And there are fewer people in the labor force. The percentage of the working age population employed or looking for a job has fallen slightly but remains high. In 2005 the

² Department of Labor and Human Resources. Educational Level of the Labor Force in Puerto Rico.

employment rate was 47.7% and in 2011 it fell to 40.5%. This suggests that an increasing number of people have left the formal employment market.

According to the U.S. Census the majority of the population lives in urban areas. This is a significant change from the period 1900 to 1930, when almost 80% of the island's population was rural (U.S. Census Bureau, 1900-1930, 2000).

Today, more than half of the population lives in the San Juan Metropolitan Area. The metropolitan municipalities, like San Juan and Carolina, are where activities and services are concentrated: Puerto Rico's main seaport and airport; the most important healthcare center of Puerto Rico and the Caribbean (Centro Médico) and the major universities. Government services are also highly concentrated in San Juan. The coastal zone of the San Juan Metropolitan Area as well as other coastal areas is where most hotels, essential infrastructure, and electric power plants are located. In fact, some power plants are less than 160 feet from the waterline and less than six feet above sea level. Most businesses and other forms of economic activity are located in the coastal zone as well.

The rapid urbanization of the Commonwealth that occurred during past decades has drastically covered Puerto Rico's watersheds with impervious surfaces. Impervious surfaces like asphalt, cement and roofing prevent infiltration of rainfall into the soil, disrupting the water cycle and affecting both the quantity and quality of our water resources. As a result, there are thousands of people living

in flood-prone areas. As of 2010, it was estimated that 237,050 people live in floodways; subject to material damages and potential losses of life.

The increased amount of impervious surfaces and resulting flooding has also contributed to outbreaks of the dengue virus as communities struggle with eliminating breeding sites of the predominant mosquito vector, *Aedes aegypti*. In fact, Puerto Rico experienced the largest dengue virus outbreak in its history in 2010, recording over 21,000 reported cases. About 75% of the reported cases could be laboratory confirmed and, because mild cases are often not reported, the incidence was probably at least several times higher.

In addition to floodways, 105,116 people live in areas subject to storm surges, which are extreme increases in sea level caused by tropical cyclone paths.

In Puerto Rico, the southern and eastern coasts are most vulnerable to the impact of storm surges due to its shallow coastline and hurricane trajectories. Seven months after Hurricane Irene struck Puerto Rico in August 2011, the island was continuing to recover from the heavy rains, flooding, landslides and mudslides left by the

⁴ Estimates were calculated combining GIS layers of 2010 US Census Bureau and FEMA Flood Insurance Rate Maps (AE Floodway) as of 2009.

⁵ AE floodway is defined as a "special flood hazard area with a recurrence period of 100 years, determined by specific methods and for which the elevations of the base flood is indicated. According to the extent of the study, it may include the determination of the floodway. According to the Puerto Rico Planning Board, Regulation on Special Flood Hazard Areas or Planning Regulation No. 13, this area must remain free of obstructions to allow the downward flow of flood waters. The placement of filling material and/or the construction of buildings on it may obstruct the free flow of the waters and increase flood levels.

⁶ One Puerto Rico-specific study demonstrated that increased temperature and rainfall are associated with increased dengue transmission in subsequent months across Puerto Rico. The study also demonstrated that differences in local climate within Puerto Rico can explain local differences observed in the relationship between weather and dengue transmission (Johansson et al. 2009).

³ Center for Sustainable Development Studies. (2009). Sustainability of Land Use in Puerto Rico.

hurricane. The Government of Puerto Rico and the Federal Emergency Management Agency cited the approval of more than \$83.9 million in federal grants for disaster aid (FEMA 2012). Effects can be long-lasting, such as with the diminishment of the coffee and plantain industries on the island after two strong hurricanes in 1928 and 1932 or the long lasting impacts to agriculture and infrastructure after hurricanes Hugo (1989) and Georges (1998). After hurricane Georges the National Weather Service reported enormous damage to Puerto Rico's utility infrastructure. Electricity was lost to 96% of the island 1.3 million customers, while water and sewer service was lost to 75% of the islands 1.83 million customers. It was estimated that at least 50% of the electrical poles and cables were damaged. Many roads were impassable by floods or destruction. A large number of road signs were twisted and destroyed, while electric post and cables were strewn on the ground, along with trees and foliage. Damage to roads was estimated at \$21,995,975. More than 217,000 homes were damages and over 29,000 people were left homeless. Telephone service was also affected as 8.4% of telephone customers lost their service. Hurricane Georges' extensive damages to the agricultural sector including losses of 75% of the island's coffee crop, 95% of the plantain and banana crops, and 65% of its live poultry. Loss to equipment, manufacturing, and agriculture was estimated at \$212.9 million daily. Damage to houses was significant, especially those constructed of wood with wood-zinc system roofs. In all 28,005 house were totally destroyed and 72, 605 houses

of all type were partially damaged. On the small island of Culebra, 74 houses were totally destroyed and 89 were partially affected. Public schools suffered an estimated \$20-\$25 million dollars in damage. All of the islands 401 shelters were opened during the storm and housed 29, 107 people. An estimated \$1,673,529,890 in damages was caused to municipalities and \$233,496,484 in damages to Commonwealth agencies. Thus, the total damage

Hazards in Puerto Rico
Tropical Storms & Hurricanes
Coastal & Riverine Flooding
Storm Surges
Winter Swells from Atlantic Winter Storms
Landslides
Earthquakes, Liquefaction & Ground
Shaking
Tsunamis
Erosion
Drought

in Puerto Rico was estimated at \$1,907,026,374. Landslide hazards are also a growing concern in Puerto Rico. Bursts of heavy rainfall from intense storms trigger numerous landslides in the mountain areas of the island every year, causing substantial property damage and sometimes loss of life. Construction on vulnerable slopes exposes population particularly in rural areas to these hazards. In 2010, it was estimated that 49% of the population in Puerto Rico lives in areas ranging from moderate susceptibility to landslides to the highest susceptibility.

Through PRCCC partner, Puerto Rico Emergency Management Agency, the PRCCC was able to collect most of the hazard mitigation plans for the

⁷ Estimates were calculated combining GIS layers of FEMA FIRMS (2009) and 2010 US Census Data.

⁸ Puerto Rico's hurricane season is from June to November.

78 municipalities of Puerto Rico. In brief, existing hazards that affect Puerto Rico today are: riverine and coastal inundation, landslides, tropical storms and hurricanes, earthquakes, tsunamis, winter swells, coastal erosion and drought. Structures that are considered at-risk due to the already existing hazards listed are: residential homes, power generation plants, sewage systems, cemeteries, recreational areas, community centers/libraries, government buildings and facilities, schools, and hospitals. Working Group 3 determined through discussions and the use of the municipal hazard mitigation plans that, according to the historically observed climate trends, Puerto Rico is currently at-risk from:

- Continuing development in high hazard areas or poor drainage areas
- Increasing land use change and area of impermeable surfaces
- Inappropriate use of shoreline stabilization structures in certain areas
- Poor maintenance of existing shoreline stabilization structures
- Poor maintenance and dredging of rivers, canals and reservoirs
- Inadequate capacity and poor maintenance of storm-water management systems
- Poor soil management practices on land and coastal watersheds
- Inadequate construction practices that do not follow established codes
- Elimination of dunes, reefs, mangroves, and other naturally protective features

Of all the hazard mitigation plans for Puerto Rico's municipalities only Naguabo, Peñuelas, Yauco, Hatillo, Salinas, and Toa Baja mention the terms "climate change", "global warming", or "sea level rise".

The socioeconomic conditions and existing vulnerabilities in Puerto Rico described above are the most important considerations when addressing how to meet the new challenge of climate change. The changes in climate that the PRCCC's Working Group 1 report described - will not necessarily create new vulnerabilities for Puerto Rico, but rather are expected to exacerbate the existing vulnerabilities Puerto Rico already faces today. The high proportion of population living in areas vulnerable to natural hazards, growing numbers of the elderly and other at-risk groups, and a relatively high poverty rate (by U.S. if not Caribbean standards) increase the island's social and economic vulnerability to climate change impacts. At the same time, Puerto Rico's relatively high per capita fuel and energy consumption - in electricity and transportation (one automobile per 1.3 Puerto Ricans) - contributes to the causes of global climate change. Municipalities in Puerto Rico are already concerned about climate change as evidenced by the following excerpt from one coastal municipality's hazard mitigation plan: "It is expected that as the years pass the likelihood of flooding in [the municipality] and Puerto Rico in general will increase because of all the climate changes that are occurring in the world." When assessing how climate change could affect Puerto Rico it is important to consider that the real concern is how Puerto Rico's way of life will change, rather than the change itself. An informal survey by the PRCCC to coastal municipalities

"The [municipalities], through their history, have suffered from floods and landslides, as has the rest of Puerto Rico. At the global scale, no other type of disaster exists that compares to flooding because of its high frequency and for being the principal cause of life and property lost. The combination of weather events, such as hurricanes and heavy rains, with the location of properties (residential and commercial) in vulnerable flooding areas or poor drainage areas, increases the incidence of these phenomena in [Puerto Rico's municipalities]."

Excerpt taken from the Multi-Hazard Mitigation Plans of multiple municipalities in 2005 and 2006

showed that, according to municipal planners, public works officers and emergency managers, the most concerning social issues affecting their communities are crime and drug addiction, unemployment, housing, poverty or low income levels, loss of industry, school dropout rates, and coastal erosion. Climate change should not be considered a separate social issue, but rather another stress on the already existing vulnerabilities and social issues. This Working Group 3 report is a first attempt to identify and highlight these topics. Future work is needed to expand and refine the information provided.

Working Group 3 Report Organization

The PRCCC Working Group 3 Society and Economy Report describes the existing vulnerabilities to

natural hazards and climate change by sector (Table 1) and assesses how the climate parameters temperature, changes in precipitation, sea level rise, and changing storm intensities could affect each sector. To validate preliminary results of the vulnerability assessment, the society and economy Working Group 3 and PRCCC partners conducted risk assessment workshops with coastal municipalities on March 6th and 8th, 2012: *Workshops for the Evaluation of Current and Future Risks in the Coastal Zone*. Thirty of the forty-four coastal municipalities of Puerto Rico attended with representatives from planning offices, emergency managers, and public works officers (figure 1). The PRCCC coordinators presented the preliminary findings of the Working Group 1 (Geophysical and Chemical Scientific Knowledge) and WG 2 (Ecology and Biodiversity), and through a series of facilitated small group discussions the participants confirmed the main climate stressors impacting important sectors of their municipalities (e.g., infrastructure assets, economic development areas, and natural resources); further quantified the magnitude and likelihood of impacts occurring for the features assessed; and discussed the linkages between Island-wide concepts and municipal realities. Additionally, the last session of each workshop was devoted to the brainstorming of adaptation strategies by sectors identified as the most important by the workshop participants. Many of the consequences of certain climate stressors that the Working Group had identified as possibilities for the future, the municipal representatives identified as already occurring. This information was factored into the final results of this report, specifically into the development of a risk matrix.

The changes in climate that the PRCCC's Working Group 1 report described - will not necessarily create new vulnerabilities for Puerto Rico, but rather are expected to exacerbate the existing vulnerabilities Puerto Rico already faces today.

Additionally, as with the reports from Working Groups 1 and 2, Working Group 3 solicited peer reviews and received comments for individual sections and the overall report.





Figure 1 The PRCCC conducted two *Workshops for the Evaluation of Current and Future Risks in the Coastal Zone*. Planners, public workers officers and emergency managers of these 30 municipalities attended on either March 6th or March 8th, 2012.

Working Group 3: Society and Economy Sectors Assessed

- Critical Infrastructure
 - Stormwater and Wastewater
 - Energy Generation
 - Air and Sea Ports
 - Public Buildings and Structures
 - Private Buildings and Structures
- Water Resources
 - Economic Development
 - Manufacturing
 - Tourism and Outdoor Recreation
 - Cinema
 - Livelihoods
- Historical and Cultural Resources
- Naturally Protective Coastal Features

Climate Change and Puerto Rico's Society and Economy (by sector)

Critical Infrastructure

Climate change is challenging the way critical infrastructure agencies such as the Puerto Rico Aqueduct and Sewers Authority, the Electric Power Authority, the Department of Transportation and Public Works, as well as the Health and Education departments plan for the future. Observed warming and climate model projections (see PRCCC Working Group 1 report) now call into question the stability of future conditions for existing and future infrastructure. Sea level rise may impact the operations of assets like roads and highways, telecommunication networks, important buildings and facilities, electrical power providers and generators, as well as bridges and ports. Increased frequency and intensity of storm surges could close down port operations, drastically increase flooding near critical infrastructure assets and have other consequences. With changes in water quantity and quality, water utilities may be greatly affected. In the face of climatic changes, we must reconsider existing assumptions relative to infrastructure capacity and vulnerability. The PRCCC was unable to find the infrastructure category in Puerto Rico with the greatest total capital investment on the island, however, according to one newspaper article, managing issues related to water quality alone could cost Puerto Rico about \$4 billion in infrastructure (Millán 2011). With such investments, planning for future scenarios becomes even more critical to avoid a situation where new infrastructure quickly become obsolete. The challenge is that with anthropogenic warming past climate is no longer a reliable guide to the future.

A critical facility is defined as a facility in either the public or private sector that provides essential products and services to the general public, if

otherwise necessary to preserve the welfare and quality of life in the community, or fulfills important public safety, emergency response and/or disaster recovery functions. Infrastructure, as the Latin root of the term suggests (*infra* meaning “below” or “beneath”), refers to an interconnected system of assets and services that are not readily evident, yet provide critical functions to society. The great importance of infrastructure becomes apparent in its absence. We take for granted most of the infrastructure services we rely on in our daily lives, yet when they are suspended their inherent value becomes clear. In most cases the “value of infrastructure derives from the service it provides” and how many people it provides it to. For this reason it is important to qualify and quantify the vulnerability of critical infrastructure systems. Climate stressors associated with climate change, particularly sea level rise, increased temperatures, changes in precipitation patterns, and hurricanes of increased intensity, are anticipated to directly impact these systems and disrupt essential services.

This section attempts to identify the critical infrastructure in Puerto Rico that would be negatively impacted by the following climate stressors associated to climate change: (1) flooding and storm surge as a result of sea level rise; (2) increased average air temperatures; (3) changes in precipitation patterns; and (4) more intense tropical storms and hurricanes. The critical infrastructure is outlined into sections and then divided into more specific sub-sections. The existing vulnerabilities to critical infrastructure due to the aforementioned climate stressors are identified and described. In this regard this report is qualitative and does not intend to quantify the amount of infrastructure that would be vulnerable to the effects of climate change. Quantifying the critical infrastructure assets and the services they provide that would be negatively affected

¹⁰ Esther Conrad, Climate Change and Infrastructure in the Gulf of Mexico and Caribbean Basin: New Risks to Building Blocks of Resilience.

is essential to properly determine priorities and plan an adequate adaptation strategy. The PRCCC recommends a more-specific vulnerability assessment be done for Puerto Rico's most important assets at the agency level, municipal level, and the site level. This report is meant to lay the groundwork for these future assessments.

Energy

Power Generation Plants

Most of the energy in Puerto Rico is generated by the burning of fossil fuels and all of the major power generation plants are located on the coast. The main reason is that most of the fuel is unloaded by ocean vessels to the plants. There are some hydroelectric generators located further inland, but they constitute a small fraction of the energy potential in Puerto Rico. Accordingly, all of Puerto Rico's power generation plants are at risk of structural damage due to flooding from sea level rise, floods, and storm surges. Additionally, the higher temperatures associated with climate change could also result in an increased demand for electricity to be used for cooling, further taxing the system. Seventeen power generation plants are located in Puerto Rico on the coast. It is known that two of the generation plants were susceptible to floods caused by tsunamis. These two power plants are the Palo Seco and Turbinas De Gas Mayaguez power plants. Four others could also be inundated by future storm surges: Costa Sur, Turbinas De Gas Mayaguez, San Juan Steam Plant and Palo Seco. According to a Worcester Polytechnic Institute Study (2011) that was completed for the Puerto Rico Coastal Zone Management Program and used available flooding data two plants affected in particular would be the Turbinas De Gas Mayaguez and the San Juan Steam Plant, both located in the FEMA AE flood zones, deemed high risk areas.

Transmission and Distribution

The PRCCC was unable to find Puerto Rico specialists on transmission and distribution system and climate change, thus PRCCC was unable to conduct a detailed analysis of potential stresses for the 2010-2013 report. However, according to PREPA, as of September 30, 2012 there were 2,450 circuit miles of transmission lines and 32,548 circuit miles of distribution lines. The total length of transmission lines within the coastal region is 161 miles (WPI 2011). Flooding in the coastal zone from sea level rise, increased storm intensity and associated storm surges could result in structural damage to transmission line towers, substations and transformers. Past storm events indicate that Puerto Rico's transmission and distribution system is already affected by weather events and frequently suffers from losses in services. Therefore the system may not be able to withstand increased flooding events in its current form. This situation has prompted PREPA to complete an underground 115kV transmission circuit line around the San Juan metropolitan area in order to reduce power loss incidents in the aftermath of hurricanes and other major storms that strike Puerto Rico. Additionally, they have improved underground 38kV lines in Vega Baja and Mayaguez and are improving 38 kV subtransmission systems by constructing underground lines in Carolina, Guaynabo and San Juan. Other projects may be planned by PREPA for other parts of the island and would be expected to significantly improve the reliability of the subtransmission system. More information is needed to assess the whole transmission and distribution system as related to climate change and the PRCCC recommends a thorough analysis to be completed in the near future.

Communications

The PRCCC was also unable to find specialists on communication infrastructure and climate change

in Puerto Rico, however, anecdotally at multiple public meetings and municipal risk assessment workshops the issue of lack of communications after storms was often raised. This is an issue of great importance in terms of both emergency management and economic development. Response efforts after storms, heavy rain events, earthquakes and landslides require adequate communications. Additionally, many industries rely on stable communication services and interruptions in services disrupt production (Puerto Rico Manufacturers' Association *personal communication* 2012).

Transportation

Roads, Bridges and Associated Structures

The Commonwealth's approximately 26,718 km of paved highways, roads and streets (Government Development Bank for Puerto Rico July 2011/ Department of Transportation and Public Works 2010) and other associated infrastructure come in many shapes and sizes, and with differing surfaces and foundations. The road density in Puerto Rico is 298 per 100 km². Like other infrastructure, roads and bridges are not expected to escape the effects of climate change. However, little documented information is so far available examining the topic. Traditionally, roadway design in Puerto Rico has proceeded on the assumption of static climate conditions where historic weather data provided adequate roadmaps for future designs.

Long-term fluctuations in temperature associated with climate change could cause thermal cracking. Higher in-service temperature for roadways could increase the potential for rutting and generally, maintenance, rehabilitation and reconstruction will be needed earlier in the design life. Climate change effects on transportation infrastructure also include the increased vulnerability of roadways, particularly low-lying ones, to increased vulnerability from flooding due to precipitation and sea level rise, coastal floods and

erosion, more frequent and intense rainstorms, or from overflowing streams and water bodies. Bridges, depending on their height, may need to be raised if the water bodies they cross increase in water level due to increased precipitation or sea level rise. New bridges design may also need modification, construction and maintenance to account for additional flooding. Existing bridges may have to be raised to accommodate higher flood or sea levels, as was done in the municipality of Peñuelads after Hurricane Georges. The hurricane destroyed three bridges, and the Río Tallaboa bridge had to be raised to avoid future problems. As the seas rise more bridges around Puerto Rico will need to be raised. This is especially true for low-lying bridges. On the main island of Puerto Rico, there are 240 bridges located within the coastal zone. Many are used to pass over rivers or wetlands on coastal routes. Mapping by WPI showed that there are at least 30 bridges that are potentially vulnerable. Since the heights of the bridges were not able to be obtained, a more thorough analysis of inundation was not possible. These bridges constitute important links to the communities they serve. Flooding from sea level rise could result in structural damage to bridges, or they might become completely submerged and therefore unusable.

Roads are absolutely essential in Puerto Rico because most of the transportation is conducted by private car and commercial vehicles. In fact, 89% of work related trips are done by private vehicles, according to the 2000 Census. Because most of the urbanization in Puerto Rico is in the coastal zone (40%), this area contains a large proportion of the roads on the island. Flooding from sea level rise could result in structural damage to roads, or they might become completely submerged and therefore unusable. And because asphalt softens in high heat, roads will require more repair more often as they are exposed to the higher projected temperatures.

Mass Transit (Passenger Rail and Buses)

Puerto Rico has a relatively new passenger rail system in the San Juan metropolitan area. Even though most of the system is elevated, there are potential risks. In particular, flooding in the coastal zone could result in structural damage to passenger rail stations, or they might become completely submerged such that the system will not be accessible at those points.

Many bus routes and other mass transportation vehicles in Puerto Rico have coastal routes and inland routes that are frequently flooded. As these areas become more inundated from sea level rise or the increase in downpour events travel routes may have to be reconfigured. New projects, like the Metro Urbano which consists of building a special lane along PR-22 that will be used for a new bus rapid transit (BRT) system to connect Toa Baja to the final urban train station stop in Bayamón, may experience flooding during certain events that could be avoided if future scenarios are factored in during the planning and construction processes. By planning today for future flooding scenarios we can avoid costly investments and cut down on traffic congestion in the urban areas.

Passenger Ferries

Passenger ferries are especially important in the eastern coast of Puerto Rico, because it is the main form of transportation for most residents of the island municipalities of Vieques and Culebra. Passenger ferry terminals are especially vulnerable to the effects of climate change. Flooding from sea level rise could result in structural damage to the passenger ferry system or cause the same to become completely submerged and therefore unusable. On the other hand, demand for passenger ferries may increase as bridges and roads become inundated and certain roads impassable.

Ports Airports

Puerto Rico has both international and local airports located within the coastal zone. As an island, Puerto Rico relies on air travel infrastructure for most of the passenger movement to and from the island. Flooding due to sea level rise could completely impair the use of airport runways, cause structural damage to airport buildings, and prevent access to the airport. Two notable cases are the Luis Muñoz Marín International Airport and the Isla Grande Airport, both located on the coast and at great risk to from sea level rise. Higher overall temperatures can also cause thermal cracking of the airport runway tarmac.

Of the fourteen airports that are located in Puerto Rico, only five are situated along the coast. The Antonio Rivera Rodríguez Airport is located on the island of Vieques and the Culebra Airport is located on the island of Culebra. There are three airports situated along the coast on the main island. These Airports are the Patillas Airport located in Patillas, the Luis Muñoz Marín International Airport in San Juan, and the Fernando Luis Ribas Dominicci also located in San Juan. It has been reported that the airport in Ceiba has plans to expand in the future. All these coastal airports are at risk to possible future sea level rise.

Possible climate change impacts to airports in Puerto Rico are flooded runways, flooding of out-buildings and access roads, and disruption to fuel supply and storage.

Seaports

As with airports, seaports represent one of the most important infrastructure elements in Puerto Rico. Most of the food consumed on the island is imported, and a great part of Puerto Rico's economic activity relies on the import and export of goods. Climate change could affect the operation

of the different types of ports on the island: cargo ports, used principally for imports and exports of goods; cruise ship ports, used principally for tourism; fishing ports, used by fishermen for their commercial activities; and marinas, used by owners of recreational water craft such as power boats and sail boats. Sea level rise creates a unique challenge for seaports as all functions are closely associated to the current levels of the sea. Flooding from sea level rise could cause structural damage to docks, buildings and heavy machinery, and eliminate much of the surface area currently used adjacent to the water.

Arecibo seaport already experiences regular problems with their platform due to the port being a high wave energy area. Additionally, the Pan American dock in San Juan frequently experiences riverine flooding. Ponce's port reportedly shuts down at least once a year due to riverine flooding as well. There are no known capital improvement plans for maritime transport by the Puerto Rico Ports Authority as the ports have many different tenants and operations requirements and capital improvement plans would be determined by the individual companies (Ports Authority, *personal communication*, July 18, 2012). The PRCCC recommends a more in-depth analysis of Puerto Rico's ports and vertical measurements relevant to sea level as this is outside the scope of this report.

Waste Management and Recycling

According to the U.S. Environmental Protection Agency, "The management and disposal of solid waste – more commonly trash or garbage – in Puerto Rico has long been a challenge. The problem is intensified by the limited disposal space available on an island community and Puerto Rico's delicately balanced ecosystem." (EPA 2012). Puerto Rico residents generate more waste than U.S. mainlanders and recycling rates are lower as well. Much of Puerto Rico's solid

waste ends up in one of the island's 32 landfills, most of which do not comply with Commonwealth and federal landfill requirements (EPA 2012).

Flooding due to sea level rise could open landfill layers and release chemicals and solid waste (i.e., trash) into the ocean and subsequently damage or destroy marine ecosystems. More intense storm events could mean that roadways will become inaccessible after storms. This would disrupt waste management as it is currently run on the island, as it would impede the movement of solid waste to landfills and recycling facilities. A detailed analysis would need to be conducted to determine land fill proximities to potential sea levels.

The Industrial Landscape and Brownfields

There are 29 Superfund sites between the National Priorities List and the Resource Conservation and Recovery Act. The majority are related to petrochemical and pharmaceutical production or Naval Base activities (EPA 2008). There is a great risk to the closed oil refineries in Puerto Rico as they are located extremely close to the coast and are at great risk of flooding due to sea level rise. Flooding events could cause environmental degradation, contamination, and affect coastal and marine ecosystems. Flooding could also cause underground storage tanks at operating gas stations to break and spill their contents, causing the migration of pollutants to the water table through percolation and direct contact with infringing surface waters.

Buildings

Puerto Rico's thousands of buildings exist in a bewildering array of sizes, shapes, designs, and configurations and perform many functions. This is the case with: (1) public infrastructure systems, including government, police and fire stations, educational, health, cultural, recreational,

transportation terminals, public housing, certain hospitals, prisons and other facilities; (2) para-public infrastructure, including churches, sports venues, certain hospitals and transportation terminals, which though privately owned, receive widespread public use; (3) privately owned and privately used structures, including single, detached dwellings like single-family homes, multifamily homes, office buildings, commercial buildings, shopping malls, and hotels.

Traditionally, designers of Puerto Rico's buildings relied on the built-in assumption that the climatic patterns present at the time of design and construction would stay fairly constant throughout the structure's useful life. However, information in this report and myriad other sources now casts serious doubt on assumptions about climatic conditions staying constant. The data point to possibilities of some fairly rapid climatic changes. Supporting evidence for this comes in the form of increasing temperatures, rising sea levels, higher average wind speeds, as well as changing precipitation patterns.

In many cases, climate change could leave Puerto Rico's buildings vulnerable to:

- Technical inability to cope with failures, with resulting harm to occupants, equipment and materials;
- Disruption or limitations in the delivery of services; or
- Added costs in the delivering of services (such as from increasing cooling costs due to higher air temperatures).

Engineers, consulting firms and other involved in the design, construction, maintenance, operation and use of buildings will be called upon to identify and respond to such vulnerabilities. Many factors could come into play and have to be considered – among them:

- Building materials, building envelopes and building stability;
- Accelerated physical weathering, due to changing atmospheric physical, chemical properties and biological – including wind-driven rain and abrasive materials, broad-spectrum solar and ultraviolet radiation; mould, mildew, rot and possible pest infestations;
- Effective function of air and vapor barriers;
- Impacts related to water levels – notably in flood plains and coastal areas;
- Shifting daytime and night-time heating patterns;
- Changes in ground conditions
- Wetter conditions leading to wetting and drying, moisture and penetration of doors, windows and other areas;
- Maintenance challenges and, due to climate changes, widening of existing infrastructure deficits
- Need to apply revised building codes and standards, as well as design values relating to expected changes in frequency of certain weather events;
- Resiliency, strength and durability of materials – including concrete, stone, masonry, and plaster – and how they are used;
- Structural integrity of walls and roofs in the face of stronger winds, and more frequent and intense precipitation; and
- Heating ventilation and cooling – including possible lessened reliance on fossil fuels (for heating) and more dependence on electrical power (for cooling).

The degree of change, consideration of different factors and the consequences will differ from

municipality to municipality. Furthermore, it is difficult to forecast the magnitude of certain anticipated changes, especially those related to wind, using current climate models. With rare exceptions, buildings are not stand-alone infrastructure. Almost invariably, buildings need the support of other infrastructure – be it water supply, sewer, roadway, electrical or communications systems. Failures in any of these systems, possibly a sewer backup brought on by sudden flooding, can affect individual buildings. The buildings, in turn, may house critical components (power generation, water treatment, instrumentation, etc) of the supporting infrastructures. In short, buildings left vulnerable to climate change may expose other infrastructure to vulnerability. Choices made today for new and existing building could either intensify or mitigate buildings' vulnerabilities to climate change in coming decades.

Some technical inabilities to cope with such failures and disruptions are expected, resulting in harm to occupants, equipment and materials. This in turn, might cause disruption or limitations in services delivery and operations, as well as added costs in delivery of any services. Lastly, older structures may be more at-risk due to the likelihood of construction before building codes and planning and zoning requirements were implemented.

Climate change imposes a unique challenge to all coastal cities and communities, as many of the island's buildings could be at risk, depending on their locations. Most of the people in Puerto Rico live within the coastal zones and thus public, para-public, and private buildings are also mostly located in the coastal zones. The San Juan Metropolitan Area and the cities of Ponce and Mayagüez, the three largest cities in Puerto Rico, are all coastal cities. In the San Juan Metro Area, the most densely populated areas are right on the coast. Neighborhoods like Condado and Isla Verde

are populated by various multi-family housing towers, hotels, and businesses at close proximity to the water.

The principal risk associated with climate change and buildings is that of structural damage from the impact of flooding from changes in precipitation, sea level rise, and storms. Structural damage can make a building unusable if it becomes a safety risk to human life. The location of these structures is the primary way to determine vulnerability to future conditions. For instance, a rough analysis shows on the main island of Puerto Rico there are approximately 62 hospitals located within the coastal zone. Of these, eight hospitals are vulnerable to tsunamis, potential sea level rise, and storm surge. Of the 2,398 schools located on the mainland, 310 reside in the coastal zone and 26 schools may be potentially susceptible to storm surge, sea level rise, and tsunamis.

In regards to hotels, a study from the WPI team interviewed representatives of an upscale resort located in Condado. The manager of the hotel stated the biggest problem facing the hotel was coastal erosion. Every few months, new sand must be added to the beach (WPI 2011). Renace Condado is an organization working towards improving the quality of life in Condado; one of its concerns is beach erosion. People from different support sponsors meet regularly to discuss how to better protect the area and prevent more damage from occurring. There was even an attempt at securing the sands by planting palm trees to stabilize the beach; however, these trees were easily swept away right along with the sand. Years ago the coastline was a good distance from the hotel but as the years have gone by the shore has lost its width. The interview subject mentioned that during stronger storms, the water hits the walls of the hotel. In an effort to protect these walls, a much stronger type of glass was used which can withstand winds of up to 120 meters per hour. This prevents the water from actually entering the

building. Sandbags are also utilized in an effort to protect against flooding in the event that a larger storm impacts the area. In the event of a hurricane or flooding, the hotel manager stated the hotel would lose power. Backup generators are located in the underground parking lot and are used to ensure the computer systems and phone lines stay operational. This generator does not power the rooms themselves. Because the generators are located at the basement level should there ever be a substantial amount of flooding, the generators would not be operational and the building would lose power completely.

Historic and Cultural Sites

Puerto Rico has a wide variety of buildings that have historic and cultural significance, many of which are located on the coast. A sampling of these would include the Spanish forts of Old San Juan, as well as the series of light houses, churches, and historic homes located around the island. Many coastal towns, such as Cataño, Hatillo, and Arecibo, have their historic city centers located adjacent to the water and vulnerable to the effects of climate

change. Information collected by Working Group 3 during risk assessment workshops with the coastal municipalities indicates that certain historic properties in Puerto Rico are already exposed to flooding events, such as the Catholic church *Santa Rosa de Lima* in Rincón and remnants of the old train along the west coast, *Antigua Casa de la Real Aduana* in **Fajardo**, numerous archaeological sites of Taino and Spanish artifacts (e.g., cooking areas and canons), the ruins of *Hacienda María Antonia* in Guanica, and *Castillo Villa del Mar* in Naguabo. In fact, the remains of the Castillo in Naguabo, located on route 3 and one of the few examples of late Victorian architectural style in Puerto Rico, has already suffered serious damage from Hurricane Hugo in 1989. Despite that tragedy and a subsequent fire the municipality and other government agencies are hoping to restore the building. Increased frequency of flooding from sea level rise and heavy precipitation events could cause more structural damage to this historic building and many others, perhaps even complete loss of such treasures.



Examples of Potentially Vulnerable Historical Sites in Puerto Rico

- *Spanish forts in Old San Juan*
- *Various archaeological sites of Taino and Spanish artifacts (e.g., cooking areas and canons)*
- *Historic city centers (e.g., Cataño, Hatillo, and Arecibo)*
- *Rincón church: Santa Rose de Lima*
- *Fajardo's Antigua Casa de la Real Aduana*
- *Ruins of Hacienda María Antonia in Guanica*
- *Castillo Villa del Mar in Naguabo*
- *Church San Carlos Borromeo of Aguadilla*
- *Old Municipal Cemetery of Aguadilla*

Aguadilla Plaza, Puerto Rico.



Water Resources

Urban modes of development have increasingly divorced us from our natural environment where water plays a vital role. Climate change is expected to exacerbate water regimes in extensive macro-regional swaths with impacts in both large and small scales of development. Puerto Rico's water resources are key assets that exist at both the surface and subsurface levels. Surface water resources are lakes, reservoirs, dams, rivers, wetlands, streams and canals (figure 2).

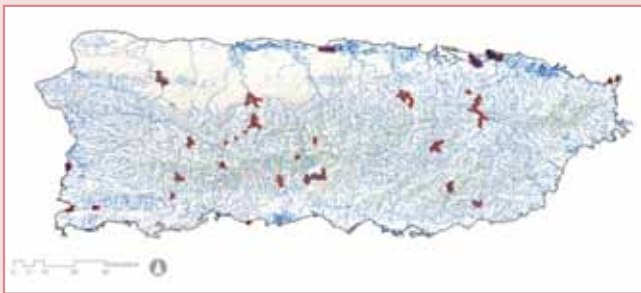


Figure 2: Surface Water Resources: Lakes, Reservoirs, Dams, Rivers, Wetlands, Streams and Canals. Map Source: ae.iou. 2009. Based on data collected from USGS. Lakes, Reservoirs, Lagoons (red outline), rivers, canals, and streams (blue lines)

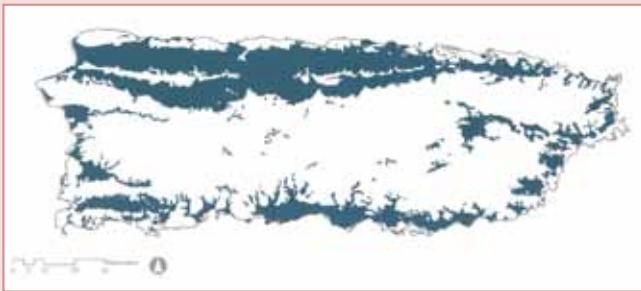


Figure 3 Groundwater & Subsurface Water: Aquifers, Saturated Zone, Subsurface Infiltration. Map Source: ae.iou. 2009. Based on data collected from USGS. Aquifers, Saturated Zone (blue color)

Groundwater and Subsurface water resources are aquifers, saturated zones, and subsurface infiltration zones (figure 3).

Traditionally, water resource planning has used recorded weather and hydrology to represent future supply conditions. Many sophisticated methods are used for reconstructing, resampling, and analyzing hydrology and other weather-

related conditions. It was assumed that the hydrologic determinates of future water resources – temperature, precipitation, streamflow, groundwater, evaporation and other water dependent factors – would be the same as they had been in the past. While there may have been large variations in observed weather, it was assumed that weather statistics would stay the same and variability would not increase in the future. This core planning assumption is often referred to as *climate stationarity* (Edward Means III 2010). Now, we must plan for a changing climate.

Water is vital to all sectors and aspects of life in Puerto Rico – including human health, agriculture, industry, local governments, energy production, recreation and aquatic systems. Research and scientific literature present mounting evidence that climate changes will alter where, when and how precipitation falls and water flows. This, in turn, will impact the quantity and quality of surface water and groundwater. Water's essential importance to human health, the economy and the environment means that water resources facilities are among the most critical and perhaps the most vulnerable categories of infrastructure relative to climate change. Many questions remain regarding climate change's impact on water resources infrastructure and how water resources infrastructure can and will respond to climate change when added to other human induced impacts such as sedimentation of water reservoirs and lakes which greatly reduce freshwater storage capacity.. This report is part of the search for answers.

The global impacts of climate change on freshwater systems and their management are mainly due to the observed and projected increases in temperature, sea level and precipitation variability (Kundzewicz et al 2007). Sea-level rise will extend areas of salinization of groundwater and estuaries, resulting in a decrease in freshwater availability for humans and ecosystems in coastal areas. Increased

precipitation intensity and variability is projected to increase the risks of flooding and drought in many areas. Higher water temperatures, increased precipitation intensity, and longer periods of low flows exacerbate many forms of water pollution, with impacts on ecosystems, human health, water system reliability and operating costs. These pollutants include sediments, nutrients, dissolved organic, pathogens, pesticides, salt, and thermal pollution.

Vulnerability assessments for public infrastructure have been completed around the world (APEGBC 2010; NYPCC 2010). To our knowledge, none have been completed for Puerto Rico. Results from other vulnerability assessments have found that climate change affects the function and operation of existing water infrastructure as well as water management practices. The functioning of existing facilities that are not designed to accommodate climate change impacts (different temperatures, precipitation and flow changes for example) may increase the chances of infrastructure failure, insufficient supply, inadequate protection from floods and unacceptable water quality conditions.

Aspects of water resources likely to be influenced by climate changes include the following, in brief:

- Seasonal shifts in stream flows that could lead to increased and decreased flows in certain seasons. This could impact water storage and electrical power generation and cause possible flooding. In the longer term, this also means depletion of water storage.
- Greater and more intense precipitation events and lengthened dry spells in given locations could increase both flooding and drought.
- Higher water temperature and more intense precipitation, accompanied by extended periods of lower flows, could increase water pollution. By extension, this could impact the ecosystems, human health as well as

the reliability and operating costs of water systems.

- Droughts and decreased availability of water may reduce streamflows, lower lake and reservoir levels, deplete soil-moisture reserves and diminished groundwater reserves. By extension, this will likely aggravate water conflicts between various users.
- Sea level rise could extend existing areas of salinization of groundwater estuaries leading to less available freshwater for human populations and ecosystems.

Generally, higher evaporation associated with warming trends tends to offset effects of more precipitation while magnifying the effect of less precipitation. Climatic shifts and resulting changes in available water resources could require modifications in water allocations. Such changes could require adjustments to the design, construction, maintenance and operation of water resource infrastructure supplying municipal, industrial, and agricultural water users. It could prompt consideration of the robustness, vulnerability, and adaptive capacity of current infrastructure, as well as whether additional water resource infrastructure might be needed.

Some specific categories of water resource infrastructure that might be subject to climate-change consideration are listed below:

- **Dams, Reservoirs and Hydropower:** Dams help to reduce flooding, allow harnessing of energy and provide for reliable water sources for domestic, industrial and agricultural use. Puerto Rico withdrawals 15.73 million gallons per day of surface waters from dammed water bodies in order to irrigate 40.83 thousand acres of agricultural lands and golf courses (DNER Plan de Agua 2010). And in 2008, Puerto Rico had 36 reservoirs (PIRA 2008). Issues arising in

connection with dams include long-term supply and availability of water. Changes in precipitation patterns raise questions about erosion, dam failure, safety and contingency planning. Besides supporting electrical generation, dams along with diversions and dykes can control or reduce flooding.

- **Irrigation and Drainage Infrastructure:** Climate change could increase needs for dams, reservoirs, and diversions to meet added demand for irrigation. Other adaptive infrastructure traditionally used – such as wells, pipelines and dugouts – may also be called into use. Besides obtaining water when there is too little, agriculture must remove excess water from crop-producing areas, often via drainage ditches. Climate change may produce increased run-off and require added infrastructure to handle this excess water.
- **Water Supply and Treatment:** The vast majority of water in Puerto Rico is used for household consumption. Climate change could affect water systems and supply sources. The timing and availability of water could vary if annual and seasonal rainfall increase, and if rainfall events are more frequent and intense. Higher temperatures could reduce available water or cause droughts leading to water supply shortages. Changing patterns of flooding could affect intakes of water systems. Both drought and flooding could require additional water treatment, thereby placing further demands on

treatment plants. Additionally, treatment plants on the coast could be affected by storm surge and storms. When there are power outages during storms the treatment plant pumps stop working and can cause sewage overflows.

- **Industrial Water Supply:** Water is critical to manufacturing and thermal power production for cooling, condensing and steam generation, and for conveying waste material. Higher temperatures may increase industrial demand by industry for cooling at a time when water supplies could become scarcer.

Unaccounted-for Water in Municipal Water Supply

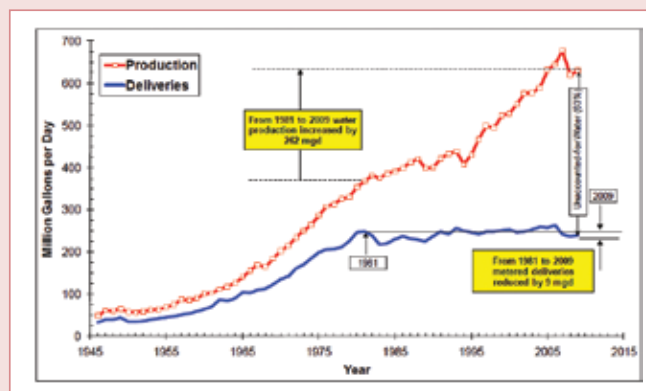


Figure 4 Unaccounted-for water trend for PRASA's water production. Source: PRASA 2010

One of the biggest threats to achieving sustainable water supply for all uses (domestic and industrial consumption, irrigation, hydroelectric, recreational, fish and wildlife refuges, etc.) is the increasing trend of PRASA's Unaccounted-for Water volume. In 2009, 63% of all of PRASA's water production was unaccounted-for water, which translates into Non-Revenue Water (NRW) for the public corporation (figure 3). Such a high volume of NRW might compromise safe yields in a future where a changing climate may reduce precipitation in many of the available reservoirs.

¹¹ References: Puerto Rico Aqueduct and Sewer Authority (2010). *Study of Desirability and Convenience for the Implementation for Advanced Technologies for the Reduction of Non-Revenue Water*. Puerto Rico Public-Private Partnerships Authority.
 Puerto Rico Department of Environmental and Natural Resources (2008). *Plan Integral de Recursos de Agua de Puerto Rico*.
 Gregory Morris Engineering PSC (2009). *Water Accountability Pilot Project Final Report*. Puerto Rico Aqueduct and Sewer Authority.

NRW has two possible types of water loss or sources. The first and main one is physical losses, which includes leakage in water mains, water main breaks, storage tanks overflows and leaks, and hydrant use for firefighting and other authorized, but unmetered uses. The second one is commercial losses, which comprises theft or unauthorized consumption, metering equipment deficiencies, meter estimates or misreads, and PRASA customer database problems.

During future drought periods, an increasing trend in NRW could substantially compromise water availability, which could cause water rationing that will ultimately affect the island's economic interests (industrial, commercial, touristic, etc.), availability for irrigation, fish and wildlife refuge sustenance, as well as the most vulnerable populations (sick, elderly, etc.). Institutionally, this scenario has serious and stressful implications, not only for PRASA, but also for PREPA, PRDNER, PRDH, PRDA, and the PRPB. PREPA is the public corporation with jurisdiction over irrigation channels, and the PRDA has state jurisdiction over agricultural matters. PRDNER has various fish and wildlife refuges located in many of the reservoirs, and an unstable water level could have serious repercussions on aquatic life. The health impacts of water rationing can cause additional and unsuspected institutional stress on the PRDH. Land-use planning that has had deteriorating consequences over water distribution can cause sudden institutional burden on the PRPB.

Although PRASA has implemented various projects to reduce NRW (a pipe pressure stabilizing project to reduce physical losses, and the NRW Reduction Program to reduce commercial losses), their degree of success has yet to be measured in a recent water balance. A land-use master plan that aims to reduce stress on the water distribution system has not been approved by the PRPB yet. Also, a long-term and wider-in-scope water infrastructure repair and renewal project will be needed to reduce physical losses by a substantial

margin. Water conservation and water theft prevention measures at the household level will have to be implemented with interagency and community participation.

Impacts of Specific Climate Stressors on the Water Resources of Puerto Rico

Sea Level Rise

Surface Water Resources: New climate models suggest that sea level rise will have severe consequences on coastal areas where aquatic habitats are important components of the hydrologic cycle. Rising sea levels will affect the tidal regimes that control the hydrology of many coastal ecosystems in Puerto Rico. These habitats rely on the accumulation of organic matter to maintain their profile elevation with respect to sea level. As sea level rise accelerates, some mangrove fringes and wetlands will be unable to keep pace and could be significantly eroded to the open sea and thus may speed up the sea level rise process via coastal erosion. Other coastal wetlands and mangrove forests will be able to migrate inland as sea inundates coastal areas. Roads and buildings as well as insufficient sediment availability could impede wetland's vegetation to migrate inland. Sea level rise will also produce more severe tropical storms, causing storm surges that could significantly affect tidal wetlands through increased coastal flooding and increased salinity of estuaries. In addition, these will completely modify tidal ranges in rivers and bays and bring new forms of contamination in coastal areas and atypical transport of sediments and nutrients that degrade coastal ecosystems.

¹² IPCC, 2007: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Parry, Martin L., Canziani, Osvaldo F., Palutikof, Jean P., van der Linden, Paul J., and Hanson, Clair E. (eds.)]. Cambridge University Press, Cambridge, United Kingdom, 1000 pp.

Ground Water Resources: Coastal aquifers are important strategic resources that may be at risk of salt intrusion as a consequence of increased coastal flooding due to sea level rise. Timms et. al (2008) points out that: “saline intrusion and/or inundation caused by rising sea-level would probably be the most significant impact on coastal groundwater resources due to climate change, particularly for shallow sandy aquifers along low-lying coasts.” Aquifers that could be threatened by SLR are important resources that provide water for many important ecological functions and ecosystem services.

Rising Temperatures

Surface Water Resources: An important driver of land use adaptation will be new temperature regimes resulting from changes in weather, rainfall patterns, and ecosystem loss. Rising temperatures may cause a decline in precipitation and an increase of evaporation, resulting in a substantial drop of fresh water availability in reservoirs and lake systems. Also, the rising heat levels will produce direct increases in the temperatures of rivers and streams which will further exacerbate water stress in some areas. As described by Working Group 1 drought conditions may be increasingly likely for the Caribbean. As a result, climate change is expected to create serious water supply problems in dry periods. In addition, the urban heat island effect -- a process which today leads to more than a 10.8 °F degree increase in urban air temperatures -- will also bring about changes. These changes will affect the network of surface water bodies in many cities. And since rivers, streams and wetlands play such a critical role in moderating global climate by capturing and storing atmospheric carbon, protecting biodiversity and mitigating flood impacts, the disruption caused by rising temperatures

and urban heat island effect would be further disruptive.

Ground Water Resources: Groundwater supplies will be affected by higher temperatures. The drying off of vegetation swaths produce watershed scale variances that will alter soil composition, making soils less porous, thus reducing groundwater recharge rates. This will in turn increase rainwater runoff, exacerbate flood threats and lead ultimately to mudslides. Less subsurface water also entails that in dry months higher temperatures will cause changes in vegetative cover that could succumb to wildfires and other deforestation hazards.

Changing Precipitation Patterns

Surface Water Resources: Fundamental to climate change is recognizing how design parameters are changing. In this way precipitation will usher in new extremes. Climate change is expected to increase the frequency of heavy rain events precisely in the latitudes where Puerto Rico is located. Higher volumes of stormwater runoff produce more water quality issues when large precipitation events occur. Urbanized land use increases the amount of impervious surface that, in turn, increases the volume of stormwater runoff to be managed. Altered precipitation patterns resulting from climate change threatens rivers and streams as higher pollution levels from runoff could be registered.

Ground Water Resources: The natural processes that recharge aquifers will suffer and could have serious implications for maintaining water supplies in the future. Moreover, measures to combat these issues, like building dams to

¹³ Timms, W, Andersen, M.S. and Carley, J (2008). Fresh-saline groundwater boundaries below coastlines - potential impacts of climate change. Coast To Coast Crossing Boundaries Conference, 18-22 August, 2008, Darwin.

¹⁴ Climate Change: Global, Regional, and Urban – An Introduction. Climate Change Literature Review. http://urpl.wisc.edu/ecoplan/content/lit_climate.pdf

¹⁵ Environmental Protection Agency. Heat Island Effect: Basic Information. 2009 <http://www.epa.gov/heatisl/about/index.htm> 16 Peter H. Gleick, Briane Adams. (2000) Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States. Pacific Institute for Studies in Development, Environment, and Security and U.S. Geological Survey.

store water will further impact aquatic habitats by increasing fragmentation that inhibits the movement of flora and fauna over time.

Increasing Intensity of Storm Events

Climate change is increasing, and will continue to increase, the intensity, and possibly the frequency, of storm events. The mounting intensity of storms will require comprehensive action to reduce stormwater runoff and to minimize its impact on Puerto Rico's water resources. Many existing developments were not planned and designed to ensure adequate water sensitive development standards and lessen storm damage. Even modest disruptions to infrastructure can have significant effects on daily life. Projected changes in the frequency or intensity of those disruptions could have profound consequences for economic and human well-being. Future changes in climate that may alter precipitation intensity or duration would likely have consequences for urban stormwater discharge, particularly where stormwater detention and conveyance facilities were designed under assumptions that may no longer be correct. The social and economic impact of increasing the capacity of undersized stormwater facilities, or the disabling of key assets because of more severe flooding, could be substantial. Because a change in climate is expected to affect oceanic and atmospheric circulation that produces more precipitation, we will also see alterations in the intensity, frequency and distribution of tropical storm systems. Bigger storm surges will damage coastal ecosystems by eroding the natural defenses that protect our coasts. Rivers and streams will be overloaded by larger precipitation volumes, and lakes will become flooded by rainwater and by stormwater runoff that carries heavily contaminated pollutants. As the surface water network becomes compromised, overburdened,

eroded and ultimately polluted, so will the ground water resources. Hurricane and tropical storm often produce long periods of infrastructural collapse that disrupt water supplies and generate serious water demand stress throughout the population.

Environmental Degradation

The effects of climate change are likely to be exacerbated by a wide variety of human development and polluting activities. Poor land use practices have resulted in sedimentation of river channels, lakes and reservoirs and changes in hydrological processes. Deterioration of the quality of water resources resulting from further increases in nutrient loads from agricultural irrigation and the domestic industrial and pharmaceutical sectors has also significantly affected available fresh water resources. Increased human activities lead to the exposure of the water environment to a range of chemical and biological pollutants, as well as micro-pollutants. The oil refinery and pharmaceutical industrial sectors in particular produce high concentrations of effluents that act as non-point sources of water quality degradation, including the unprecedented effects of unknown chemical interactions which currently pollute our groundwater resources. While oil refineries no longer operate in Puerto Rico areas of previous operation should be assessed for their contamination potential. Environments are already under pressure from human activities that drain natural water bodies and introduce pollutants that wash out to coastal ecosystems, such as mangroves, sea-grass and coral reefs. From a Society and Economy point of view, environmental degradation is enveloped with climate change for the reasons outlined and for many more reasons beyond the scope of this report.

¹⁷ Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds., 2008: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Water Supply

Water supply infrastructure constitutes all of the elements that relate to the processing and distribution of potable water for consumption. Water supply infrastructure includes, but is not limited to storage structures, main water pipes, etc. Because water is essential to human life, water supply infrastructure should be considered essential to health and livelihoods in the context of climate change.

Sea level rise will likely cause the salinization of aquifers, creating a need for higher levels of water

treatment before distribution for consumption. Changes in precipitation patterns and the higher temperatures projected could also impact the availability of water and create water supply shortages because of droughts and evaporation. The latter stressor could also increase the demand of water for cooling. The Department of Natural and Environmental Resources has initiated discussions with the U.S. Geological Services Caribbean Water Science Center to develop a network of water monitoring stations to specifically detect, monitor, and assess salt water intrusion and potential impacts on ground water resources in Puerto Rico.



¹⁸ UNESCO, The United Nations World Water Development Report 2 (2006)

¹⁹ UN Environment Programme Global Environment Monitoring System (GEMS)/Water Programme. (2008) Water Quality for Ecosystem and Human Health, 2nd Edition.

Box 1: POSSIBLE IMPACTS OF CLIMATE CHANGE ON PUERTO RICO'S AGRICULTURAL WATER RESOURCES BY ERIC W. HARMSSEN

The Intergovernmental Panel on Climate Change (IPCC) has recently reported that in the future the Caribbean Region will receive less annual rainfall, however, severe storms, which occur during the wet season, will become more intense. How might the combination of higher temperatures and changing rainfall patterns affect Puerto Rico's agriculture? Here is what we might expect: Rising temperatures will increase heat stress in livestock and crops, which will reduce agricultural production. With increasing evapotranspiration (evaporation from soil and transpiration from plant leaves) during drier months, crop water requirements will increase, therefore the agricultural sector's demand for water will increase. If Puerto Rico's population continues to rise, competition for water and land will become more intense between agriculture and the other sectors of society. Drier soils will result in less annual surface runoff needed to fill our reservoirs and less annual aquifer recharge. A reduction in aquifer recharge will cause water tables to drop and may result in saltwater intrusion along the coasts, a problem which will be exacerbated by rising sea levels. With higher temperatures and drier conditions, soils may lose organic matter, which is essential to healthy agricultural systems. Climate change may adversely affect organisms which play important roles within the plant/soil/water system, for example, soil bacteria, which mediate many chemical reactions in the soil, and bees, which pollinate many agriculture plants.

The majority of soil erosion occurs during severe storms, therefore, with more intense tropical storms during the wet season, additional soil erosion can be expected, which will reduce surface water quality and contribute to the loss of storage space in our reservoirs. Flooding may increase, resulting in the loss of crops, and sea level rise may eliminate some of the agricultural land along the coasts, causing the affected populations to migrate to the higher elevations or urban areas. The loss of this land will result in a direct loss of agricultural production.

These threats to Puerto Rico's agriculture must be viewed within the bleak context of today's current situation. It is estimated that today greater than 75 percent of the Puerto Rican diet comes from imported food, and should the imports cease for any reason, the island has only a fifteen day food supply. Per capita food production continues to decline and farm land continues to be lost to the development of residential urbanizations and other non-agricultural uses. Puerto Rico's Agricultural Reserves, set-aside areas devoted to agricultural activities, continue to be under-utilized.

The future agriculture of Puerto Rico described above will exist within a society which is also suffering the adverse effects of climate change. As one example, Dr. Parham of the Caribbean Agriculture and Research Development Institute (CARDI) has described how tourism may be affected negatively because the Caribbean region may not be a desirable vacation destination in the future. People may not want to vacation here because of coastal erosion, coral bleaching, fear because of more frequent natural disasters, and higher temperatures causing vacation activities, for example hiking, to become less attractive. Warmer temperatures may also result in new pests and diseases in the region. A reduction in tourism would result in reduced agricultural sales to the tourist and hotel industry.

In a recent study conducted at the University of Puerto Rico, crop water requirements were predicted for the next 100 years for three locations in western Puerto Rico. The findings were consistent with the recently released report by the IPCC on global climate change, predicting that September will have excess water for plant growth, but during every other month of the year rainfall will be insufficient to meet plant water requirements.

The implications of these results suggest that additional water might be saved during the wet month(s), which could then be used to offset increased irrigation requirements during other months. The storage of additional water would require the construction of additional reservoirs in the mountainous regions of the island. Improving farm water use efficiency may also help to alleviate the problem of water shortages in the future. Educational programs should be directed towards farmers to assist them to manage their irrigation water more efficiently. Developing plant varieties which have higher tolerance for drought conditions is another way to prepare for the future. At the University of Puerto Rico, for example, we are studying different varieties of common beans and their response to drought stress. We hope that the study will lead to bean varieties which are more drought-tolerant. Development of drought resistant varieties of common bean is important since it is a staple in many poor countries.



Figure. Victor H. Ramirez, graduate student in Agronomy at UPRM, is describes a drought tolerance study of common beans currently being conducted at the UPR Agricultural Experiment Station at Juana Diaz.

Waste Water and Storm Water

Understandably, the design and magnitude of the Commonwealth's stormwater and wastewater systems varies greatly depending on location and the features of the communities served. For more detailed assessments, municipalities and agencies should look into their specific systems. Stormwater and wastewater infrastructure systems have many components, including:

- Collection and transmission structures – gutters, pipes, streets, channels, swales, urban creeks and streams, and pumps;
- Quantity-control structures – ponds, urban lakes and infiltration devices and roof tops;
- Quality-control structures (e.g., grit chambers);
- Storage structures;
- Overflow systems for carrying both waste and stormwater;
- Water treatment facilities; and
- Discharge systems for the release of treated water.

The infrastructure will vary depending on whether it entails: (1) a combined system carrying wastewater and stormwater together in the same system; (2) a fully separated system carrying wastewater and stormwater in separate systems; or (3) a partially separated system with some divided wastewater and stormwater flows.

Present configurations can affect the degree to which climate change will impact stormwater and wastewater infrastructure. Climate changes could alter rainfall events, their annual volume, frequency and intensity. All of these factors might place added demands on collection and treatment systems (Engineers 2008).

Temperature changes are other influencing factors on wastewater and stormwater infrastructure. Warmer weather could decrease base flows and affect odor in discharge processes. During drier periods, dry soil could increase the possibility of pipe failures. Higher water temperatures

could intensify pollution and adversely affect ecosystems, human populations and the reliability and cost of the collection and treatment systems. Changing conditions that affect the performance or cause failure to wastewater and stormwater systems represent a threat not only to the infrastructure itself but also to human health and safety, the economy, and the environment.

Waste water infrastructure in particular deals with used water management and treatment. Waste water infrastructure includes, but is not limited to pipe systems and waste water treatment plants. Flooding from sea level rise could cause structural damage to water treatment plants located in the coastal zone.

Storm water infrastructure, on the other hand, includes, but is not limited to, the system of pipes and channels that collect rainwater and divert it to the ocean or store it for detainment. Flooding from sea level rise could render existing storm water discharge pipes useless because these systems work by taking advantage of gravity (figure 4). Discharge areas would have to be adapted through the use of pumps. In addition, changes in precipitation patterns could negatively affect storm water infrastructure, if larger amounts of water need to be diverted and/or stored.

One wastewater treatment plant in San Juan is more critical than all others (WPI 2011). The San Juan treatment plant is the largest capable of treating up to 150 million gallons per day (mgd) of wastewater; the average rate is about 75 mgd. The excess capability is for times of heavy rains. During an extreme storm or tsunami the wastewater will most likely exceed 150 mgd of wastewater. In such an event, wastewater could potentially spill out into the streets and beaches of San Juan. Treatment plants in Puerto Rico are usually located in flood zones because these zones are at the lowest elevations, and the plants rely on gravity. These plants are built to withstand flooding by having the pit walls of the plants raised. The stations are sealed off so that they are capable of operating during flooding and the plants themselves are capable of running for 8-10 hours on reserve generators. These generators

must be refueled after such a reserve event and if a large storm impedes access to roadways leading to the plants it will also prevent the refueling of the generators.

Of the 65 waste water treatment plants (WWTPs) that are located in Puerto Rico, only 17 are situated along the coast. WPI found that three plants are specifically vulnerable to sea level rise and storm surge. These plants are the Arecibo Regional



Figure 5 Gravity stormwater drainage under average tidal conditions, with sea level rise, and when combined with extreme precipitation events. (Photos 1 and 2 courtesy of the Broward County Government, Florida)

According to the WPI study, PRASA reported no future plans to address climate changes and they do not currently budget for future scenarios past 50 years. The WPI study also found:

The total length of aqueducts within the coastal region of Puerto Rico is 1,095,712 meters. Of these, 208,632 meters (~18%) are susceptible to flooding caused directly from tsunamis. Of those that are located in FEMA flood zones, 47,074 meters are in the 0.2% annual chance flood hazard, 16,638 meters are in flood zone A, 252,666 meters are in flood zone AE, 203 meters are in flood zone AH, 7,974.46 meters are in AO, and finally 44,529.97 meters are located in flood zone VE.

WWTP, La Parguera WWTP, and the Boqueron plant at Villa Taina (WPI 2011).

Dams, Levees and Flood Control

The PRCCC was unable to find experts on climate change and Puerto Rico’s dams and levees in regards to flood control and thus this should be a priority topic for future climate change vulnerability assessments. It can be assumed that current dams, levees and flood control structures might not be structurally suited to handle larger levels of water due to increased precipitation, and would be at risk of failure. Particularly when combined with sedimentation from poor soil and watershed management practices reducing dam capacity.



Box 2: Climate Change and Health Impacts in Puerto Rico

Climate change increases the vulnerability of Puerto Rico's population by affecting health and increasing mortality and morbidity. The age groups at high risk, such as the elderly and children, are not prepared to withstand higher temperatures or to face a higher thermal gradient (drastic changes in temperature). Added temperatures from global warming to urban heat islands, like San Juan, could add 15°F to normal temperatures. In Puerto Rico, extreme high temperatures have been recorded more frequently than ever before.

We can associate a higher incidence of respiratory diseases and skin cancer to conditions of global change. The increased incidence of asthma, skin cancer and a higher prevalence of cataracts in the population could be related to the effects of climate change. Already, the amount of ozone in our troposphere combined with a greater amount of particulate dust from the Sahara desert and Le Soufriere volcanic ash coming from the island of Montserrat, among other pollutants has increased the number of cases of respiratory ailments. The prevalence of the following diseases may directly be altered in Puerto Rico by climate change: dengue, malaria, malaria, ciguatera, Lyme disease, viral encephalitis, cholera, salmonellosis, E. coli, meningitis, asthma, bronchitis, pneumonia, skin cancer, cataracts and loss of immune system. More studies are needed to determine likelihood of changes in disease prevalence.

Ultraviolet radiation affects the health of Puerto Ricans to provoke a necessary adaptation to sun exposure. Currently we need preventive measures such as sunglasses with UV protection, hats and limit exposure to sun to a couple of hours. If we increased our exposure we risk increasing the occurrence of skin cancer, loss of vision and even effects on the immune and nervous systems. The increased number of cases with these conditions in Puerto Rico shows that the population is not aware or not interested in taking preventative measures to reduce the risks associated with excessive exposure to UV rays.

As the PRCCC WG ¹ report states, extreme temperatures and rainfall, heat waves, floods and droughts will be on the rise. These extreme changes have a direct effect on mortality and morbidity. Moreover, climate change also exerts its effects on biodiversity and the ecosystem in general, which also impacts health. Water resources and food are being reduced as a result of pollution and the effect of extreme catastrophic events. In the past, Puerto Rico has been impacted by shortages of basic food and water during the passage of extreme events such as Hurricane Hugo (¹⁹⁸⁹) and George (¹⁹⁹⁸). Currently our water system is quite fragile, where erosion and sedimentation affects water quality during any period of rain or drought. At this moment we are very vulnerable to extreme events and our population at risk increases because we have created very fragile and unstable environmental conditions. For example, currently Puerto Rico has more flood-prone areas than ever before because we have altered natural drainage of storm water, particularly in our cities. Food quality has declined, not only by a change of diet, but because they are imported and thus go through cycles of freezing and cooling. The use of preservatives and chemicals in food production has also decreased its quality.

Climate change is also anticipated to affect medical services as insurance companies would have a greater number of claims and service delivery. This would disrupt the way policies are implemented and their costs.

Population-related vulnerability for Puerto Rico at a glance

General^{2, 3} :

- 3.8 million Individuals; 27.5% ≤¹⁹ years, 14.1 % ≥over ⁶⁵.
- Population density ¹,115m²
- Coastal zone population ².73 million (70%)
- Population below poverty level ⁴50% (vs. ¹⁵.10% for US)
- ⁶⁸ hospitals (fiscal year ^{2001–2002}); only ²⁵ (37%) in the Metropolitan Region.
- No centralized medical care system.

Climate sensitive conditions³:

- *Cardiovascular* disease leading cause of death,
- *Asthma*^{4, 5}. Rate is ¹¹³% higher than non-Hispanic whites and ⁵⁰% higher than non-Hispanic black. The *Prevalence* and mortality of asthma attack is highest among Puerto Ricans and up to ^{41.3}% in children
- *Hypertension, diabetes and asthma* comprise ⁴⁶% of demand for health services *Anxiety/depression* comprises ^{11.6}% of demand for health services in women.

Potential affect of climate change on human health and Puerto Rico's vulnerabilities in the context of the IPCC Fourth Assessment Report (²⁰⁰⁷) and confidence levels:

- 1. Altered seasonal distribution of some allergenic pollen species (IPCC¹: high confidence)**
 - a. Puerto Rico: most aeroallergens are fungal spores⁷; no proven effect of carbon dioxide in spore's allergenicity. Increased wind speed and humidity (hurricanes/storms) may enhance spore spread. Thunderstorms and asthma exacerbations have been correlated with a doubling of ambient fungal spores⁸.
- 2. Increased heat wave-related deaths (IPCC¹: medium confidence)**
 - a. No trends recorded in Puerto Rico in relationship to climate change. Urban heat island: temperature in San Juan increased at a rate of .⁰⁶oC /year for the last ⁴⁰ years⁹ . It is predicted that the heat island effect can go up as high as ⁸oC by ²⁰⁵⁰.
- 3. Increased malnutrition and consequent disorders, including those relating to child growth and development (IPCC¹: high confidence)**
 - a. Vulnerability not assessed but ⁴⁵% of population under national poverty level. Sociopolitical relation with the U.S. may ameliorate impact.
- 4. Altered the distribution of *some* infectious disease vectors (IPCC¹: medium/high confidence)**
 - a. No published data to support change in incidence of ciguatera disease, vibrio or dengue⁶ infection.

b. No West Nile Virus or SL encephalitis reported so far (CDC).

5. **Increased burden of diarrheal diseases (IPCC¹: medium confidence)**

a. Water quality (EPA ²⁰⁰³): 40% bodies of water do not meet quality standards primarily due to discharge sewage and agro/industrial contamination³. Diseases outbreaks related to interruption of water services or contamination. Outbreaks reported¹⁰ but incidence limited; not a significant source of morbidity /mortality during natural disasters (e.g. hurricanes).

6. **Increase cardio-respiratory morbidity/mortality associated with ground-level ozone (IPCC¹:high confidence)**

a. Asthma^{4,5}. Rate in Puerto Ricans is ¹¹³⁰% higher than non-Hispanic whites and ⁵⁰⁰% higher than non-Hispanic black. Also higher incidence of asthma attacks and mortality compared to other ethnic groups, representing a major source of morbidity as air quality changes.

b. High incidence and highest cause of mortality due to cardiovascular disease. Expected increase in ground level ozone, resulting from increased temperatures and pollution, may increase mortality associated to cardiovascular diseases¹².

7. **Increased number of people suffering from death, disease and injury from: heat waves, floods, storms, fires and droughts (IPCC¹: high confidence).**

a. Hurricanes in Puerto Rico can be a source of morbidity, mortality and psychological stress (population displacement). Example:

i. Hurricane Georges¹¹: Three direct deaths; nine indirect. (heart attacks, etc.). Power and water out to ⁸⁰⁰% of the ^{3,8} million people on island. ^{33,113} homes destroyed in Puerto Rico, with nearly ^{50,000} more suffering major or minor damage.

ii. Hurricane Hugo¹³: ² direct fatalities, ²² indirect. Water services in the San Juan area were disrupted for ⁹ days. More than ^{200,000} families affected with homes destroyed or damaged. Tank trucks used temporarily to distribute water from elsewhere on Puerto Rico.

8. **Psychological/psychiatric effects of climate change (not included in IPCC ²⁰⁰⁷ assessment).**

a. Major source of morbidity and potentially mortality for **all** populations. Percent of adults reporting limited activities due to physical, mental or emotional disorders in ²⁰⁰⁹ was ^{17,30}%¹⁴.

b. Mental health care is not structured or coordinated and has deteriorated since implementation of the new health reform¹⁵.

1. http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch8.html

2. http://www.census.gov/compendia/statab/cats/puerto_rico_the_island_areas.html

3. <http://www.paho.org/HIA/archivosvol2/paisesing/Puerto%20Rico%20English.pdf>

4. <http://www.lung.org/assets/documents/publications/solddc-chapters/asthma>

5. http://www.epa.gov/asthma/pdfs/asthma_fact_sheet_en.pdf

6. PLoS Negl Trop Dis 3(2); e382.doi:101371 2009

7. Int Arch Allergy Immunol 2011;155:322-334

8. Allergy. 2010. 65(9):1073-1081

9. http://nargo.geo.uni.lodz.pl/~icuc5/text/P_6_14.pdf

10. http://www.cdc.gov/mmwr/preview/mmwrhtml/ss6012a4_w.htm?s_cid=ss6012a4_w

11. <http://www.ncdc.noaa.gov/oa/reports/georges/georges.html>

12. <http://aje.oxfordjournals.org/content/154/9/817.full>

13. <http://www.nws.noaa.gov/om/assessments/pdfs/hugo1.pdf>

14. <http://www.cdc.gov/mmwr/preview/mmwrhtml/ss6009a1.htm>

15. J Psychiatr Pract. 2010 Mar;16(2):129-37

Economic Development

A Brief Overview of Puerto Rico's Economy

In the past six decades there has been a major shift in the foundation of Puerto Rico's economy. Historically, Puerto Rico was an agricultural economy, based on sugar, tobacco, and coffee products. During that time manufacturing was a relevant but much smaller sector of the economy. Currently Puerto Rico's modern economy is oriented to industry and services. This major shift can be seen when comparing a 1940's economy to that of 2002 where agriculture went from being over one third of the total net income in 1940 to only 1% in 2002. Additionally, commercial fishing has historically been a component of the agricultural sector (with the Puerto Rico Department of Agriculture providing support to commercial fishers). Fishery statistics indicate fishery resources are declining in abundance around Puerto Rico as evidenced by a 69% decrease in the number of pounds landed between 1979 and 1990. Possible causes: (1) declining catch per unit effort; (2) marketing of species that previously had no commercial value; (3) large proportion of harvest made up of sexually immature individuals; and (4) the change to more generalist gear such as nets (CFMC 2004). In 1931, a total of 1,403 active commercial fishers were reported compared with 1,758 in 1996 and 1,163 in 2002 (Matos-Caraballo 2004). Today, approximately one quarter of commercial fishers hold a second job, usually as seasonal construction workers but occasionally as clerks or factory workers (CODREMAR 1986; CFMC 2004). Further adding to the evolving modern economy, in 1940 manufacturing represented 12.8% of the economy while in 2002 it jumped to a dominant 45.7% and in 2010 was 46%. Second to manufacturing, the financial sector today is 19% of GDP. This sector includes banking, insurance, and real estate. (Due to data limitations the financial sector is not assessed in this report as related to climate change. The Puerto Rico Coastal Zone Management Program is commissioning a study on the Puerto Rico

insurance industry for 2012-2013 and the PRCCC recommends future assessments include the financial sector in detail.)

Changes within the economic sectors have also occurred, as in the case of manufacturing. At first, this sector was a heavily labor intensive industry, due to the government-launched industrialization program known as "Operation Bootstrap", which began in 1948. Under this program the island became industrialized by providing labor locally, inviting investment of external capital, importing raw materials, and exporting the finished products to the U.S. market. To entice participation, tax exemptions and differential rental rates for industrial buildings were offered. As a result, Puerto Rico's economy shifted labor from agriculture to the manufacturing of food, tobacco, leather, and apparel products. In the last four decades, due to structural and technological advances, the sector has changed to capital and knowledge intensive industries such as pharmaceuticals, chemicals, machinery, electronics, and biotechnology. In these types of capital-intensive industries the amount of capital involved is much higher than the proportion of labor. The industrial structure and industry type require high value investments in capital assets. Another factor in Puerto Rico's evolving economy is its human capital. The population of Puerto Rico has access to local, affordable, high quality education, and many, perhaps a majority of institutions (and, as a result, their graduates) are bilingual, providing further incentive for the shift to capital and knowledge intensive industries.

An important economic consideration is that Puerto Rico has fiscal autonomy with regards to the United States due to the Commonwealth status, which implies that Puerto Rico residents do not pay federal income taxes (unless income comes directly from the Federal government; though they do pay into social security) and the local authorities have discretion to design tax incentives to attract foreign direct investment. Due to its fiscal autonomy several Puerto Rican

administrations have been able to develop the manufacturing and services sectors of the economy in a short period of time. Further aiding Puerto Rico's economy are its extensive highways, ports, airports and modern communication systems allowing for an efficient transport of goods throughout and beyond the Island.

These factors illustrate how the private sector with assistance from the public sector developed today's economy, as according to GDP, in Puerto Rico to be dominated by manufacturing and as such an economic leader in the Caribbean and Small Island Developing States (SIDS) around the world. Out of 228 countries world-wide, six of the SIDS have GDPs in the top half relative to all 228 countries. These are Singapore, Cuba, the Dominican Republic, Puerto Rico, Bahrain and Trinidad and Tobago. Relative to their GDPs, 88% of the SIDS have GDPs that rank in the bottom half when compared to the rest of the world (CIA World Fact Book 2010). This fact makes Puerto Rico (ranked 83 worldwide and ranked 4th when compared to the SIDS) one of the wealthiest and most financially competitive SIDS in the world. In addition, Puerto Rico ranks 47th in terms of world export and 57th in terms of imports. Seen differently, compared to the other SIDS, Puerto Rico ranks 4th in terms of GDP, second to Singapore in terms of exports and imports. Compared to the other 14 colonial/territorial SIDS world-wide (American Samoa, Anguilla, Aruba, British Virgin Islands, Commonwealth of Northern Marianas, Cook Islands, French Polynesia, Guam, Montserrat, Netherlands Antilles, New Caledonia, Niue, and the U.S. Virgin Islands) Puerto Rico has the highest GDP, export, and import ranking. The two closest are the U.S. Virgin Islands and the Netherlands Antilles.

The economic indicators in Tables 2 and 3 reflect that the modern day economy of Puerto Rico are divided into a couple of major sectors, but these sectors are not where the majority of the labor force works. The two sectors that dominate the economy in terms of GDP are (1) manufacturing

and (2) finance, insurance and real estate, making up 66% of Puerto Rico's GDP combined. However, together they only employ 12.9% of the labor force. In contrast, 75.4% of the labor force is employed in the services (such as tourism and hospitality), government and trade sectors which together amount to only 29.1% of Puerto Rico's GDP. Thus, it is important to consider more than just GDP when assessing the vulnerabilities of Puerto Rico's society and economy to potential climate changes.

Puerto Rico's Economy and Climate Change

In the face of climate change, several aspects of Puerto Rico's economy must be considered. Principally, Puerto Rico's economy and workforce are heavily concentrated in sectors that strongly depend on transportation systems and telecommunication services. These two types of infrastructure could be compromised during the projected more intense and frequent extreme

40% of businesses that are affected by natural or man-made disasters never reopen

(Insurance Information Institute 2012)

weather events. Capital intensive industries that are dependent on their unique infrastructure are at risk of not recovering from the potential damage that more intense weather events can cause due to the large financial commitment that is typically required to get the first unit of good or service produced in those types of industries. In fact, 40% of businesses that are affected by natural or man-made disasters never reopen (Insurance Information Institute 2012).

Similar considerations regarding potential detrimental impacts to the proper functioning of

critical infrastructure and services (power, water, ports, etc) are also of concern for the majority of the work force. Many of these concerns stem from the fact that Puerto Rico is an island with nine (9) major ports and harbors and eleven (11) airports that are vulnerable to intense weather events. The manufacturing, services and trade sectors all rely on the regular operation of critical transportation systems (highway, ports, airports).

Puerto Rico's main trading partners are not based in the region. As of 2010 Puerto Rico's main export partners were: the United States, with 68.1% of the share; Spain, with 19.5%; Germany, with 8.1%; the Netherlands, with 4.7%; and Belgium,

with 3.7%. Major importing partners included: – the United States, with 51.2% of the share; Ireland, with 15.5%; Singapore, with 4.7%; Japan, with 4.3%; and the U.S. Virgin Islands, with 3.9% . This emphasizes Puerto Rico's reliance on transportation systems for the health of the Island's economy as well as brings attention to the global systemic problem of climate change. If climate changes in the regions of Puerto Rico's main trading partners affects those countries' production of products negatively Puerto Rico's imports could be affected. This theme will be touched on in this report, but an in-depth analysis on this specific topic is outside the scope of this PRCCC report.



²⁰ Data from Puerto Rico Planning Board (2010) and the U.S. Department of Commerce U.S. Commercial Service PR--USVI (2010, 2011, 2012).

The following figures give a summary of the Puerto Rican economy showing the composition by sector alongside the labor force by occupation as well as various economic indicators.

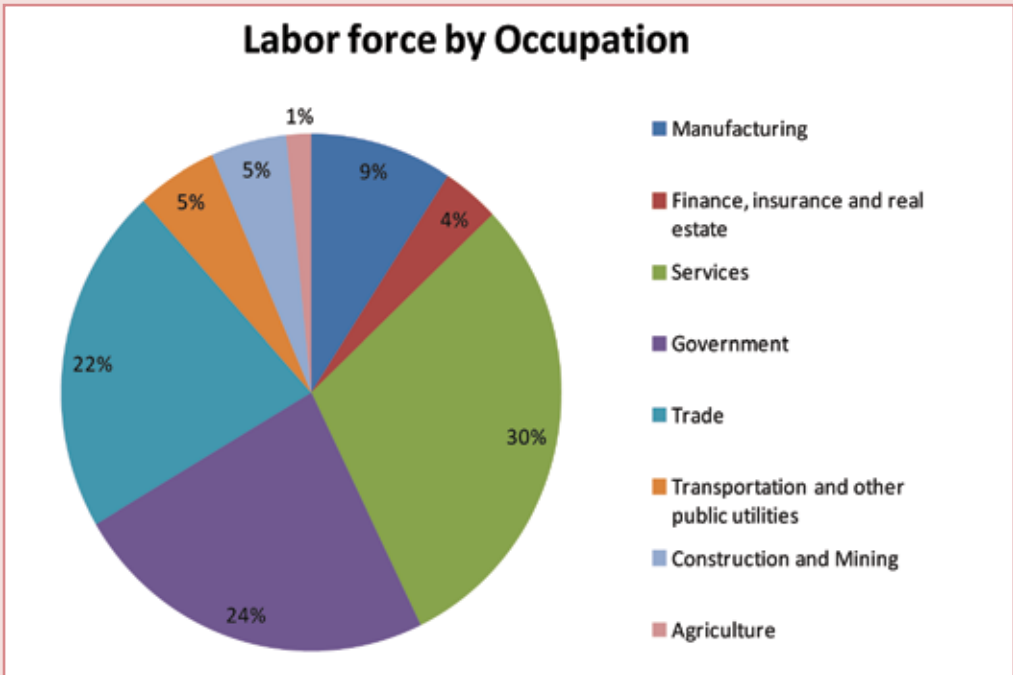


Figure 6: Puerto Rico Labor Force by Occupation. Source: Data from Government Development Bank for Puerto Rico factsheet, July 2011 (2010 data)

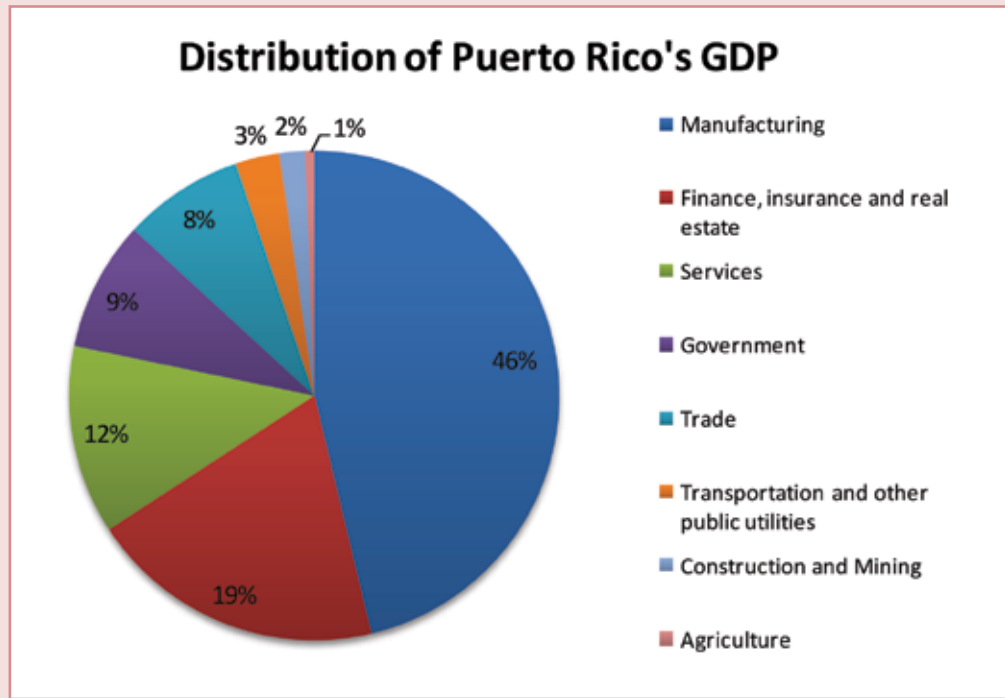


Figure 7: Distribution of Puerto Rico's Gross Domestic Profit (GDP) by sector. Source: Data from Government Development Bank for Puerto Rico factsheet, July 2011 (2010 data)

Area/Region of Puerto Rico	Unemployment Percentage as of July 2011
San Juan-Caguas-Guaynabo	15.4%
Ponce	16.3%
Fajardo	19.3%
Mayaguez	17.9%
Aguadilla-Isabela-San Sebastian	17.4%
San German-Cabo Rojo	16.1%
Yauco	18.7%

Federal funds also have an important role in the economy, as they impact personal consumption and public expenditures (funds for recurrent expenditures and construction investment). Their biggest impact, though, is on personal income and expenditures, as transfers to individuals (including Medicare and Social Security) represents, at least 67% of total receipts. Medicare and Social Security benefits account for 66% of the transfers to individuals. The next biggest item is the receipts from the Nutritional Assistance Program (PAN). They account for 12% of the total transfers to individuals as of fiscal 2009. The importance of these funds on public expenditures cannot be overestimated, as federal funds represent 23% of the total revenues of the government's consolidated budget. Federal Funds are an important source of revenue to individuals, and so to personal consumption. Total transfer payments to individuals represented 34% of personal income in 2009, from 30.2% in 2000 (in the U.S. the share is about 17%).

Population	3,791,913 (July 1, 2010 est.)
Labor Force	1.31 million (2010)
Population below poverty line	41.4% (2009)
Unemployment Rate	16% (2010)
GDP [GDP -per capita]	\$96.3 billion [\$24,229] (2010)

Of these, the share of transfer payments from the Federal Government (which includes Medicare, Social Security, PAN, and other grants) represent 22% of personal income and 65% of the total transfer payments.

Real Growth of Puerto Rico's Economy

Recent economic performance has distanced itself from the historic highs of the early 1970's. For the past decade (2000-2009) real growth averaged 0.1%, quite below that for the previous decade (2.7%). Moreover, since 2007 the economy has been going through a recessionary phase much

- **Federal Funds represent 27% of the Island's GNP.**
- **Federal Funds represent 23% of the total revenues of the Government's Consolidated Budget.**
- **Federal Transfer Payments represent 34% of personal income.**

Figure 8: Average annual growth of real GNP, 1970-2011 for Puerto Rico and the United States

more pronounced than that of the United States. More importantly, this latest contraction continued the local economy's long-term deceleration (see figure 8).

According to data reported by the Puerto Rico Planning Board (PRPB), on April 20, 2012, real growth in fiscal 2011 was -1.5%, a contraction below the revised estimate for 2011 of -3.4%. In nominal terms, GDP was \$64,106.2 million. For fiscal years 2012 and 2013, estimates are positive, a growth of 0.9% and 1.1%, respectively. However, these increases remain below the historical average. These growths are based on expected increases in personal consumption expenditures and investment in construction. Also, the gap between the growth of Puerto Rico and U.S. economies remains.

The challenge, in terms of recovery is still significant. Given that the projections of the PRPB for fiscal years 2012 and 2013 are on average 1.0%, and assuming an optimistic scenario, the

**Manufacturing Average Hourly Earning:
\$7.85**

**Manufacturing Average Weekly Earning:
\$310.86**

**Manufacturing accounts for 55.5% of
GDP:**

**manufacturing of pharmaceuticals,
chemicals,
machinery,
electronics,
apparel,
food products,
instrument,
textiles, and
clothing.**

Figure 9: Needed GNP growth to reach 2006 levels, assuming an annual growth of 2.5% from 2014 to 2018.

economy needs to grow at an annual rate of 2.5% beginning in fiscal year 2014, to achieve in 2018 the real GNP of 2006 (figure 9).

Manufacturing

In the late 1940s, manufacturing was seen as the strategy that would allow Puerto Rico to develop economically, since political leaders of the time considered agricultural countries to be underdeveloped and associated industrialization with wealth. As a consequence, the government launched an industrialization program known as “Operation Bootstrap.” Under this program the island was to become industrialized by providing labor locally, inviting investment of external capital, importing the raw materials, and exporting the finished products to the U.S. market. To entice participation, tax exemptions and differential

rental rates for industrial buildings were offered. As a result, Puerto Rico’s economy shifted labor from agriculture to manufacturing and tourism.

Over time, Puerto Rico’s manufacturing sector has shifted from the original labor-intensive industries, such as the manufacturing of food, tobacco, leather, and apparel products, to more capital-intensive industries, such as pharmaceuticals, chemicals, machinery, and electronics. Puerto Rico’s major manufacturing activities (listed in the order in which they contribute to the manufacturing domestic income) are: chemical and allied products; machinery and metal products; food and related products; apparel and related products; printing and publishing; leather and leather products; stone, clay, and glass products; tobacco, paper and allied products; and textile mill products. San Juan and Mayagüez are the leading centers for clothing production, mostly the manufacturing of uniforms through federal contracts with the United States.

Storms and hurricanes are a good way to test the entire system of manufacturing as related to climate change (Puerto Rico Manufacturer’s Association, *personal communication*, July 17, 2012). Past events, specifically Hurricanes Hugo and Georges, disrupted transportation systems and thus disrupted many industries’ operations greatly. However, there are few reports of atmospheric conditions causing structural damage to company infrastructure. Yet on a regular basis there are floods regionally in Puerto Rico and these events do disrupt industry production. Examples include, business being interrupted when workers are absent because their children’s schools are closed due to flooding. Or if workers are unable to reach the manufacturing plants due to impassable roads. Or if communication lines are down due to the majority of areas having above ground lines the company might lose business. Depending on the industry and its size the companies might be able to sustain two to three days of service interruption. Chances are higher of resistance to events if there is sufficient

time to prepare. Some industries in Puerto Rico require specific equipment that cannot shut down without corrupting whole batches of raw materials and these businesses are more susceptible to being negatively affected by service interruptions. Furthermore, the ability of industry to ship their products off island is an important consideration. As previously mentioned, flooding events from sea level rise, storms, and heavy rains, might shut

“This will take some time. The problem is that time isn’t something we have very much of, given the way climate change is accelerating, so we have to move very quickly.”

~ Geannette Siberón, chairwoman of the Puerto Rico Manufacturer’s Association Environment Committee

(2012 Environmental Awards, March 30th, 2012)

down air and seaports. Most products are flown out via airports and not seaports, like pacemakers and pills, however, certain items like alcoholic beverages from the rum distilleries or beer bottling plants cannot be exported via airports and rely on functioning sea ports.

Currently there are no water quality or quantity restraints for the manufacturing industry, a plus for Puerto Rico in terms of economic competitiveness. Many companies have their own wells and are not connected to PRASA. An independent study is needed to determine how future droughts in the Caribbean will affect Puerto Rico’s water resources and dependent industries, like manufacturing.

Adaptive capacity of Puerto Rico’s manufacturing industry may be sufficient to deal with climate change as there is a functioning network for emergency management. This network may prove useful in the future as sites become more exposed to climate changes. The network right now mostly shares their inventory of supplies (e.g., nitrogen), helicopter landing sites, contact information, tents, etc and each firm is given the resources by the Puerto Rico Manufacturers’ Association to develop emergency plans. However, this network, and therefore the industry’s adaptive capacity, has not yet been tested by a large hurricane.

From the experience of past storm events it can be inferred that climate change may affect manufacturing indirectly, like human resource issues and service interruptions, and to a lesser extent from direct structural damages. This highly depends on the location of the industry facilities, their method of export (i.e., air versus sea), their connection to the network for emergency management, and the type of industry.



Box 3: Film and Entertainment Industry

The last few years Puerto Rico has promoted the film industry like never before, managing to put Puerto Rico on the map as a unique and attractive destination for film and television production. The film industry is one of the most important lines, not only for economic development, but for cultural development. This in turn influences other activities like the rental equipment and hotel industries, ultimately greatly impacting the consumption of goods. The filming, the core of the film industry, has the characteristics of a mass consumer product, also as an economic and cultural phenomenon, presents a great opportunity to advance jobs and economic development, especially with the competitive advantages of our island: our professional technicians, our localities, our world-renowned artists and actors, the natural and cultural resources of our beautiful island. The implications of climate change for tourism, natural resources, and the services industry could deter filmmakers from choosing Puerto Rico as a filming location. The following are just a few of the major films shot in Puerto Rico:

- *Pirates of the Caribbean filmed in Palomonitos Island off of Fajardo and Castillo de San Cristobal Fort in Old San Juan*
- *Fast Five filmed in multiple urban areas of San Juan and Carolina*
- *Golden Eye (James Bond) and Contact filmed in Arecibo Observatory*
- *Amistad filmed in El Morro*
- *Che filmed near a beach in Luquillo within the Northeast Ecological Corridor*
- *The Lord of the Flies filmed in various locations like Aguadilla, El Yunque and Vieques*

Tourism

Small Island Developing States (SIDS) can be viewed as “Gardens of Eden”, “luxurious vacation spots”, or “sun and sand destinations” – in other words, tourism hotspots. Puerto Rico’s rainforests, mangroves, and many miles of coast, provide beach, sand, and sun to tourists and residents alike. Indeed, tourism is a large part of Puerto Rico’s economic well-being and is the leading segment in the service industries. It accounts for 7.0% of the gross domestic product and 6.7% of employment. In 2010-2011 Puerto Rico received 4,213,673 visitors, and tourist receipts reached 3.4 billion (Puerto Rico Tourism Company *personal communication* June 2012). According to the Planning Board tourism employs 65,304 people directly and indirectly. And tourism is on the rise. The total number of visitors in Puerto Rico increased from 4.6 million in 1999 to 4.9 million in 2010 (PRTC 2011). The number of tourists staying in hotels increased by 28% between 1999 and 2010. Total tourism-related employment increased from 30,225 in 1985 to 54,656 in 2010, or by a factor of 81%¹.

Climate not only determines the length and quality of the tourism season, it is also an important driver of tourism demand to some regions. Climate affects the natural environment in ways that can either attract or deter visitors. The economic drivers of tourism in Puerto Rico (i.e., beaches, coral reefs, mangroves, rainforests, etc.) are extremely vulnerable to climate change² and, as reflected in Table 4 and the PRCCC Working Group 2 report, all of these assets are threatened by climate change. Moreover, Puerto Rico has invested heavily in tourism-related infrastructure, most of which lies in the coastal zone.

An economic valuation study of coral reefs and associated resources in eastern Puerto Rico, conducted by the Department of Natural and Environmental Resources in 2007, reported that

²² Edwin A. Hernández- Delgado, Carlos E. Ramos-Scharrón, Carmen R. Guerrero-Pérez, Mary Ann Lucking, Ricardo Laureano, Pablo A. Méndez-Lázaro and Joel O. Meléndez-Díaz. 2011. Long-Term Impacts of Non-Sustainable Tourism and Urban Development in Small Tropical Islands Coastal Habitats in a Changing Climate: Lessons Learned from Puerto Rico. In “Visions for Global Tourism Industry – Creating and Sustaining Competitive Strategies”.

the direct contribution of recreational activities and tourism to the Island’s economy was of \$ 939.8 million. A total of \$747.7 million were in consumer spending: \$340.3 million were direct consumer spending on beaches; en \$589.7 millions in nautical activities; \$2.7 millions were spent in diving and related activities and \$3.9 millions kayaking.³

Additionally, a 2006 study of visitor use of El Yunque National Forest, conducted by the U.S. Forest Service, sheds light on what visitors are looking for in Puerto Rico’s tropical montane settings. They found that most national forest visitors participate in several recreation activities during each visit. Hiking/walking (55%) and viewing scenery (20%) are the dominant primary activities. Those same activities are participated in by more than three-quarters of the visits to this forest. Nearly two-thirds spend time viewing wildlife. Other activities include driving for pleasure, relaxing, nature center activities, visiting historic sites, nature study, and picnicking.

Temperature

One of the main tourism assets of Puerto Rico is the Caribbean’s predictable sunny and warm conditions, particularly during the winter in major market regions in North America and Europe. With changing climatic conditions, two potentially negative impacts are possible. First, Puerto Rico may become “too hot” for tourists during some seasons. Surveys of European tourists have revealed the optimal conditions for beach tourism of 27°–32°C, roughly 80°–90° F (Rutty and Scott 2010). As the number of months in this optimal climatic zone decline somewhat, Puerto Rico may become too hot during the summer for most tourists, although little impact in the peak winter tourism season is anticipated. What is more, hotter local temperatures, along with warmer winters

²³ See the on-line documents from the May 8-10, 2007 roundtable of experts “Facing the Consequences of Climate Change in Puerto Rico,” organized by The University of Puerto Rico at Mayagüez (UPRM): <http://academic.uprm.edu/abe/ClimateChangePR>

²⁴ Economic Valuation of Coral Reefs and associated resources in Eastern Puerto Rico: Fajardo, Arrecifes La Cordillera, Vieques and Culebra. (2007). Prepared by Estudios Técnicos, Inc. for the Department of Natural and Environmental Resources. .

in northern latitudes may eventually reduce the number of tourist visits, especially when combined with decreasing beach aesthetics as erosion from sea level rise increases and safety concerns the destructive forces of stronger hurricanes, ocean surges and heavy rains.

The second negative impact is related to the temperature in those countries from which tourists mostly come from. As temperatures increase, demand for winter getaway holidays is anticipated to decline, though the extent of this has not yet been quantified. Similarly, if

climatic conditions in other destinations, like the Mediterranean, for instance, improve sufficiently, they may become more competitive with the Caribbean. The warming of other regions could represent new competition for tourists during the fall and spring seasons or even during winter seasons in the northern hemisphere. For example, new competition could come from Southeastern U.S. locations such as Myrtle Beach, South Carolina, Savannah, Georgia, or the Alabama-Mississippi Gulf Coast.



Climate Stressor	Implications for Tourism
Warmer temperatures	- Altered seasonality - Heat stress for tourists - Increased cooling costs - Changes in plant-wildlife-insect populations and distribution range - Health impacts such as infectious and vector-borne disease ranges
Increasing frequency and intensity of extreme storms	- Risk for tourism facilities - Increased insurance costs/loss of insurability - Business interruption costs
Reduced precipitation and increased evaporation in some regions	- Water shortages - Competition over water between tourism and other sectors - Desertification - Increased wildfires threatening infrastructure and affecting demand
Increased frequency of heavy precipitation	- Flooding damage to historic architectural and cultural assets - Damage to tourism infrastructure - Altered seasonality (beaches, biodiversity, river flow)
Sea Level Rise	- Coastal erosion - Loss of beach area - Higher costs to protect and maintain waterfronts and sea defenses
Sea Surface Temperature Rise	- Increased coral bleaching - Marine resource aesthetic degradation in dive and snorkel destinations
Changes in terrestrial and marine biodiversity	- Loss of natural attractions and species from destinations - Higher risk of diseases in tropical-subtropical countries
More-frequent and larger forest fires	- Loss of natural attractions - Increase of flooding risk - Damage to tourism infrastructure
Soil changes (moisture levels, erosion, acidity)	Loss of archaeological assets and other natural resources, with impacts on destination attractions and agriculture

Table 4 Source: Adapted from Simpson et al. 2011 and UNWTO-UNEP-WMO, *Climate Change and Tourism: Responding to Global Challenges* (Madrid: 2008).

Sea Level Rise

A rise in sea level would negatively affect the tourism sector of Puerto Rico since it would most likely imply a loss of beaches. Importantly, Puerto Rico beaches are already suffering from heavy beach erosion due to poor coastal management (sand extraction, jettys, poorly planned marinas, etc.). Increased and more severe beach erosion from the combined effects of existing vulnerabilities and the expected climate stressors could affect hotel properties that are located in the coast. Beach erosion could even compromise the integrity of existing buildings. Like permanent residents, tourists would be affected by any impact that the rise in sea levels may have on the existing infrastructure, including utilities, roads and transit, and recreational and leisure facilities (parks, boardwalks, meeting venues, etc.)

In order to differentiate Puerto Rico from other “sun and sand” destinations in the Caribbean the Puerto Rico Tourism Company has promoted other tourism niches. One of these is the “Urban Tourism” market. There has been considerable public investment in recent years from the Commonwealth and municipal governments to turn the San Juan Metropolitan Area into an “Urban Tourism” attraction. Examples of this emphasis are the re-vitalization efforts in Condado and Isla Verde, the Coliseum of Puerto Rico, and the development of the Puerto Rico Convention Center District in Isla Grande. Other efforts that are in the planning stages or in early construction are the *Bahía Urbana* and the *San Juan Walkable City* program both on the San Juan Islet. All of these urban revitalization efforts are on or near the coast and, depending on the rate of sea level rise, might be at risk. Adaptation and mitigation efforts would be needed in order to protect these investments.

Tropical Storms and Tourism

Some models predict that climate change phenomena may increase the frequency and intensity of tropical storms in the Caribbean Basin. Anecdotal evidence shows that there is a correlation between the impacts of storms in localities in the Caribbean and a lower flow of tourists to those localities. This lower flow of tourists seems to last for about a year to two years.

One example of this trend was seen in the “Mayan Riviera”²¹ in the aftermath of Hurricane Wilma (2005)²². Another example is Grand Cayman in the aftermath of Hurricane Ivan (Category 5; September 12, 2004). Regarding Ivan’s impact on the Grand Cayman Island, Governor Bruce Dinwiddy described the damage as “very, very severe and widespread.” Despite strict building codes that made the islands’ buildings well able to withstand even major hurricanes, Ivan’s winds and storm surge were so strong that a quarter or more of the buildings on the islands were reported to be uninhabitable, with 85% damaged to some extent. Much of Grand Cayman still remained without power, water, or sewer services for several months later. After five months, barely half the pre-Ivan hotel rooms were usable.²³

Decreased Precipitation and Tourism

Some models predict that climate change will lower the rate of precipitation in Puerto Rico while other models say that the precipitation levels will increase. Should the latter be correct, Puerto Rico could expect more flooding events. Also, with changes in rainfall a sustained increase in the average number of rainy days per year might impact occupancy of hotels, particularly from local residents. During 2010-2011, the increase

25 Cancún, Cozumel, and Playa del Carmen

26 http://en.wikipedia.org/wiki/Hurricane_Wilma (retrieved on Sept. 23, 2011)

27 http://en.wikipedia.org/wiki/Hurricane_Ivan#cite_note--WMO_2004_summary--16 (retrieved on Sept. 23, 2011)

in rainy days had a recorded negative impact, according to the Puerto Rico Tourism Company.

Flooding and Tourism

Flooding is likely to impact tourism infrastructure dramatically. Recently, the Office of Planning and Development of the Puerto Rico Tourism Company conducted a flood risk analysis for endorsed lodgings in Puerto Rico. This analysis was done using the Flood Zone ArcGIS shapefile provided by the Puerto Rico Planning Board and the PRTC's endorsed lodging location shapefile. According to this study, Puerto Rico has an inventory of 14,306⁴ endorsed rooms. , 4,984 (34.8%) of which are currently in a high risk flood zone (1% chance of flooding or greater). Importantly, a significant percentage of room inventory would be negatively affected by increases in tropical cyclone events. According to this PRTC study, 3,080 endorsed rooms (21.5%) are in the VE flood zone, which is a zone at particular risk of storm surges.

Outdoor Recreation

Many of the people that participate in outdoor recreational activities are not aware of the economic and social importance of recreation and its relationship to natural resources and natural attractions. Recreation consists of activities or experiences conducted during leisure time, voluntarily chosen by the participant for purposes of relaxation, entertainment, or social or personal development. Outdoor recreation includes all of those recreational activities that cannot necessarily be practiced indoors, such as marine recreation, which involves use of coastal and marine resources as attractions by individuals or social groups. Recent studies show that we

derive the greatest satisfaction from participating in outdoor recreational activities, while at the same time sharing experiences with family and friends. Other factors that make enjoyment of the outdoors particularly rewarding include: contact with nature, the opportunity to improve physical and mental health, tranquility and enjoyment of the natural scenery.

The recreational opportunities offered by a destination are the drivers of tourism. They attract people from abroad, usually to spend their free time enjoying the sights, visiting friends or relatives, appreciating the environment, or taking part in sports or other recreational activities. Accordingly, Puerto Rico's outdoor recreation and tourism industries both depend on the health and continued viability of our beaches, rivers, mountains, wetlands, coral reefs, mangroves, fisheries, flora and fauna, geological formations, historical resources, valleys and coastal lagoons.

Recreational fishing is an important component of tourism both for locals and tourists. Alternatives include the use of charter fishing for offshore species like tuna or dorado and coastal lagoons for species such as snook and tarpon fishing as much as the shore. Several yacht clubs in Puerto Rico organize tournaments for fishing of various species. In addition to tourism activities, many people in Puerto Rico practice the sport of recreational fishing. A study of recreational fishing in Puerto Rico and the U.S. Virgin Islands found that recreational fishing on the high seas (more than 3 miles offshore) followed by fishing from the shore was very common around the island (Griffith et al. 1998; DNER 2000).

The government of Puerto Rico directly receives a large amount of revenue generated by tourism and recreation. This revenue is generated in part by the Port Authority through the collection of feeds for the use of facilities by cruise ships and

28 As informed by the PRTC's Touristic Products and Services Division, May 2011. This figure only includes the rooms and lodgings that receive tax exemption and investment incentives and that meet the standards of quality as defined by the PRTC's *Minimum Requisites for Lodging Facilities Regulation*. This does not include the whole room inventory of the island.

the granting of landing permissions and rights for both airlines and cruise ships to re-fuel and transport passengers in Puerto Rico. Tourists generate considerable local income from their use of slot machines at beach resorts and hotels. Overall, tourism spending in Puerto Rico is more than \$2 billion per year and the total indirect and direct employment induced by tourism exceeds 50,000 jobs. As tourists, recreationists spend on travel, food services, specialist equipment for the practice of recreational activities, and accommodations for overnight camping, hotels, and inns.

In 2007, the economic impact of the Puerto Rico National Parks System was estimated. During that year, the parks received 3.5 million of visitors. The National Parks Company generated a total of 645 direct jobs and \$24,209,108 in payroll. On the other hand, visitor spending generated a total of \$ 12,154,675 in direct revenues for the agency and \$ 15,705,308 in purchases of goods and services. The total impact on the economy was estimated at \$95 million in production, 1,233 direct jobs, indirect and induced, \$ 32 million in direct wages, indirect and induced effects and \$ 5.7 million in tax revenue. 80% of the economic impact occurs in the economic regions and municipalities where the facilities are located.⁵

The scientific data clearly indicates that there are certain aspects related to climate change that currently affect and threaten the natural resources and attractions that serve as the foundation for most leisure activities practiced outdoors in the archipelago of Puerto Rico. Stressors related to climate change include: sea level rise, rapid variations between periods of drought and floods, increases in average temperatures, and a marked drop in average annual rainfall.

Thus, climate change is predicted to have critical negative impacts to our very natural resources

and attractions that serve as the foundation of our outdoor recreation and tourism industries.

Flooding from Sea Level Rise and Precipitation

Among the most evident impacts expected from the projected sea level rise associated with climate change is loss of beaches due to the processes of erosion. This will represent an enormous challenge for Puerto Rico because of the extreme high costs associated with the transport of sand in order to form new beaches.

We are also losing wetlands, lagoons, and coastal valleys due to inundations, which in turn are affecting flora and fauna and the continued viability of activities such as fishing, hunting, hiking and bird watching. In addition, intense rain will provoke flooding in coastal communities and buildings close to the coast. Increased flooding will likely cause increased sedimentation in our bodies of water.

Temperature

The increase in average temperatures may limit the amount of time individuals can practice outdoor recreational activities, causes changes in the clothing required, and increase reliance on other products to protect from heat and sun. This will ultimately alter attitudes about spending time outdoors. This is of great importance as climate change will likely extend the summer season and shorten winter in northern countries, reducing the number of tourists who visit the Caribbean and Puerto Rico to escape the cold weather (i.e., shorter tourist season). Furthermore, the increase in average temperatures will affect corals and, consequently, regional fisheries. This will have a negative impact on the diving industry, recreational fishing, and the food industry. Finally, expected droughts might reduce aesthetic

attraction to portions of the landscape as scenic, vegetated areas such as forests, mountain views, and pastureland lose their greenery. A rise in sea temperatures may also affect the habitats of marine species including important species for recreational fishing like snook and tarpon, among others. In addition, some increases in sea temperature may cause the distribution of plankton to change, causing the distribution of plankton-eating species to change in response. One study found that the distribution of wild salmon was changing due to a change in plankton distribution caused by increasing temperature in the North Atlantic (Kinitisch 2006).

Finance

There are currently eighteen commercial banks in Puerto Rico, most of them local corporations. Local banking institutions include: Banco Popular, the largest banking institution, with over one hundred branches throughout the island, Banco

de San Juan, and Banco Mercantil de Puerto Rico; the local branches of US Citibank and FirstBank; and foreign banks, such as Banco Santander, the the second largest bank in Puerto Rico, and Scotia Bank. The government owns and operates two specialized banks: the Government Development Bank (GDB) and the Economic Development Bank (EDB).

Banks offer a wide range of products and services such as checking and savings accounts, CDs, IRAs, loans, credit and debit cards, and electronic banking. Automatic teller machines are abundant, commonly referred to as ATHs. Banks are insured by the Federal Deposit Insurance Corporation and are subject to all federal controls applicable to banks in the mainland United States.

Climate change could affect the financial sector if the banks' investments are susceptible to climate changes, such as the manufacturing and tourism industries.



Box 4: Where will future coastal disasters occur?

By: Ernesto L. Díaz

Coastal and beach-front development in Puerto Rico has always faced storm damage. Risks in tropical islands have been traditionally accepted as inevitable. Before the 1960s coastal development was generally sparse. After the 1960s vacation or second homes became more popular. Beach houses were relatively inexpensive. An owner accepted losses induced by severe storms and exposition to floods and beach erosion. That owner would subsequently repair or rebuild the vacation house affected by the storm.

Sea level rise continues to exacerbate the impacts associated to coastal hazards such as coastal storms, flooding, coastal erosion, and tsunamis. All of these hazards threaten lives, property, landscapes, habitats and, ultimately, coastal communities and economies.

Flooding may result from a coastal storm, tsunami, and river flooding or heavy precipitation events. Flood damages in Puerto Rico continue to escalate. Coastal erosion may result from storms, flooding, strong wave action, sea level rise, and human activities, such as inappropriate land use, alterations, and shore protection structures. Erosion undermines and often destroys homes, businesses, and public infrastructure and has short and long-term ecological, economic and social consequences.

Intensive development along 24% of Puerto Rico's coastal zone places people and property at risk to coastal hazards. Nature's ability to protect the human environment from severe hazards has been affected by the degradation of coral reefs and wetlands as well as the loss of sand dunes. As risks increase many beach front property owners resort to protect them with seawalls. Sea walls accelerate beach erosion and inhibit the beach's ability to absorb storm energy, thus exposing buildings to the full force of wind and waves. While adverse impacts can be reduced through proper planning of new coastal development, existing structures may need to be adapted, retro-fitted or protected. Managed or planned retreat may be required as shore erodes. In such cases buildings and other infrastructure are either demolished or relocated inland.

As sea level rises and storm surges and waves grow more intense traditional flood control will not be available to all potentially exposed coastal communities. Blocking, and diverting water is costly - economically and environmentally. How will decisions to protect, retrofit or letting structures flood be made? Which communities and structures will be protected? Which communities will continue to flood? The answers to these and other related questions will largely determine where next disasters will occur.

From a coastal engineering stand-point a coastal segment can be protected by blocking water. However, water will flow elsewhere. If a coastal property is protected by seawalls, the water does

not simply dissipate. The wave energy is reflected at that particular segment, but erosion of the

front, unprotected, and down-drift areas will accelerate. This is the case of vertical seawalls. Seawalls and other coastal defense structures can be designed to dissipate and reflect wave energy (i.e., curved, angled, stepped or mound). Offshore or submerged breakwaters are structures that parallel the shore and serve as wave absorbers. These forms of artificial reefs reduce wave energy in its lee side and typically create a tombolo behind the structure. In addition to protecting the coast they may enhance surf breaking for water sport activities and become habitat for marine life. However, offshore breakwaters are costly structures and relatively difficult to build. Again, costs and benefits of protecting a coastal segment will be largely determined by the type of infrastructure exposed to the risk (i.e., airports, hotels, access roads).

Sea level rise in Puerto Rico will also have legal implications on coastal properties and the coastal public trust lands. The coastal public trust lands or maritime-terrestrial public domain are recognized as the space of the coasts of Puerto Rico subject to the ebb and flow of the tides, where tides are noticeable, and where the largest waves during ordinary storms are noticeable, where the tides are not noticeable. The maritime terrestrial zone also includes ...land claimed by the sea, accessions and accretions, as well of those areas of the rivers that are navigable or up to the place where tides are noticeable.

As rising seas “threaten” shoreline property, there will be increased pressure to armor shorelines to protect shoreline property interests. Those property owners that have the economic means will attempt to hold back the water with coastal structures, rocks, or any other barriers. Some properties will be inevitably inundated by the sea. Will the flooded property become public domain?

The gradual adoption of an Island-wide policy of retreat through the use of setbacks and rolling easements needs to be examined. These options among other could be combined to create a comprehensive policy response to sea level rise. Either approach, or a combination of both, among other could be incorporated into a Puerto Rico Coastal Statute.

As sea level rises and science becomes more certain policy makers and coastal managers will be faced with important decisions about protecting coastal properties, planned retreat, adapting, retrofitting, establishing adaptation setbacks and adaptation strategies in undeveloped areas, enabling wetlands inland migration and providing connectivity through biological corridors. These decisions have legal, social, economic, ecological, and esthetic implications. The Puerto Rico Climate Change Council provides a forum to proactively discuss these issues and effectively support current and prospective decision making.

ECONOMIC STUDIES

To the knowledge of the PRCCC, only one study has been conducted to determine the costs of climate change for Puerto Rico. The study was conducted by the Stockholm Environment Institute – U.S. Center and Tufts University. They found that the cost of global climate inaction for Puerto Rico is projected to reach \$2.5 billion annually by 2050 and exceed \$5 billion by 2100 (Bueno, Herzfeld, Stanton and Ackerman 2008). These costs represent nearly three percent and six percent, respectively, of Puerto Rico’s GDP in 2004. These figures reflect impacts from only three categories, namely from decreased tourism, hurricane

damages, and infrastructure damage due to sea-level rise. The projected damages are higher, in dollars, than for most of the other Caribbean islands assessed in the same report. However, they represent a smaller fraction of Puerto Rico’s larger GDP (See table 2 below).

According to the study, most of the population lives in or near coastal zones, and most economic activity is located there as well, including most hotels, hospitals, and electric power plants; some power plants are less than 160 feet from the waterline and less than six feet about sea level. More than half of the population lives in the San Juan metropolitan area, which is very close to sea

(High-Impact minus Low-Impact Scenarios)

Puerto Rico	Cost of Inaction (\$US Billions)			
	2025	2050	2075	2100
Storms	0.2	0.4	0.7	1.1
Tourism	0.2	0.5	0.7	1.0
Infrastructure	0.8	1.6	2.4	3.2
Total	\$1.2	\$2.5	\$3.8	\$5.2
% Current GDP	1.4%	2.8%	4.4%	6.0%

Sources: Authors’ calculations. Amounts in 2007 dollars; percentages based on 2004 GDP.

Table 5. Puerto Rico—Low- and High-Impact Scenarios

Puerto Rico	Climate Change Scenarios: \$US Billions			
	2025	2050	2075	2100
LOW-IMPACT				
Storms	0.3	0.3	0.3	0.3
Tourism	0.1	0.1	0.2	0.2
Infrastructure	0.1	0.3	0.4	0.6
Total	\$0.5	\$0.7	\$0.9	\$1.1
% Current GDP	0.5%	0.8%	1.0%	1.3%
HIGH-IMPACT				
Storms	0.4	0.6	0.9	1.3
Tourism	0.3	0.6	0.9	1.2
Infrastructure	0.9	1.9	2.8	3.8
Total	\$1.7	\$3.1	\$4.7	\$6.3
% Current GDP	1.9%	3.6%	5.4%	7.3%

Sources: Authors’ calculations. Amounts in 2007 dollars; percentages based on 2004 GDP.

Table 1: From Report Bueno, Herzfeld, Stanton and Ackerman 2008

level. A rise of three feet (almost a meter) in sea level could flood large parts of the city.

Puerto Rico was largely spared by major hurricanes during its decades of industrialization after WWII. In the last two decades, however, the island has faced damaging storms. For example, in 1989 Hurricane Hugo (a Category 3 storm) passed over the northeast corner of Puerto Rico and caused an estimated \$1 billion in damages; Hurricane Georges (Category 2) crossed the island in 1998, leaving behind 12 dead and total damages amounting to \$2.3 billion (Center for Integrative Environmental Research (CIER) 2007).

Economic studies are greatly needed for Puerto Rico in order to determine the real costs of the outcomes and consequences from climate change, both historically and projected into the future. By knowing the costs we can design adaptation strategies to reduce risks without breaking the bank. Because of Puerto Rico's dependence on the service industry and tourism, any future economic studies that are conducted should incorporate the losses from disrupted ecosystem services.

RESULTS FROM RISK ASSESSMENT WORKSHOPS

To validate preliminary results of the vulnerability assessment, the society and economy PRCCC Working Group 3 and various partner organizations and individuals conducted risk assessment workshops with coastal municipalities: *Workshops for the Evaluation of Current and Future Risks in the Coastal Zone*. Thirty of the forty-four coastal municipalities of Puerto Rico attended with representatives from planning offices, emergency managers, and public works officers (figure X). The PRCCC coordinators presented the preliminary findings and through a series of facilitated small group discussions the participants confirmed the main

climate stressors impacting important sectors of their municipalities (e.g., infrastructure assets, economic development areas, and natural resources); further quantified the magnitude and likelihood of impacts occurring for the features assessed; and discussed the linkages between Island-wide concepts and municipal realities. Additionally, the last session of each workshop was devoted to the brainstorming of adaptation strategies by sectors identified as the most important by the workshop participants. Many of the consequences of certain climate stressors that the Working Group had identified as possibilities for the future, the municipal representatives identified as already occurring. This information was factored into the final results of this report, specifically into the development of a risk matrix.

RISK MATRIX FOR SOCIETAL ASSETS OF PUERTO RICO

To determine which societal assets of Puerto Rico were most at-risk due to climate change Working Group 3 developed a risk matrix. The preliminary information to form the risk matrix was collected at initial organizational meetings, where the working group members compiled a list of features and, as necessary, sub-features of their assigned subject. These features and sub-features were then aggregated into planning areas, and assessed during the risk assessment process. While the risk assessment described below utilized what appears to be a quantitative approach, the inherent limitations of the analytical tools delivered a more qualitative result. These results allowed us to develop a gross prioritization which will enable the PRCCC to focus their attention on the appropriate planning areas doing further analyses. Furthermore, these analyses were broad based; a more defined vulnerability analysis may be needed to define specific adaptive strategies though this is a good first step.

The risk assessment process was conducted through a mix of meetings, workshops and an online survey tool. Working group members completed the risk assessment survey and the information from the municipal risk assessment workshops were factored into the survey as well. Group discussion using a facilitated diagramming process (e.g., VCAPS), recorded by a facilitator, and the surveys were completed for each planning area and certain features. The risk matrix provided a space for each individual to evaluate the planning areas or features by the (1) likelihood impact by climate change by the year 2080 (Likelihood of Occurrence), (2) the severity of impact by 2080 (Magnitude of Impact), (3) the primary climate driver, and (4) the likely time horizon for impacts to occur and urgency for action during the temporal benchmarks of 2020, 2050, or 2080 (Time Urgency).

Risk for each feature was quantified by assigning positive or negative values of 1 (risk category= low) through 4 (risk category= high) to the Likelihood of Occurrence and 1 (risk category= low) through 3 (risk category= high) to the Magnitude of Impact components of the matrix. Likelihood and magnitude scores were multiplied to calculate values ranging from 1-12 for each of the blocks in the ranking table. Responses from each participant were thus transformed into numerical values that were averaged to produce risk scores. Each feature then was ranked by risk scores with time urgency listed.

The results of the risk assessment workshops with the coastal municipalities were included in the calculations. Table 2 is the result of this exercise.



Área de planificación	Planning Area	Average Likelihood	Average Magnitude	Average Risk Score	Climate Driver	Most often Given Time Answer
Características naturales que protejan la costa (Barreras naturales, como manglares, dunas, rocas o arrecifes de coral)	Natural characteristics that protect the coasts (natural barriers like mangroves, beach dune systems, rocks, and coral reefs)	3.88	3.00	High 11.63	No consistent answers (all 4)	2020; 2050
Estructuras de propiedad privada (viviendas unifamiliares y múltiples, edificios de oficinas, hoteles, edificios comerciales, estaciones de gasolina, y centros comerciales)	Private Structures (single and multi-family homes, office buildings, hotels, commercial buildings, gas stations, centers of commerce)	3.88	2.94	High 11.38	Sea Level; Storms	2020
Instalaciones y Edificios Públicos (gobierno, educación, salud, parques culturales, áreas recreativas, etc)	Public Buildings and Facilities (government, education, health, parks, recreation areas)	3.86	2.81	High 10.90	Sea Level; Storms	2020
Infraestructura de aguas usadas y escorrentía (Estructuras de recolección y transporte (canales, tuberías, bombas, alcantarillas, arroyos urbanos, quebradas); estructuras de captación (estanques, lagos urbanos, y sistemas de recolección de agua de lluvia), estructuras de control de calidad (por ejemplo, desarenadores); estructuras de almacenamiento, sistemas de desbordamiento de aguas residuales y pluviales, plantas de tratamiento y sistemas de descarga de aguas tratadas)	Wastewater and Stormwater Infrastructure (collection and transport structure - canals, pipes, pumps, sewers, urban creeks and streams), catchment structures (ponds, lakes, urban systems and rainwater), quantity control structures, storage structures, overflow systems, wastewater treatment plants)	3.69	2.88	High 10.60	Precipitation; Temperature; Storms	2020

Transporte (puertos, carreteras, puentes)	Transportation (ports, roads, bridges)	3.75	2.75	High 10.31	Precipitation; Sea Level	2020
Infraestructura de Generación de Energía (Plantas de generación de energía; infraestructura de transmisión e infraestructura de distribución)	Energy Generation Infrastructure (energy generation plants, transmission and distribution infrastructure)	3.56	2.69	High 9.57	Sea Level; Storms	2020
Servicios de Agua (estructuras de almacenamiento, procesamiento y distribución de agua potable (tuberías principales de agua, etc.))	Water Services (structures for processing and distribution of drinking water - water mains, etc)	3.38	2.63	Medium 8.86	Precipitation; Temperature; Storms	2050; 2080
Suministro de Agua (recursos de agua superficial, aguas subterráneas y del subsuelo; acuíferos costeros; represas y energía hidroeléctrica)	Water Storage (surface water resources, groundwater resources; coastal aquifers; dams and hydropower)	3.38	2.56	Medium 8.65	Precipitation; Temperature	2080
Recursos de Agua para Irrigación y Drenaje	Water Resources for Irrigation and Drainage	3.38	2.53	Medium 8.55	Precipitation; Temperature	2050
Recursos Históricos y Culturales (lugares de interés histórico y significado cultural)	Historical and Cultural Resources (places of historical and cultural interest/significance)	2.94	2.60	Medium 7.64	Sea Level; Storms	2050

Box 5: The psycho-spiritual value of nature conservation in the face of climate change

By: Dr. Antares Ramos

When we talk about the social importance for natural resources conservation, especially in the climate change scenario, we always discuss ecosystem services: coastal defense from natural events (e.g., the 100yr wave, hurricanes, tsunamis, etc.), fresh air, clean water, and even the enjoyment of future generations. But one vital aspect of nature conservation is the spiritual value of nature for human well-being, or mental well-being how colleagues from the health sector refer to it. I am not referring to spiritual from a religious point of view, even though for some it may transcend to that. It is that experience and connection that in some way gives meaning to one's existence in relation to the world we live in. It's "nature as an arena for the quality of life" (Hågvær 1999). It goes along the lines of 'going for a walk to clear the mind', to restore that mental balance and even become inspired. To facilitate the discussion presented here, I will use Schroeder's (1992) definition of spiritual:

"Spiritual" refers to the experience of being related to or in touch with an "other" that transcends one's individual sense of self and gives meaning to one's life at a deeper than intellectual level.

The spiritual value of nature has long been celebrated in art, literature, and music (Fairchild 1989, Schroeder 1992), but in the natural science sector it tends to be a taboo. Scientists trained in the natural sciences tend to avoid discussions on the spiritual phenomena. Easily understandable since it's a sector where we focus on facts and on tangible things. The human spiritual side is more of a social science topic, and it's only in recent years that social scientists have been integrated into natural resources conservation. If, however, we conceptualize the spiritual phenomena as being psychological in nature, it becomes a legitimate topic for scientific discussion (Maslow 1974, Schroeder 1992). I will therefore, refer to this needed human connection to nature and its importance in nature and ecosystem conservation as "psycho-spiritual values" (Callicott 1997).

Contact with nature has a high recreational value for mentally fatigued people (a phenomena we see on the rise, due to increase in constant sensorial stimulation in every life setting, even while driving), since it offers time of silence and distance from the sources of stress, which in turn allow for recharging energy and attention (Kaplan & Kaplan 1989). It allows us to clear the mind and reflect over the real values in life. One of Kaplan and Kaplan's (1989) conclusion was that "people feel more satisfied with their homes, with their jobs, and with their lives when they have sufficient access to nature in the urban environment".

New age medical doctors in Puerto Rico are using "green therapy", where part of the patient's treatment (e.g., cancer patients) involves some sort of contact with nature such as walks or even planned hike expeditions (depending on the condition of the patient). So even the medical sciences are beginning to recognize the importance of nature in the well-being of humans. It is important to understand that humans and nature cannot be separated, that the psycho-spiritual aspect is therefore an important component in nature conservation.

Especially in current times where climate change threatens many of the spaces we enjoy and also adds a stress to humankind, when we are losing homes due to coastal erosion and sea level rise, aquifers are in threat of becoming salinized, and changes in weather pattern are directly affecting our food production. Just as management efforts cannot ignore ecological interrelations among species and habitats, we need to recognize that ignoring the spiritual and psychological connections between humans and the natural world, and not allowing space for those experiences, can result in detrimental implications for society.

In Puerto Rico we are facing hard times as a society, with a decrease in education, a rise in criminality, and a tendency to focus in the material. We place mental health on a second plane and forget that the well-being of society depends on the well-being of its individuals who make the whole. In a time where our coastal areas are in peril due to sea-level rise, uncontrolled development, and coastal erosion due to harsher storms as a result to changes in long-term weather patterns, we need to further protect these areas that we as a society value. The Puerto Rican beach is an area where you will daily observe, no matter what time of day, people walking or jogging, playing with children, watching sunrises and sunsets and even meditating. A way to clear the mind and connect with nature and to satisfy our human need to understand and explore (Kaplan & Kaplan 1989). The loss of natural areas also implies that the country loses some of its identity (Kaplan & Kaplan 1989). Imagine Puerto Rico without its beaches? It even transcends to cultural values (Verschuuren 2006; Convention of Biological Diversity, 1992).

We do not need to go too far to see and understand the psycho-spiritual value of nature conservation. Many of us even seek it unconsciously. For others of us, it might even be a reason to continue defending nature. It is part of “ensuring that we leave a healthy and viable world for future generations” (Convention of Biological Diversity, 1992).

Literature cited

Convention of Biological Diversity (1992). 1760 UNTS 79; 31 ILM 818

Fairchild, J. (ed.) (1989). *Trees: A celebration*. New York: Weidenfeld and Nicolson. 128pp.

Hågvar, S. (1999). Nature as an arena for the quality of life: psycho-spiritual values-the next main focus in nature conservation?

Kaplan, R. & Kaplan, S.(1989). *The experience of nature: A psychological perspective*. Cambridge University Press.

Maslow, A.H. (1974). *Religions, values, and peak experiences*. New York: Viking Express. 123pp.

Schroeder, H.W. (1992). The spiritual aspect of nature: A perspective from Depth Psychology. In *proceedings of Northeastern Recreation Research Symposium* (p. 25-30), April 7-9, 1991, Saratoga Springs, NY.

Verschuuren, B. (2006). An overview of cultural and spiritual values in ecosystem management and conservation strategies. In *proceedings of Endogenous Development and*

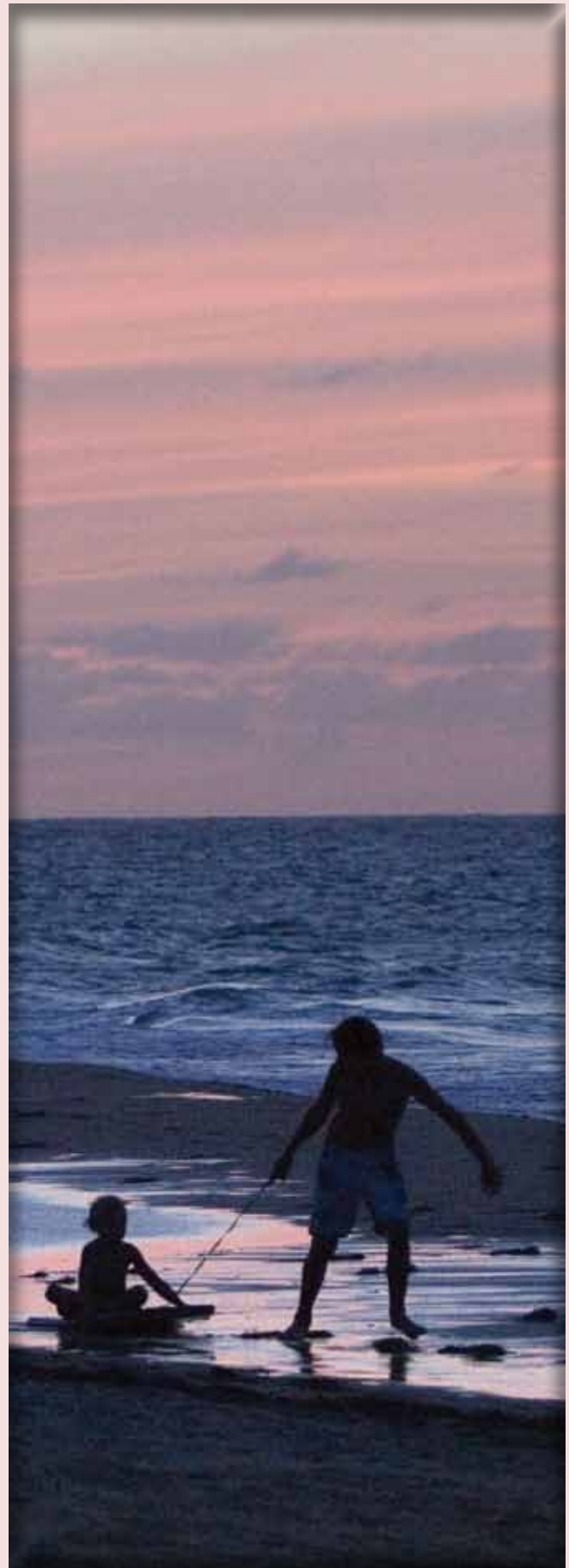
Bio-Cultural Diversity: The interplay of worldviews, globalization and locality (p. 299-325), 3-5 October 2006, Geneva, Switzerland.

CONCLUSION

Temperatures are increasing, precipitation patterns are changing, extreme events are occurring more frequently, oceans are more acidic, and sea level is rising. These climatic changes are projected to occur at much faster than natural rates. Some types of extreme weather and climate events have already increased in frequency and intensity and these changes are projected to continue.

Climate changes are already affecting some aspects of society, the economy and natural ecosystems of Puerto Rico and these effects are expected to increase. Not all of these changes will be gradual. When certain tipping points are crossed, impacts can increase dramatically. Past climate is no longer a reliable guide to the future. This affects planning for public and private infrastructure, tourism and industry, water resources, energy and all other social and economic systems.

In response to these changes, the Puerto Rico Climate Change Council (PRCCC) was convened in November 2010 to assess Puerto Rico's vulnerabilities and recommend strategies to respond to changes. The PRCCC is comprised of four working groups: (WG1) Geophysical and Chemical Scientific Knowledge; (WG2) Ecology and Biodiversity; (WG3) Society and Economy; and (WG4) Communicating Climate Change and Coastal Hazards. Based on the results of PRCCC's WG1, WG2 and WG3 as well as the results of coastal hazards risk assessment workshops conducted with thirty of the forty-four coastal municipalities, the PRCCC concludes that Puerto Rico's climate is changing and coastal communities of Puerto Rico, critical infrastructure, wildlife and ecosystems are all vulnerable to various impacts associated with changes in global, regional, and island weather and oceanographic conditions.



WORKS CITED

- NYPCC 2010. Climate Change Adaptation in New York City: Building a Risk Management Response. New York City Panel on Climate Change 2010 Report: pp. 354.
- APEGBC. 2010. Report of the Climate Change Task Force. Professional Engineers and Geoscientists of British Columbia. February 2010.
- Adger, W. N. (1996). Approaches to vulnerability to climate change. Working paper no. GEC 96-05. London: Centre for Social and Economic Research on the Global Environment.
- Adger, W. N. (1999). Social vulnerability to climate change and extremes in coastal Vietnam. *World Development*. 27(2), 249-269.
- Adger, W. N., Brooks, N., Kelly, M., Bentham, G., Agnew, M. & Erisen, S (2004). New Indicators of Vulnerability and Adaptive Capacity. Technical Report Number 7. Norwich, UK: Tyndall Centre for Climate Change Research, University of East Anglia.
- Adger, W. N. & Vincent, K. (2005). Uncertainty in adaptive capacity. *Comptes Rendus Geoscience*. 337(4), 399-410.
- Allen Consulting (2005). Climate Change Risk and Vulnerability. Canberra: Australian Greenhouse Office, Department of Environment and Water Resources.
- Bellamy, J., Smith, T., Taylor, B., McDonald, G., Walker, M., Jones, J. & Pero, L. (2005). Criteria and Methods for Monitoring and Evaluating Healthy Regional Planning Arrangements. Darwin: Tropical Savannas Management CRC.
- Brooks, N., Adger, W. N. & Kelly, P. M. (2005). Determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change*. 15, 151-163.
- Cain, J. (2001). Planning improvements in natural resources management. Guidelines for using Bayesian networks to support the planning and management of development programmes in the water sector and beyond. Centre for Ecology and Hydrology, Wallingford, UK.
- CFMC (Caribbean Fishery Management Council). 2004. Final Environmental Impact Statement for the Generic Essential Fish Habitat Amendment to: Spiny Lobster, Queen Conch, Reef Fish, and Coral Fishery Management Plans for the U.S. Caribbean. Volume 1: Text, San Juan, PR.
- CODREMAR (Corporation for the Development and Administration of Marine, Lacustrine, and Fluvial Resources of Puerto Rico). 1986. Survey of Associated and Independent Fishermen.
- CSIRO & BOM (Bureau of Meteorology) (2007). Climate change in Australia: technical report 2007. CSIRO Marine and Atmospheric Research and the Bureau of Meteorology, Aspendale and Melbourne.
- Department of Natural and Environmental Resources (DNER). 2000. Activity and Harvest Patterns in Puerto Rico Marine Recreational Fisheries. Annual Report, Project F-42.1, Puerto Rico Marine Recreational Fishery Statistic Program, San Juan, PR.
- Dybas, C.L. 2006. On a collision course: Ocean plankton and climate change. *BioScience* 56(8): 642-646.

- Folk, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C. S., Walker, B., Bengtsson, J., Berkes, K., Colding, J., Danell, K., Falkenmark, M., Gordon, L., Kasperson, R., Kautsky, N., Kinzig, A., Levin, S., Maler, K., Moberg, F., Ohlsson, L., Olsson, P., Ostrom, E., Reid, W., Rockstrom, J., Savenije, H., & Svedin, U. (2002). *Resilience and Development: Building Adaptive Capacity in a World of Transformations*. ICSU Series on Science for Sustainable Development: Resilience and Sustainable Development, No. 3. Stockholm.
- Füssel, H.-M. (2007). Adaptation planning for climate change: concepts, assessment approaches, and key lessons. *Sustainability Science*. 2, 265-275.
- Griffith, D.C., J.C. Johnson, R. Chaparro Serano, M. Valdes Pizzini, and J.D. Murray. 1988. *Developing Marine Recreational Fishing in Puerto Rico and the U.S. Virgin Islands*. Final Report for NOAA/NMFS Grant NA86WC-H-06108.
- Inman, M. 2005. Fish moved by warming waters. *Science* 308: 937.
- Intergovernmental Panel on Climate Change (2001). In: McCarthy, J., Caziani, O., Leary, N., Dokken, D. & White, K. (eds.) *Climate change 2001: Impacts, adaptation, and vulnerability*. Cambridge: Cambridge University Press.
- Intergovernmental Panel on Climate Change. (2007). *Climate change 2007: the physical science basis. Summary for policymakers. Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC Secretariat, 21 pp.
- Jensen, F. V. (1996). *An introduction to Bayesian networks*. Springer-Verlag: New York.
- Kintisch, E. 2006. As the seas warm. *Science* 313: 776-779.
- Kjaerulff, U. B. & Madsen, A. L. (2008). *Bayesian Networks and Influence Diagrams: A Guide to Construction and Analysis*. Springer: New York.
- Lebel, L., Anderies, J. M., Campbell, B., Folke, C., Hatfield-Dodds, S., Hughes, T. P. & Wilson, J. (2006). Governance and the capacity to manage resilience in regional social-ecological systems. *Ecology and Society*. 11(1): 19. [online] URL: <http://www.ecologyandsociety.org/vol11/iss1/art19/>
- Naess, L. O., Bang, G., Eriksen, S., & Vevatne, J. (2005). Institutional adaptation to climate change: Flood responses at the municipal level in Norway. *Global Environmental Change*. 15(2), 125-138.
- Matos-Caraballo, D. 2004. *Comprehensive Census of the Marine Fishery of Puerto Rico, 2002*. Final Report submitted to National Marine Fisheries Service, Job 3, Department of Natural and Environmental Resources, San Juan, PR.
- Office of Urban Management. (2005). *South East Queensland Regional Plan 2005-2026*. Brisbane: Queensland Department of Local Government, Planning, Sport and Recreation.
- Portner, H.O., and R. Knust. 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science* 315: 95-97.
- Preston, B. L. & Jones, R. N. (2006). *Climate Change Impacts on Australia and the Benefits of Early Action to Reduce Global Greenhouse Gas Emissions*. A consultancy report prepared for the Australian Climate Change Business Roundtable.

- Preston, B. L., Smith, T., Brooke, C., Gorddard, R., Measham, T., Withycombe, G., McInnes, K., Abbs, D., Beveridge, B. & Morrison, C. (2008). Mapping Climate Change Vulnerability in the Sydney Coastal Councils Group. Canberra: Sydney Coastal Councils Group, the Commonwealth Department of Climate Change, CSIRO Climate Adaptation Flagship, Canberra.
- Queensland Department of Infrastructure and Planning (2008). Sunshine Coast population and housing fact sheet. Brisbane: Queensland Department of Infrastructure and Planning, February 2008.
- Richardson, A.J., and D.S. Schoeman. 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. *Science* 305: 1609-1612
- Sen, A. (1981). *Poverty and Famines*. Oxford: Clarendon Press.
- Smith, T. F. (in press). Beyond knowledge: A neo-research approach to enhance climate change adaptation. In J. Martin (ed.) *Climate Change Responses across Regional Australia: Social Learning and Adaptation*. Victoria: VURRN Press.
- Smith, T. F., Brooke, C., Measham, T. G., Preston, B., Gorddard, R., Withycombe, G., Beveridge, B. & Morrison, C. (2008). Case Studies of Adaptive Capacity: Systems Approach to Regional Climate Change Adaptation Strategies. Canberra: Sydney Coastal Councils Group, the Commonwealth Department of Climate Change, CSIRO Climate Adaptation Flagship, Canberra.
- Smith, T. F. & Smith, D. C. (2006). Institutionalising Adaptive Learning For Coastal Management. In Lazarow, N., Souter, R., Fearon, R. and Dovers, S. (eds.) *Coastal Management in Australia: Key institutional and governance issues for coastal natural resource management and planning*. Brisbane: CRC for Coastal Zone, Estuary and Waterway Management. pp. 115-120.
- Stokestad, E. 2004. Changes in planktonic food web hint at major disruptions in Atlantic. *Science* 305: 1548-1549.
- Tompkins, E. L. & Adger, W. N. (2004). Does adaptive management of natural resources enhance resilience to climate change? *Ecology and Society*. 9(2): 10. [online] URL:<http://www.ecologyandsociety.org/vol9/iss2/art10/>
- Woodruff, D., Hales, S., Butler, C. & McMichael, A. (2005). *Climate Change Health Impacts in Australia: Effects of Dramatic CO2 Emissions Reductions*. Australian Conservation Foundation and the Australian Medical Association.
- Yohe, G. & Tol, R. S. J. (2002). Indicators for social and economic coping capacity: Moving towards a working definition of adaptive capacity. *Global Environmental Change*, 12 (1), 25-40.
- Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds., 2008: *Climate Change and Water*. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.
- Ecological Society of America (1997). *Climate Change, Hurricanes and Tropical Storms and Rising Sea Level Rise in Coastal Wetlands*. *Ecological Applications*, 7(3), 1997, pp. 770-801
- IPCC (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Parry, Martin L., Canziani, Osvaldo F., Palutikof, Jean P., van der Linden, Paul J., and Hanson, Clair E. (eds.)].

Cambridge University Press, Cambridge, United Kingdom, 1000 pp.

Millán Rodríguez, Yamilet . 2011. Costosa solución para la calidad del agua. El Vocero 26 December 2011.

National Wildlife Federation. (2011) Global Warming is Affecting Weather. (<http://www.nwf.org/Global-Warming/What-is-Global-Warming/Global-Warming-is-Causing-Extreme-Weather/Hurricanes.aspx>)

UNWTO (World Tourism Organization), UNEP (United Nations Environment Programme), and WMO (World Meteorological Organization). 2008. *Climate Change and Tourism: Responding to Global Challenges*. Madrid and Paris.

Peter H. Gleick, Briane Adams. (2000) Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States. Pacific Institute for Studies in Development, Environment, and Security and U.S. Geological Survey.

Timms, W, Andersen, M.S. and Carley, J (2008). Fresh-saline groundwater boundaries below coastlines - potential impacts of climate change. Coast To Coast Crossing Boundaries Conference, 18-22 August, 2008, Darwin.

UNESCO, The United Nations World Water Development Report 2 (2006) Section 2: Changing Natural Systems, Chapter 4 (UNESCO & WMO, with IAEA), Part 3. Human Impacts, p.136

USGS.(1989) Water Resources in Puerto Rico and the US Virgin Islands 8(5/6):1-8. US Department of the Interior Geological Survey. San Juan, PR.

Rutty, M., and D. Scott. 2010. Will the Mediterranean become “too hot” for tourism? A reassessment. *Journal of Tourism Hospitality and Planning Development* 7 (3): 267–81.

Bueno, Ramón, Herzfeld, Cornelia, Stanton, Elizabeth A. and Ackerman, Frank (2008) ‘The Caribbean and Climate Change: The Costs of Inaction’, in: Stockholm Environment Institute and Tufts University): 37.

Center for Integrative Environmental Research (CIER) (2007) ‘The US Economic Impacts of Climate Change and the Costs of Inaction’, in (College Park, MD: University of Maryland).

Edward Means III, Maryline Laugier, Jennifer Daw, Lorna Kaatz, Marc Waage, Denver Water (2010) ‘Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning’, in Water Utility Climate Alliance (WUCA) (ed) (Irvine, CA: Malcolm Pirnie, Inc.): 102.

Engineers, Canadian Council of Professional (2008) ‘Adapting to Climate Change: Canada’s First National Engineering Vulnerability Assessment of Public Infrastructure’, in: 71.

FEMA (2012) ‘Seven months later, disaster aid surpasses \$83.9 million’, in, *Press Release* (Online: www.fema.gov: Federal Emergency Management Agency).

References – Working Group 3: Society and Economy

- (APEGBC) Association of Professional Engineers and Geoscientists of British Columbia. 2010. Report of the Climate Change Task Force. Professional Engineers and Geoscientists of British Columbia. February 2010.
- Adger, W. N. (1996). Approaches to vulnerability to climate change. Working paper no. GEC 96-05. London: Centre for Social and Economic Research on the Global Environment.
- Adger, W. N. (1999). Social vulnerability to climate change and extremes in coastal Vietnam. *World Development*. 27(2), 249-269.
- Adger, W. N., Brooks, N., Kelly, M., Bentham, G., Agnew, M. & Erisen, S (2004). New Indicators of Vulnerability and Adaptive Capacity. Technical Report Number 7. Norwich, UK: Tyndall Centre for Climate Change Research, University of East Anglia.
- Adger, W. N. & Vincent, K. (2005). Uncertainty in adaptive capacity. *Comptes Rendus Geoscience*. 337(4), 399-410.
- Allen Consulting (2005). Climate Change Risk and Vulnerability. Canberra: Australian Greenhouse Office, Department of Environment and Water Resources.
- Bates, B.C., Z.W. Kundzewicz, S. Wu and J.P. Palutikof, Eds., 2008: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.
- Bellamy, J., Smith, T., Taylor, B., McDonald, G., Walker, M., Jones, J. & Pero, L. (2005). Criteria and Methods for Monitoring and Evaluating Healthy Regional Planning Arrangements. Darwin: Tropical Savannas Management CRC.
- Brooks, N., Adger, W. N. & Kelly, P. M. (2005). Determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change*. 15, 151-163.
- Bueno, R., C. Herzfeld, E.A. Stanton, F. Ackerman. (2008). The Caribbean and Climate Change: The Costs of Inaction. Stockholm Environment Institute and Tufts University: 37.
- Cain, J. (2001). Planning improvements in natural resources management. Guidelines for using Bayesian networks to support the planning and management of development programmes in the water sector and beyond. Centre for Ecology and Hydrology, Wallingford, UK.
- (CIER) Center for Integrative Environmental Research. (2007). 'The US Economic Impacts of Climate Change and the Costs of Inaction', in (College Park, MD: University of Maryland).
- (CFMC) Caribbean Fishery Management Council. (2004). Final Environmental Impact Statement for the Generic Essential Fish Habitat Amendment to: Spiny Lobster, Queen Conch, Reef Fish, and Coral Fishery Management Plans for the U.S. Caribbean. Volume 1: Text, San Juan, PR.

- (CODREMAR) Corporation for the Development and Administration of Marine, Lacustrine, and Fluvial Resources of Puerto Rico. (1986). Survey of Associated and Independent Fishermen.
- CSIRO & BOM (Bureau of Meteorology). (2007). Climate change in Australia: technical report 2007. CSIRO Marine and Atmospheric Research and the Bureau of Meteorology, Aspendale and Melbourne.
- (DNER) Department of Natural and Environmental Resources. (2000). Activity and Harvest Patterns in Puerto Rico Marine Recreational Fisheries. Annual Report, Project F-42.1, Puerto Rico Marine Recreational Fishery Statistic Program, San Juan, PR.
- (DNER Plan de Agua) Puerto Rico Department of Environmental and Natural Resources. (2008). Plan Integral de Recursos de Agua de Puerto Rico.
- Dybas, C.L. (2006). On a collision course: Ocean plankton and climate change. *BioScience* 56(8): 642-646.
- Ecological Society of America (1997). Climate Change, Hurricanes and Tropical Storms and Rising Sea Level Rise in Coastal Wetlands. *Ecological Applications*, 7(3), 1997, pp. 770–801
- Edward Means III, Maryline Laugier, Jennifer Daw, Lurna Kaatz, Marc Waage, Denver Water (2010) 'Decision Support Planning Methods: Incorporating Climate Change Uncertainties into Water Planning', in Water Utility Climate Alliance (WUCA) (ed) (Irvine, CA: Malcolm Pirnie, Inc.): 102.
- Engineers, Canadian Council of Professional (2008). Adapting to Climate Change: Canada's First National Engineering Vulnerability Assessment of Public Infrastructure', in: 71.
- (EPA) Environmental Protection Agency. (2008). Online resources.
- (EPA) Environmental Protection Agency. (2012). Solid Waste in Puerto Rico. Online resource: http://www.epa.gov/region2/cepd/solidwaste_in_puerto_rico.html
- FEMA (2012) 'Seven months later, disaster aid surpasses \$83.9 million', in, *Press Release* (Online: www.fema.gov: Federal Emergency Management Agency).
- Folk, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C. S., Walker, B., Bengtsson, J., Berkes, K., Colding, J., Danell, K., Falkenmark, M., Gordon, L., Kasperson, R., Kautsky, N., Kinzig, A., Levin, S., Maler, K., Moberg, F., Ohlsson, L., Olsson, P., Ostrom, E., Reid, W., Rockstrom, J., Savenije, H., & Svedin, U. (2002). Resilience and Development: Building Adaptive Capacity in a World of Transformations. ICSU Series on Science for Sustainable Development: Resilience and Sustainable Development, No. 3. Stockholm.
- Füssel, H.-M. (2007). Adaptation planning for climate change: concepts, assessment approaches, and key lessons. *Sustainability Science*. 2, 265-275.
- Gleick, P.H. and B. Adams. (2000). Water: The Potential Consequences of Climate Variability and Change for the Water Resources of the United States. Pacific Institute for Studies in Development, Environ-

ment, and Security and U.S. Geological Survey.

Gregory Morris Engineering PSC. (2009). Water Accountability Pilot Project Final Report. Puerto Rico Aqueduct and Sewer Authority.

Griffith, D.C., J.C. Johnson, R. Chaparro Serano, M. Valdes Pizzini, and J.D. Murray. (1988). Developing Marine Recreational Fishing in Puerto Rico and the U.S. Virgin Islands. Final Report for NOAA/NMFS Grant NA86WC-H-06108.

Inman, M. (2005). Fish moved by warming waters. *Science* 308: 937.

Insurance Information Institute. (2012). Online Access: <http://www.iii.org/>

Intergovernmental Panel on Climate Change. (2001). In: McCarthy, J., Caziani, O., Leary, N., Dokken, D. & White, K. (eds.) *Climate change 2001: Impacts, adaptation, and vulnerability*. Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change. (2007). *Climate change 2007: the physical science basis. Summary for policymakers. Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva: IPCC Secretariat, 21 pp.

IPCC (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Parry, Martin L., Canziani, Osvaldo F., Palutikof, Jean P., van der Linden, Paul J., and Hanson, Clair E. (eds.)]. Cambridge University Press, Cambridge, United Kingdom, 1000 pp.

Jensen, F. V. (1996). *An introduction to Bayesian networks*. Springer-Verlag: New York.

Kintisch, E. 2006. As the seas warm. *Science* 313: 776-779.

Kjaerulff, U. B. & Madsen, A. L. (2008). *Bayesian Networks and Influence Diagrams: A Guide to Construction and Analysis*. Springer: New York.

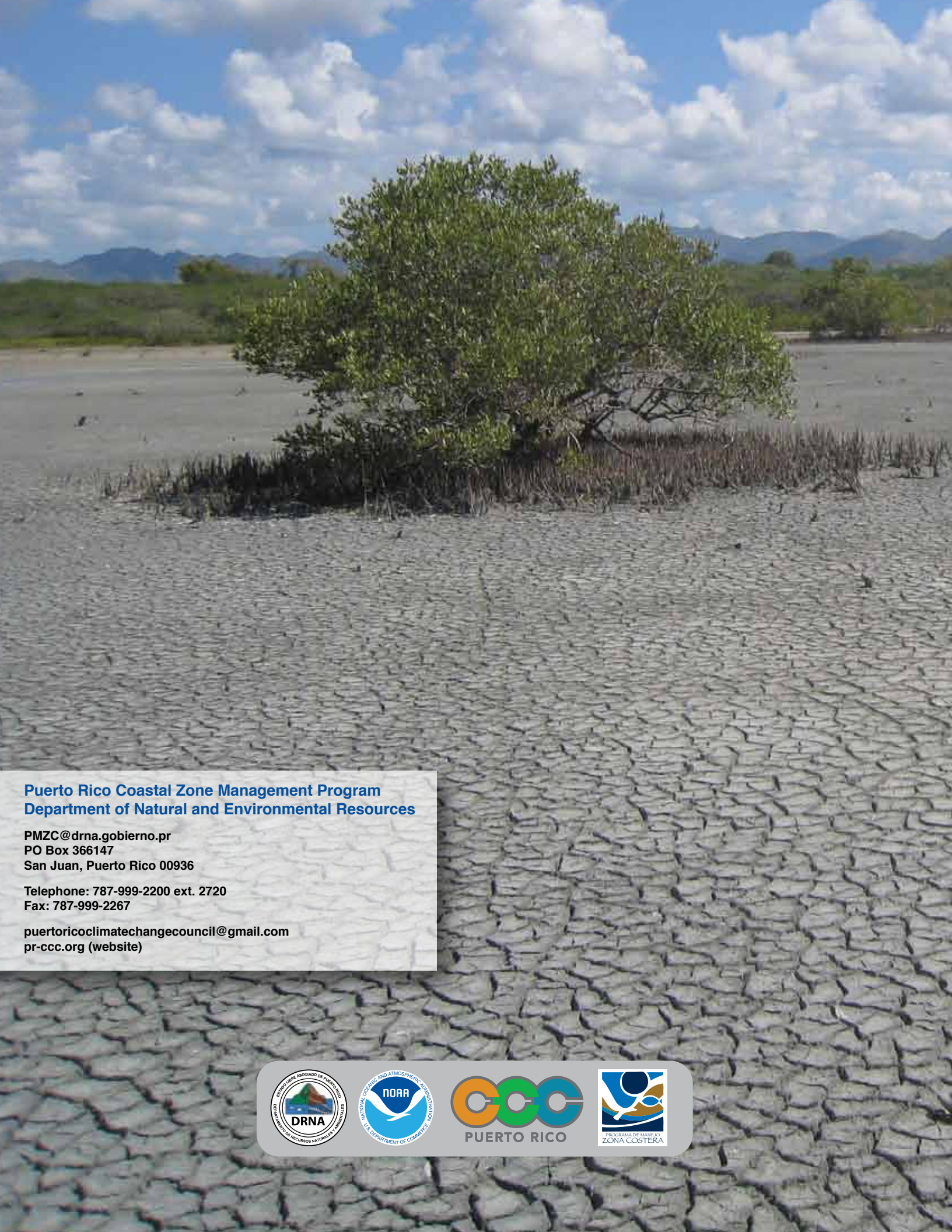
Kundzewicz, Z. W., Mata, L. J., Arnell, N., Döll, P., Kabat, P., Jiménez, B., Miller, K., Oki, T., Şen, Z. & Shiklomanov, I. (2007) Freshwater resources and their management. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden & C. E. Hanson), 173–210. Cambridge University Press, UK. <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter3.pdf>

Lebel, L., Anderies, J. M., Campbell, B., Folke, C., Hatfield-Dodds, S., Hughes, T. P. & Wilson, J. (2006). Governance and the capacity to manage resilience in regional social-ecological systems. *Ecology and Society*.11(1): 19. [online] URL: <http://www.ecologyandsociety.org/vol11/iss1/art19/>

Matos-Caraballo, D. (2004). *Comprehensive Census of the Marine Fishery of Puerto Rico, 2002*. Final Report submitted to National Marine Fisheries Service, Job 3, Department of Natural and Environmental Resources, San Juan, PR.

- Millán Rodríguez, Yamilet. (2011). Costosa solución para la calidad del agua. *El Vocero* 26 December 2011.
- Naess, L. O., Bang, G., Eriksen, S., & Vevatne, J. (2005). Institutional adaptation to climate change: Flood responses at the municipal level in Norway. *Global Environmental Change*. 15(2), 125-138.
- National Wildlife Federation. (2011) Global Warming is Affecting Weather. (<http://www.nwf.org/Global-Warming/What-is-Global-Warming/Global-Warming-is-Causing-Extreme-Weather/Hurricanes.aspx>)
- (NYPCC) New York City Panel on Climate Change. 2010. Climate Change Adaptation in New York City: Building a Risk Management Response. New York City Panel on Climate Change 2010 Report: pp. 354.
- Office of Urban Management. (2005). South East Queensland Regional Plan 2005-2026. Brisbane: Queensland Department of Local Government, Planning, Sport and Recreation.
- (PIRA) Plan Integral de Recursos de Agua (2008). Plan Integral de Recursos de Agua de Puerto Rico. <http://www.recursosaguapuertorico.com/Plan-Integral-Aguas-.html>
- Portner, H.O., and R. Knust. 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. *Science* 315: 95-97.
- (PRASA) Puerto Rico Aqueduct and Sewer Authority (2010). Study of Desirability and Convenience for the Implementation for Advanced Technologies for the Reduction of Non-Revenue Water. Puerto Rico Public-Private Partnerships Authority.
- Preston, B. L. & Jones, R. N. (2006). Climate Change Impacts on Australia and the Benefits of Early Action to Reduce Global Greenhouse Gas Emissions. A consultancy report prepared for the Australian Climate Change Business Roundtable.
- Preston, B. L., Smith, T., Brooke, C., Gorddard, R., Measham, T., Withycombe, G., McInnes, K., Abbs, D., Beveridge, B. & Morrison, C. (2008). Mapping Climate Change Vulnerability in the Sydney Coastal Councils Group. Canberra: Sydney Coastal Councils Group, the Commonwealth Department of Climate Change, CSIRO Climate Adaptation Flagship, Canberra.
- Queensland Department of Infrastructure and Planning (2008). Sunshine Coast population and housing fact sheet. Brisbane: Queensland Department of Infrastructure and Planning, February 2008.
- Richardson, A.J., and D.S. Schoeman. (2004). Climate impact on plankton ecosystems in the Northeast Atlantic. *Science* 305: 1609-1612.
- Rutty, M., and D. Scott. 2010. Will the Mediterranean become “too hot” for tourism? A reassessment. *Journal of Tourism Hospitality and Planning Development* 7 (3): 267–81.
- Sen, A. (1981). *Poverty and Famines*. Oxford: Clarendon Press.

- Smith, T. F. (in press). Beyond knowledge: A neo-research approach to enhance climate change adaptation. In J. Martin (ed.) *Climate Change Responses across Regional Australia: Social Learning and Adaptation*. Victoria: VURRN Press.
- Smith, T. F., Brooke, C., Measham, T. G., Preston, B., Gorrdard, R., Withycombe, G., Beveridge, B. & Morrison, C. (2008). *Case Studies of Adaptive Capacity: Systems Approach to Regional Climate Change Adaptation Strategies*. Canberra: Sydney Coastal Councils Group, the Commonwealth Department of Climate Change, CSIRO Climate Adaptation Flagship, Canberra.
- Smith, T. F. & Smith, D. C. (2006). Institutionalising Adaptive Learning For Coastal Management. In Lazarrow, N., Souter, R., Fearon, R. and Dovers, S. (eds.) *Coastal Management in Australia: Key institutional and governance issues for coastal natural resource management and planning*. Brisbane: CRC for Coastal Zone, Estuary and Waterway Management. pp. 115-120.
- Stokestad, E. (2004). Changes in planktonic food web hint at major disruptions in Atlantic. *Science* 305: 1548-1549.
- Timms, W, Andersen, M.S. and Carley, J (2008). Fresh-saline groundwater boundaries below coastlines - potential impacts of climate change. *Coast To Coast Crossing Boundaries Conference*, 18-22 August, 2008, Darwin.
- (UNEP) United Nations Environment Programme Global Environment Monitoring System (GEMS)/Water Programme. (2008) *Water Quality for Ecosystem and Human Health*, 2nd Edition.
- UNESCO, United Nations World Water Development Report 2 (2006) Section 2: Changing Natural Systems, Chapter 4 (UNESCO & WMO, with IAEA), Part 3. Human Impacts, p.136
- (UNWTO) United Nations World Tourism Organization, UNEP (United Nations Environment Programme), and (WMO) World Meteorological Organization. (2008). *Climate Change and Tourism: Responding to Global Challenges*. Madrid and Paris.
- USGS. (1989) *Water Resources in Puerto Rico and the US Virgin Islands* 8(5/6):1-8. US Department of the Interior Geological Survey. San Juan, PR.
- Tompkins, E. L. & Adger, W. N. (2004). Does adaptive management of natural resources enhance resilience to climate change? *Ecology and Society*. 9(2): 10. [online] URL:<http://www.ecologyandsociety.org/vol9/iss2/art10/>
- Woodruff, D., Hales, S., Butler, C. & McMichael, A. (2005). *Climate Change Health Impacts in Australia: Effects of Dramatic CO2 Emissions Reductions*. Australian Conservation Foundation and the Australian Medical Association.
- Yohe, G. & Tol, R. S. J. (2002). Indicators for social and economic coping capacity: Moving towards a working definition of adaptive capacity. *Global Environmental Change*, 12 (1), 25-40.



**Puerto Rico Coastal Zone Management Program
Department of Natural and Environmental Resources**

PMZC@drna.gobierno.pr
PO Box 366147
San Juan, Puerto Rico 00936

Telephone: 787-999-2200 ext. 2720
Fax: 787-999-2267

puertoricoclimatechangecouncil@gmail.com
pr-ccc.org (website)

