20 U.S. Caribbean

Federal Coordinating Lead Author

William A. Gould
USDA Forest Service International Institute of Tropical Forestry

Chapter Lead

Ernesto L. Díaz
Department of Natural and Environmental Resources, Coastal Zone Management Program

Chapter Authors

Nora L. Álvarez-Berríos
USDA Forest Service International Institute of Tropical Forestry

Felix Aponte-González
Aponte, Aponte & Asociados

Wayne Archibald
Archibald Energy Group

Jared Heath Bowden
Department of Applied Ecology, North Carolina State University

Lisamarie Carrubba
NOAA Fisheries, Office of Protected Resources

Wanda Crespo
Estudios Técnicos, Inc.

Stephen Joshua Fain
USDA Forest Service International Institute of Tropical Forestry

Grizelle González
USDA Forest Service International Institute of Tropical Forestry

Annmarie Goulbourne
Environmental Solutions Limited

Eric Harmsen
Department of Agricultural and Biosystems Engineering, University of Puerto Rico

Azad Henareh Khalyani
Natural Resource Ecology Laboratory, Colorado State University

Eva Holupchinski
USDA Forest Service International Institute of Tropical Forestry

James P. Kossin
National Oceanic and Atmospheric Administration

Amanda J. Leinberger
Center for Climate Adaptation Science and Solutions, University of Arizona

Vanessa I. Marrero-Santiago
Department of Natural and Environmental Resources, Coastal Zone Management Program

Odalys Martínez-Sánchez
NOAA National Weather Service

Kathleen McGinley
USDA Forest Service International Institute of Tropical Forestry

Melissa Meléndez Oyola
University of New Hampshire

Pablo Méndez-Lázaro
University of Puerto Rico

Julio Morell
University of Puerto Rico

Isabel K. Parés-Ramos
USDA Forest Service International Institute of Tropical Forestry

Roger Pulwarty
NOAA Earth System Research Laboratory

William V. Sweet
NOAA National Ocean Service

Adam Terando
U.S. Geological Survey, Southeast Climate Adaptation Science Center

Sigfredo Torres-González
U.S. Geological Survey (Retired)

Review Editor

Jess K. Zimmerman
University of Puerto Rico

Technical Contributors are listed at the end of the chapter.

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20 U.S. Caribbean

San Juan, Puerto Rico

Key Message 1

Freshwater

Freshwater is critical to life throughout the Caribbean. Increasing global carbon emissions are projected to reduce average rainfall in this region by the end of the century, constraining freshwater availability, while extreme rainfall events, which can increase freshwater flooding impacts, are expected to increase in intensity. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers. Increasing variability in rainfall events and increasing temperatures will likely alter the distribution of ecological life zones and exacerbate existing problems in water management, planning, and infrastructure capacity.

Key Message 2

Marine Resources

Marine ecological systems provide key ecosystem services such as commercial and recreational fisheries and coastal protection. These systems are threatened by changes in ocean surface temperature, ocean acidification, sea level rise, and changes in the frequency and intensity of storm events. Degradation of coral and other marine habitats can result in changes in the distribution of species that use these habitats and the loss of live coral cover, sponges, and other key species. These changes will likely disrupt valuable ecosystem services, producing subsequent effects on Caribbean island economies.

Key Message 3

Coastal Systems

Coasts are a central feature of Caribbean island communities. Coastal zones dominate island economies and are home to critical infrastructure, public and private property, cultural heritage, and natural ecological systems. Sea level rise, combined with stronger wave action and higher storm surges, will worsen coastal flooding and increase coastal erosion, likely leading to diminished beach area, loss of storm surge barriers, decreased tourism, and negative effects on livelihoods and well-being. Adaptive planning and nature-based strategies, combined with active community participation and traditional knowledge, are beginning to be deployed to reduce the risks of a changing climate.

Key Message 4

Rising Temperatures

Natural and social systems adapt to the temperatures under which they evolve and operate. Changes to average and extreme temperatures have direct and indirect effects on organisms and strong interactions with hydrological cycles, resulting in a variety of impacts. Continued increases in average temperatures will likely lead to decreases in agricultural productivity, changes in habitats and wildlife distributions, and risks to human health, especially in vulnerable populations. As maximum and minimum temperatures increase, there are likely to be fewer cool nights and more frequent hot days, which will likely affect the quality of life in the U.S. Caribbean.

Key Message 5

Disaster Risk Response to Extreme Events

Extreme events pose significant risks to life, property, and economy in the Caribbean, and some extreme events, such as flooding and droughts, are projected to increase in frequency and intensity. Increasing hurricane intensity and associated rainfall rates will likely affect human health and well-being, economic development, conservation, and agricultural productivity. Increased resilience will depend on collaboration and integrated planning, preparation, and responses across the region.

Key Message 6

Increasing Adaptive Capacity Through Regional Collaboration

Shared knowledge, collaborative research and monitoring, and sustainable institutional adaptive capacity can help support and speed up disaster recovery, reduce loss of life, enhance food security, and improve economic opportunity in the U.S. Caribbean. Increased regional cooperation and stronger partnerships in the Caribbean can expand the region’s collective ability to achieve effective actions that build climate change resilience, reduce vulnerability to extreme events, and assist in recovery efforts.

Executive Summary

Historically, the U.S. Caribbean region has experienced relatively stable seasonal rainfall patterns, moderate annual temperature fluctuations, and a variety of extreme weather events, such as tropical storms, hurricanes, and drought. However, the Caribbean climate is changing and is projected to be increasingly variable as levels of greenhouse gases in the atmosphere increase.

The high percentage of coastal area relative to the total island land area in the U.S. Caribbean means that a large proportion of the region's people, infrastructure, and economic activity are vulnerable to sea level rise, more frequent intense rainfall events and associated coastal flooding, and saltwater intrusion. High levels of exposure and sensitivity to risk in the U.S. Caribbean region are compounded by a low level of adaptive capacity, due in part to the high costs of mitigation and adaptation measures relative to the region's gross domestic product, particularly when compared to continental U.S. coastal areas.[1] The limited geographic and economic scale of Caribbean islands means that disruptions from extreme climate-related events, such as droughts and hurricanes, can devastate large portions of local economies and cause widespread damage to crops, water supplies, infrastructure, and other critical resources and services.[1]

The U.S. Caribbean territories of Puerto Rico and the U.S. Virgin Islands (USVI) have distinct differences in topography, language, population size, governance, natural and human resources, and economic capacity. However, both are highly dependent on natural and built coastal assets; service-related industries account for more than 60% of the USVI economy. Beaches, affected by sea level rise and erosion, are among the main tourist attractions. In Puerto Rico, critical infrastructure (for example, drinking water pipelines and pump stations, sanitary pipelines and pump stations, wastewater treatment plants, and power plants) is vulnerable to the effects of sea level rise, storm surge, and flooding. In the USVI, infrastructure and historical buildings in the inundation zone for sea level rise include the power plants on both St. Thomas and St. Croix; schools; housing communities; the towns of Charlotte Amalie, Christiansted, and Frederiksted; and pipelines for water and sewage.

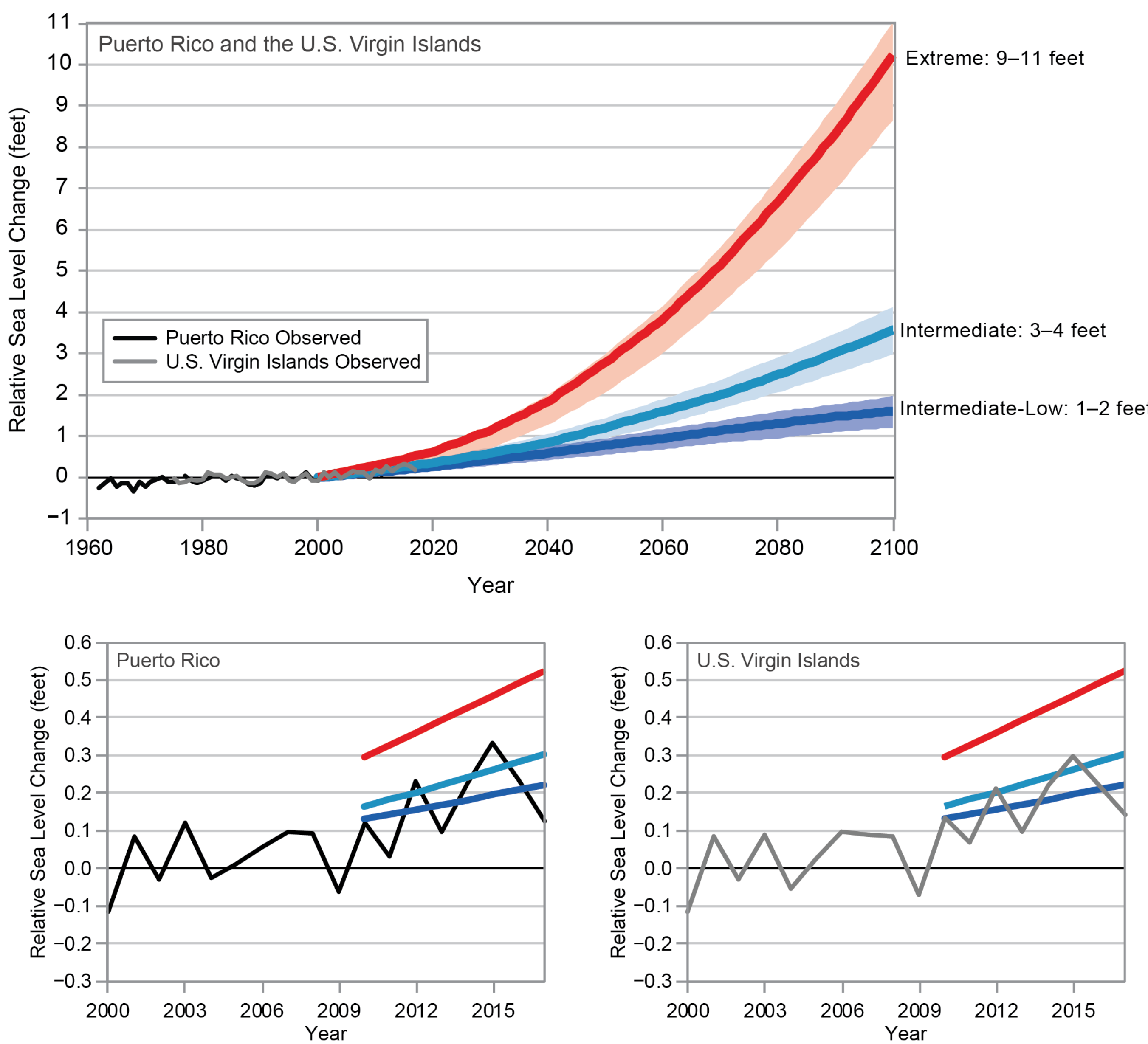
Climate change will likely result in water shortages due to an overall decrease in annual rainfall, a reduction in ecosystem services, and increased risks for agriculture, human health, wildlife, and socioeconomic development in the U.S. Caribbean. These shortages would result from some locations within the Caribbean experiencing longer dry seasons and shorter, but wetter, wet seasons in the future. [2,3,4,5,6,7,8] Extended dry seasons are projected to increase fire likelihood.[9,10] Excessive rainfall, coupled with poor construction practices, unpaved roads, and steep slopes, can exacerbate erosion rates and have adverse effects on reservoir capacity, water quality, and nearshore marine habitats.

Ocean warming poses a significant threat to the survival of corals and will likely also cause shifts in associated habitats that compose the coral reef ecosystem. Severe, repeated, or prolonged periods of high temperatures leading to extended coral bleaching can result in colony death. Ocean acidification also is likely to diminish the structural integrity of coral habitats. Studies show that major shifts in fisheries distribution and changes to the structure and composition of marine habitats adversely affect food security, shoreline protection, and economies throughout the Caribbean.

In Puerto Rico, the annual number of days with temperatures above 90°F has increased over the last four and a half decades. During that period, stroke and cardiovascular disease, which are influenced by such elevated temperatures, became the primary causes of death.[11,12] Increases in average temperature and in extreme heat events will likely have detrimental effects on agricultural operations throughout the U.S. Caribbean region.[13,14] Many farmers in the tropics, including the U.S. Caribbean, are considered small-holding, limited resource farmers and often lack the resources and/or capital to adapt to changing conditions. [15]

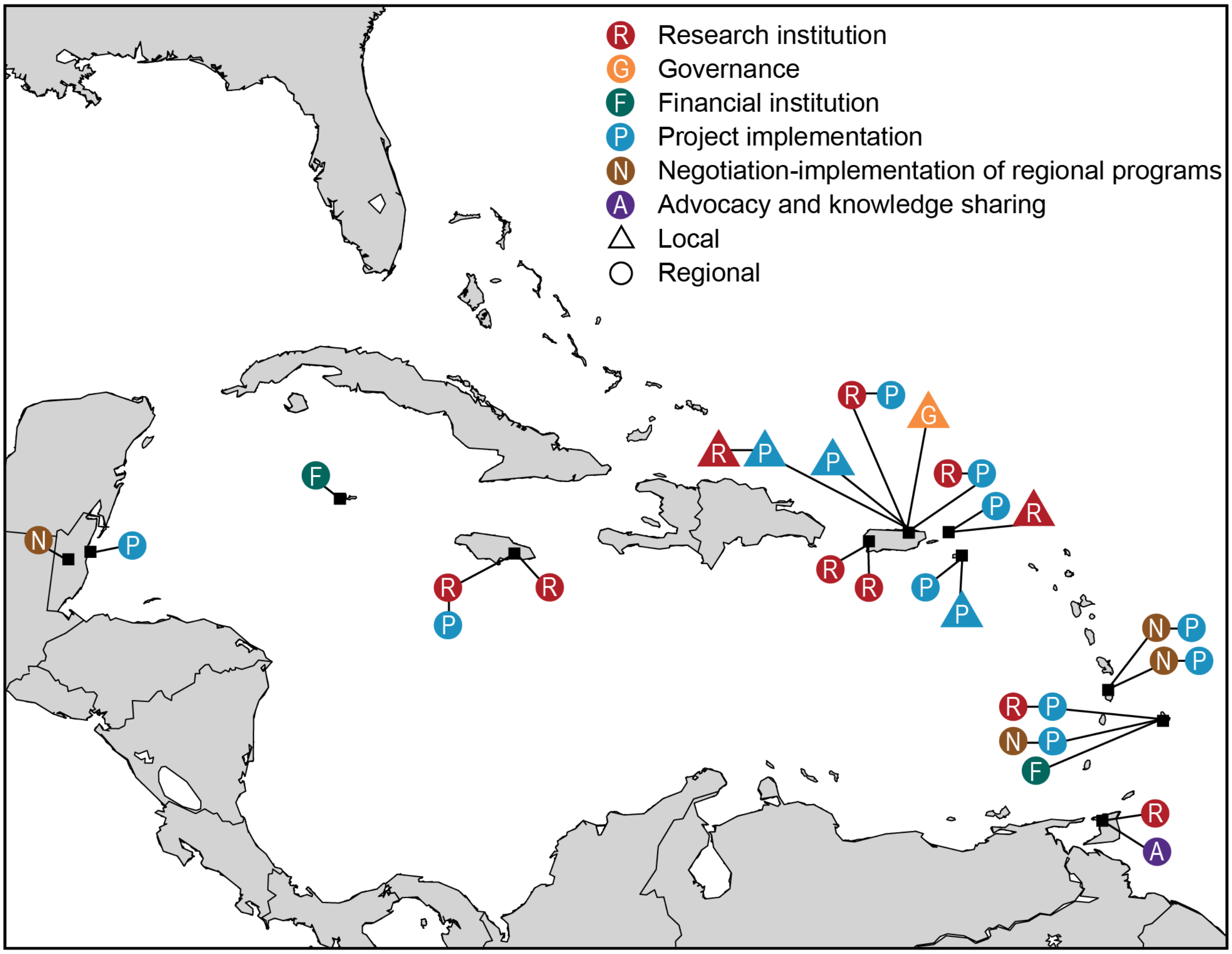
Most Caribbean countries and territories share the need to assess risks, enable actions across scales, and assess changes in ecosystems to inform decision-making on habitat protection under a changing climate.[16,17] U.S. Caribbean islands have the potential to improve adaptation and mitigation actions by fostering stronger collaborations with Caribbean initiatives on climate change and disaster risk reduction.

Observed and Projected Sea Level Rise



(top) Observed sea level rise trends in Puerto Rico and the U.S. Virgin Islands reflect an increase in sea level of about 0.08 inches (2.0 mm) per year for the period 1962–2017 for Puerto Rico and for 1975–2017 for the U.S. Virgin Islands. The bottom panels show a closer look at more recent trends from 2000 to 2017 that measure a rise in sea level of about 0.24 inches (6.0 mm) per year. Projections of sea level rise are shown under three different scenarios of Intermediate-Low (1–2 feet), Intermediate (3–4 feet), and Extreme (9–11 feet) sea level rise. The scenarios depict the range of future sea level rise based on factors such as global greenhouse gas emissions and the loss of glaciers and ice sheets. *From Figure 20.6. (Sources: NOAA NCEI and CICS-NC).*

Climate Risk Management Organizations



Some of the organizations working on climate risk assessment and management in the Caribbean are shown. Joint regional efforts to address climate challenges include the implementation of adaptation measures to reduce natural, social, and economic vulnerabilities, as well as actions to reduce greenhouse gas emissions. See the online version of this figure at http://nca2018.globalchange.gov/chapter/20#fig-20-18 for more details. *From Figure 20.18 (Sources: NOAA and the USDA Caribbean Climate Hub)*.

Background

Puerto Rico and the U.S. Virgin Islands (USVI) are rich in biodiversity, cultural heritage, and natural resources. More than 3.5 million inhabitants depend on the region's natural resources and environmental services for their well-being, livelihoods, local economies, and cultural identities. Changing climate and weather patterns interacting with human activities, are affecting land use, air quality, and resource management and are posing growing risks to food security, the economy, culture, and ecosystems services.

The U.S. Caribbean (Figure 20.1) includes the inhabited commonwealth islands of Puerto Rico, Vieques, and Culebra (with a combined population of 3.4 million), along with the inhabited territorial islands of St. Croix, St. Thomas, St. John, and Water Island (with a combined population of 104,000). In addition to the principal islands, the U.S. Caribbean includes over 800 smaller islands and cays, diverse cultural and historical resources, and a rich matrix of marine and terrestrial ecosystems. The region's physical geography includes nearshore and open ocean marine areas; coastal wetlands, hills, and plains; limestone (or karst) hills; and interior mountains. Average rainfall amounts vary widely across the region, and social and ecological systems are diverse. Puerto Rico and the USVI share many vulnerabilities with coastal states and the Pacific Islands but lack much of the capacity available to the continental United States.

Shared Vulnerabilities of U.S. Caribbean and Pacific Islands

The U.S. Caribbean islands face many of the same climate change related challenges as Hawai'i and the U.S.-Affiliated Pacific Islands (Ch. 27: Hawai'i & Pacific Islands), including

- isolation and dependence on imports, making islands more vulnerable to climate-related impacts;
- critical dependence on local sources of freshwater (Ch. 27, KM 1);
- temperature increases that will further reduce supply and increase demand on freshwater (Ch. 27, KM 1);
- vulnerability to drought in ways that differ from mainland regions (Ch. 27, KM 1);
- a projected significant decrease in rainfall in all (Caribbean) or parts (Hawai'i and Pacific Islands) of these regions (Ch. 27, KM 1);
- sea level rise, coastal erosion, and increasing storm impacts that threaten lives, critical infrastructure, and livelihoods on islands (Ch. 27, KM 2–4);
- prominent concerns about the economic consequences of coastal threats (Ch. 27, KM 3);
- coral bleaching and mortality due to warming ocean surface waters and ocean acidification (Ch. 27, KM 4); and
- threats to critical economic marine resources, including fisheries (Ch. 27, KM 4).

U.S. Caribbean Region

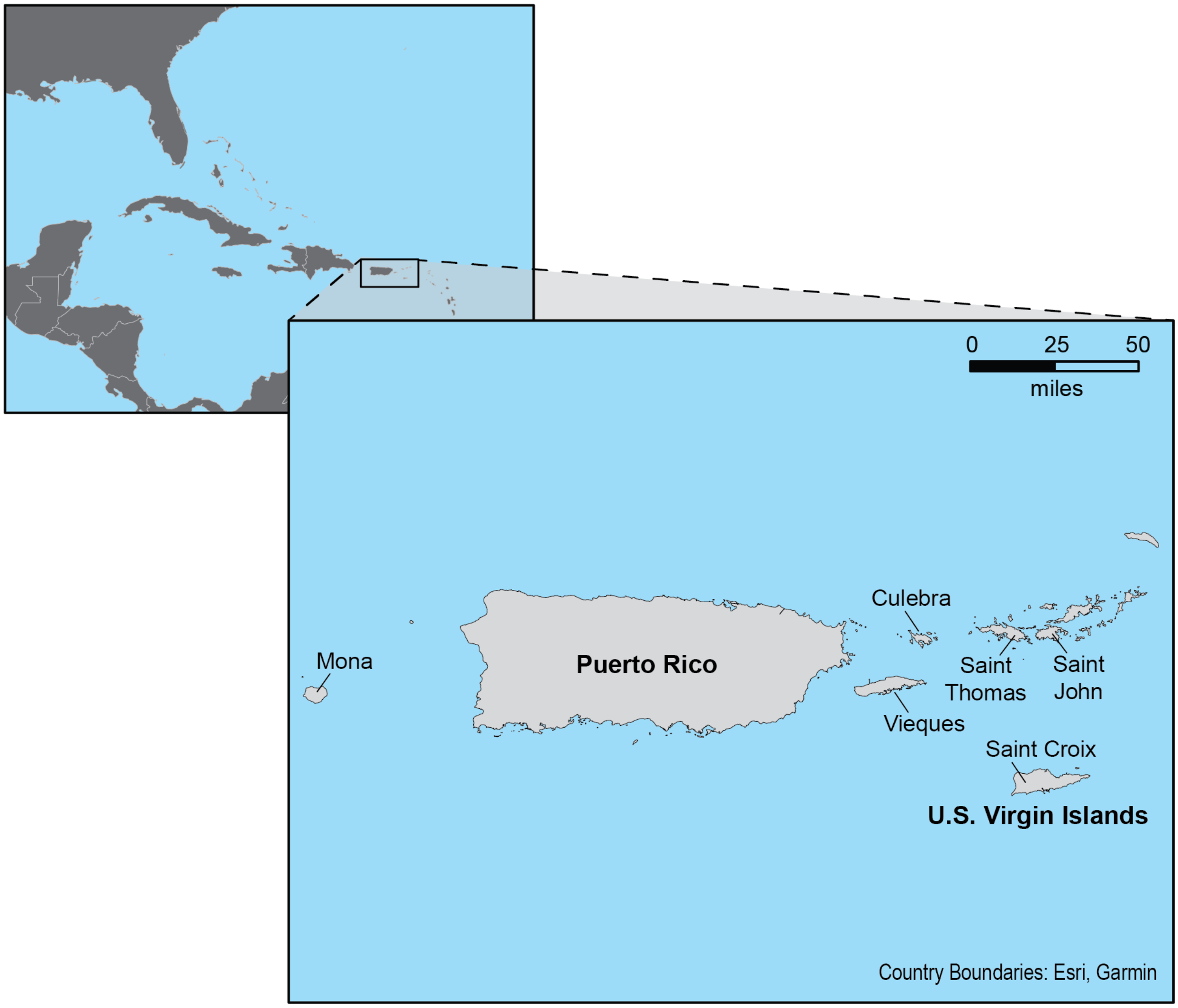
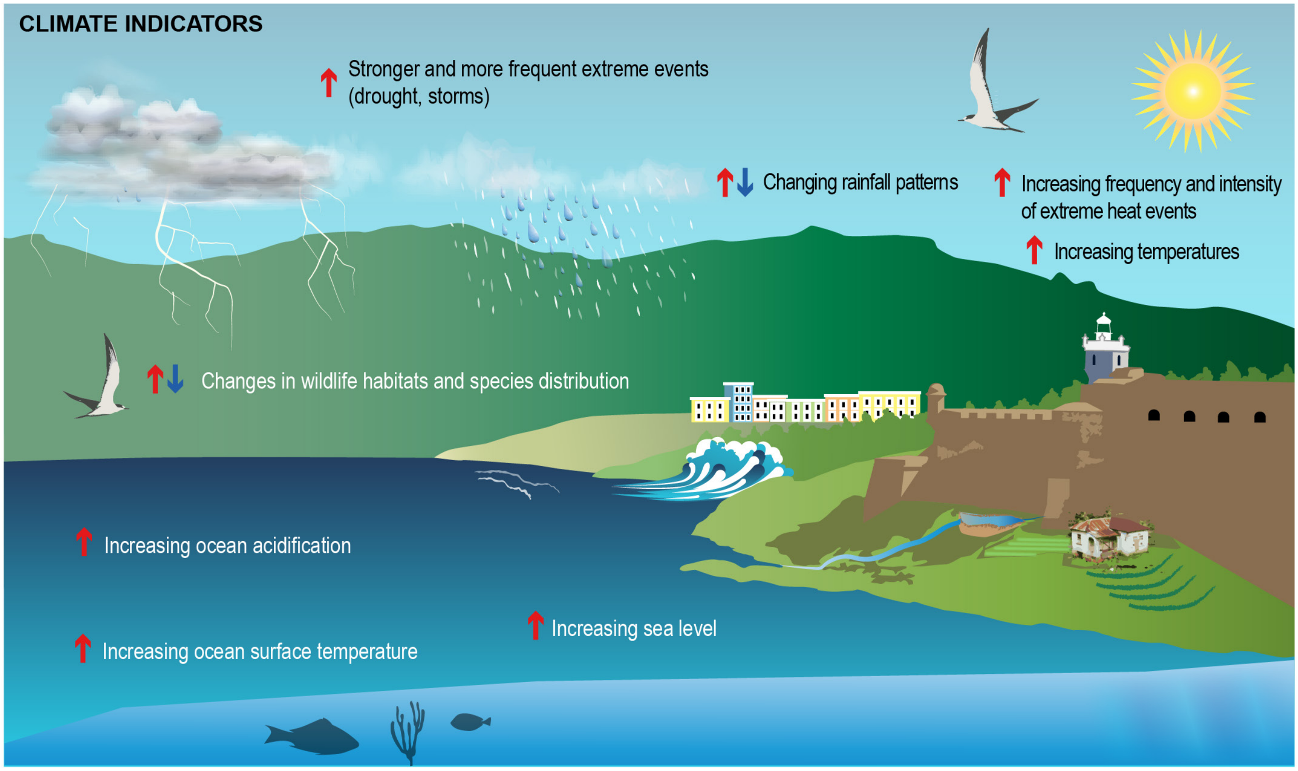


Figure 20.1: The U.S. Caribbean includes the Commonwealth of Puerto Rico and the territory of the U.S. Virgin Islands. The region includes seven inhabited islands and nearly 800 smaller islands and cays.

The islands also have unique issues related to data availability and the capacity to develop datasets comparable to those available for the continental United States. For example, the small size of the islands, particularly the USVI, affects the availability and accuracy of downscaled climate data and projections, similar to the Pacific Islands (Ch. 27: Hawai'i & Pacific Islands). Additionally, differences in the natural and social systems, and in information availability for Puerto Rico and the USVI, affect the degree of vulnerability to climate change and extreme climate events. This is reflected in different needs, priorities, and approaches to reducing vulnerability between Puerto Rico and the USVI. Historically, the U.S. Caribbean region has experienced relatively stable seasonal rainfall patterns, moderate annual temperature fluctuations, and a variety of extreme weather events, such as tropical storms, hurricanes, and drought. However, these patterns are changing and are projected to be increasingly variable as atmospheric greenhouse gas concentrations increase. Having evolved with these historic climate conditions, and given the small size and relatively isolated nature of these islands, Caribbean social, economic, and ecological systems are likely to be more sensitive to changes in temperature and precipitation than similar systems in the mainland United States (Figure 20.2).[18,19]

Climate Indicators and Impacts



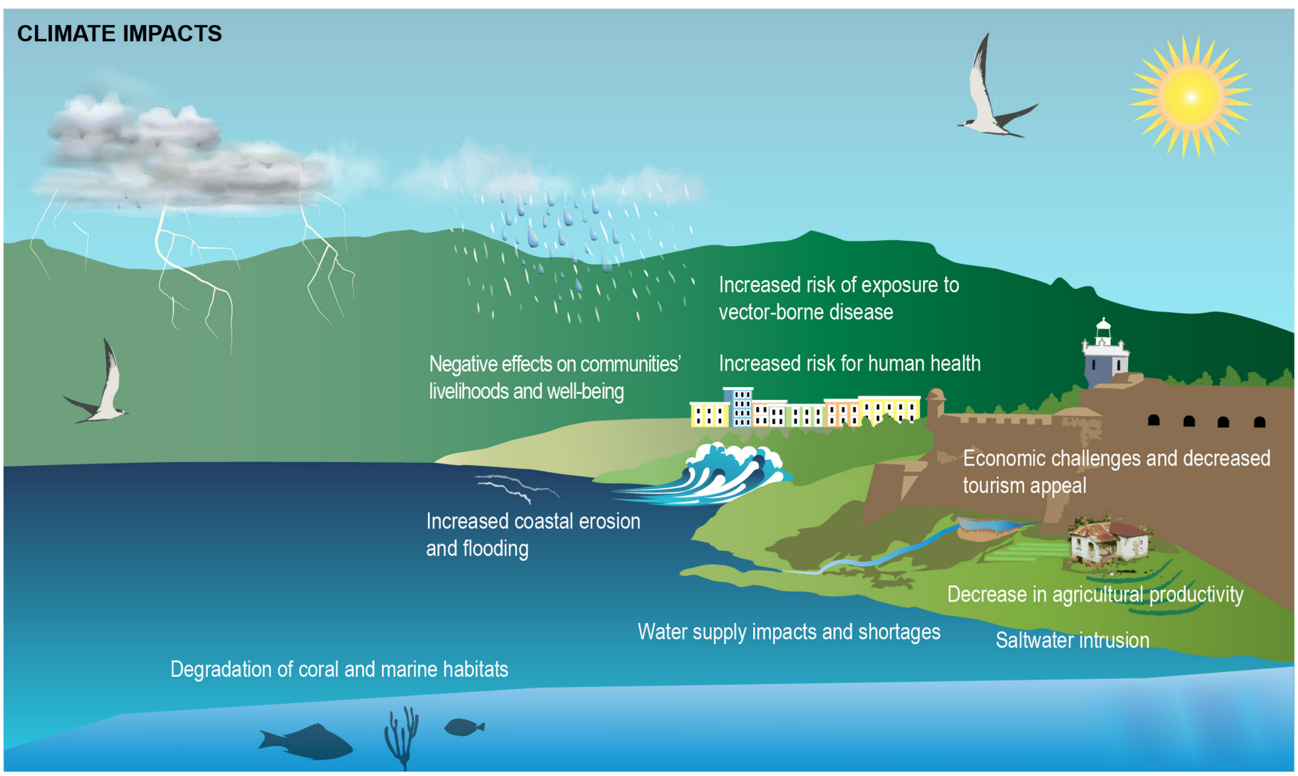


Figure 20.2: (top) Key indicators for monitoring climate variability and change in the U.S. Caribbean include sea level rise, ocean temperature and acidity, air temperature, rainfall patterns, frequency of extreme events, and changes in wildlife habitats. (bottom) Changes in these climate indicators result in environmental and social impacts to natural ecosystems, infrastructure, and society, including degradation of coral and marine habitats, increased coastal flooding and erosion, decrease in agricultural productivity, water supply shortages, negative effects on communities' livelihoods and on human health, as well as economic challenges and decreased tourism appeal. Source: Puerto Rico Department of Natural and Environmental Resources.

The vulnerability of the U.S. Caribbean region is influenced by global, regional, and local factors. The region is sensitive to large-scale patterns of natural variability in both the Atlantic and Pacific tropical basins, such as the El Niño–Southern Oscillation and the Atlantic Multidecadal Oscillation.[20] Climate variations due to these large-scale patterns directly impact the U.S. Caribbean because the islands largely rely on surface waters and consistent annual rainfall to meet freshwater demands. The high percentage of coastal areas relative to the total island land area means that a large proportion of the region's people, infrastructure, and economic activity are vulnerable to sea level rise, more frequent intense rainfall events and associated coastal flooding, and saltwater intrusion. As on islands worldwide, there are strong socioeconomic and cultural ties to diminishing marine resources and services, as well as economic dependence on tourism and imported goods.[1,13,14,21] High levels of exposure and sensitivity to risk in the region are compounded by a low level of adaptive capacity, due in part to the high costs of mitigation and adaptation measures relative to the region's gross domestic product, particularly when compared to continental U.S. coastal areas.[1]

The people of the U.S. Caribbean rely heavily on imported food and other goods and services, leaving them critically exposed to climate-related disruptions in transportation systems as well as vulnerabilities associated with source geographies.[22] Crop species key to regional economies and food security—such as coffee, plantains, and mangoes—have evolved in narrower climatic niches relative to temperate crops and are often detrimentally affected by relatively small shifts in temperature, humidity, and rainfall.[13,23,24] The limited geographic and economic scale of Caribbean islands means that disruptions from extreme climate-related events, such as droughts and hurricanes, can devastate large portions of local economies and cause widespread damage to crops, water supplies, infrastructure, and other critical resources and services.[1,25]

Observed and Projected Climate Change

The *Climate Science Special Report* (CSSR)[26] provides an in-depth assessment of observed and projected climate change in the continental United States. Because this level of assessment was not available for the U.S. Caribbean region, this section provides a brief overview of observed trends and future projections of five climate variables that are relevant to assessing climate change risk in the region: temperature, precipitation, sea surface temperature, ocean acidification, and sea level rise.

Temperature. Annual average temperatures in the U.S. Caribbean have fluctuated over the last century. However, since 1950, temperatures have increased by about 1.5°F in Puerto Rico.[27] Projected increases under both a lower and higher scenario (RCP4.5 and RCP8.5) are expected in both average and extreme temperatures, which will lead to more days per year over 95°F and more nights per year over 85°F.[28] Global climate models project about a 1.5°F to 4°F increase in average temperatures for the U.S. Caribbean by 2050. End-of-century estimates show temperature increases as high as about 9°F under a higher scenario (RCP8.5; Figure 20.3).[7]

Observed and Projected Temperature Change for Puerto Rico

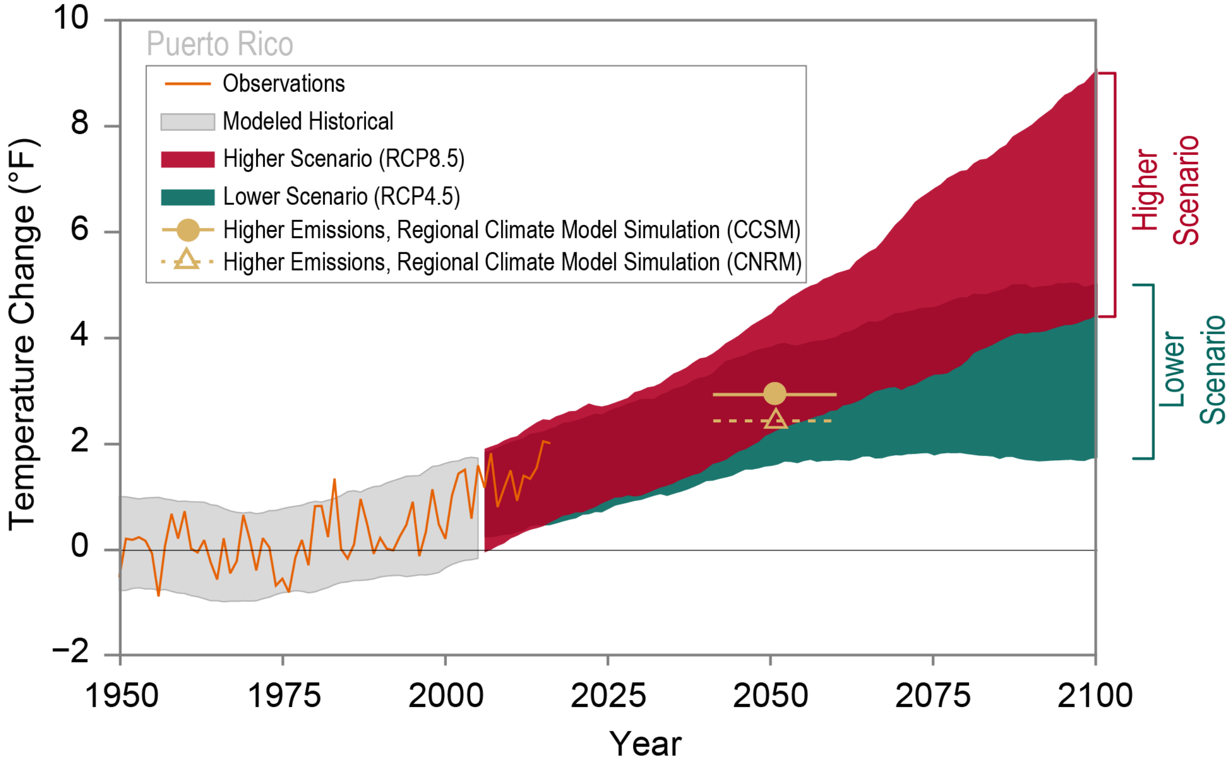


Figure 20.3: Observed and projected temperature changes are shown as compared to the 1951–1980 average. Observed data are for 1950–2017, and the range of model simulations for the historical period is for 1950–2005. The range of projected temperature changes from global climate models is shown for 2006–2100 under a lower (RCP4.5) and a higher (RCP8.5) scenario (see the Scenario Products section of App. 3). Projections from two regional climate models are shown for 2036–2065, and they align with those from global models for the same period.[29,30] Sources: NOAA NCEI, CICS-NC, and USGS.

Precipitation. Globally, subtropical regions are expected to become drier in the future, especially in regions such as the U.S. Caribbean where oceans have the largest influence on local precipitation patterns.[31] Climate model results consistently project significant drying in the U.S. Caribbean region by the middle of this century, specifically, a decline of more than 10% in annual precipitation under the higher scenario (RCP8.5; Figure 20.4).[7,28,30,32] The magnitude of this projected drying, particularly for climate scenarios with the highest amounts of warming, is in general lower in the most recently developed climate models.[28] The region is likely to experience more intense rainfall events associated with tropical cyclones;[33] however, uncertainty remains regarding various aspects of extreme rainfall within the region, such as the frequency and duration of extreme rainfall events associated with tropical cyclones.[28,34] For instance, one study[34] finds less frequent extreme rainfall events on average in the future at sub-daily and daily timescales, while another[28] finds more frequent extreme rainfall events that exceed 3 inches of rain in a day, as well as more intense rainfall associated with tropical cyclones.[28,33]

Sea surface temperature and ocean acidification. Globally, surface ocean waters have warmed by about 1.3°F per century between 1900 and 2016.[35] Over the period 1955–2016, the waters of the northeast Caribbean increased in temperature at a rate of 0.23°F per decade,[36] and over the last two decades, the sea surface warming rate has reached 0.43°F per decade (Figure 20.5).

Projected Precipitation Change for Puerto Rico

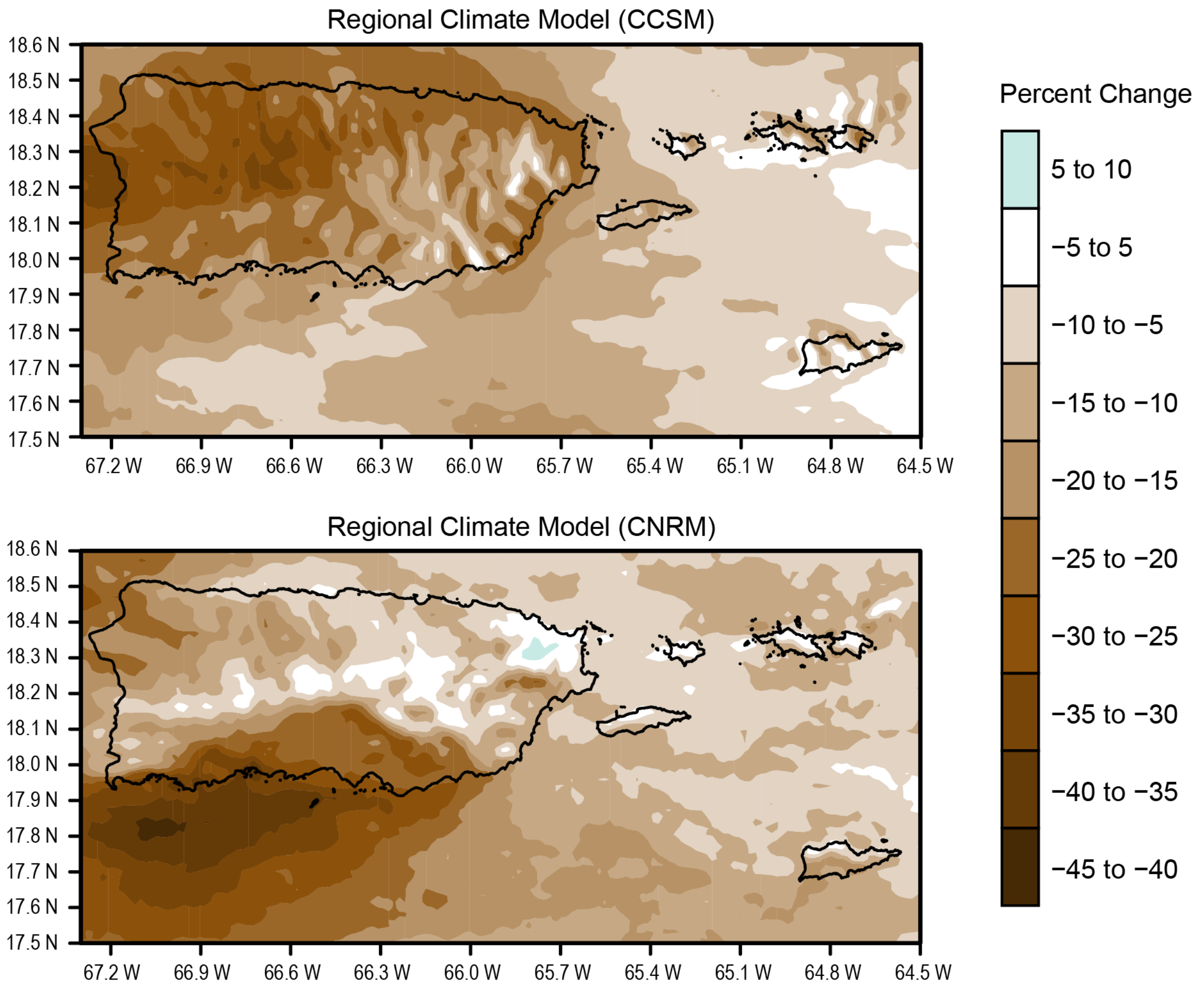


Figure 20.4: This figure shows the projected percent change in annual precipitation over the U.S. Caribbean region for the period 2040–2060 compared to 1985–2005 based on the results of two regional climate model simulations.[29,30] These simulations downscale two global models for the higher scenario (RCP8.5)[26] and show that within-island changes are projected to exceed a 10% reduction in annual rainfall. Uncertainty remains as to the location of the largest reductions within the islands. Projections of precipitation change for the U.S. Virgin Islands are particularly uncertain because of model limitations related to resolving these smaller islands. Source: Bowden et al. 2018.[30]

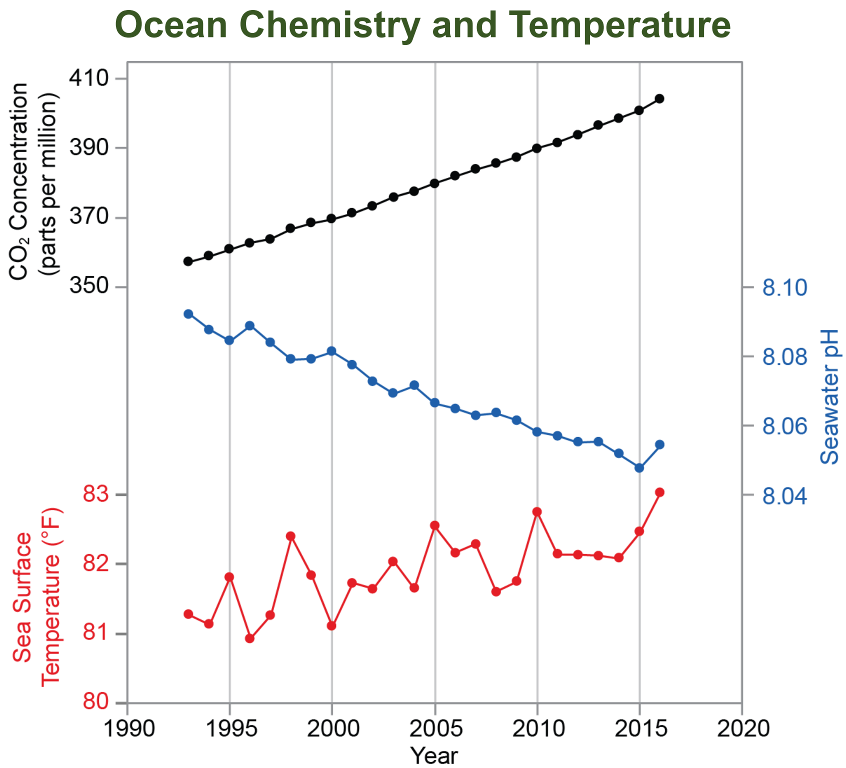


Figure 20.5: This figure represents an annual time series from 1993 to 2016 of atmospheric carbon dioxide (CO_2; black line), sea surface temperature (red line), and seawater pH (blue line) for the Caribbean region. The Caribbean ocean is subject to changes in surface pH and temperature due to the increase in atmospheric CO_2 concentrations. The oceans have the capacity to not only absorb heat from the air (leading to ocean warming) but also to absorb some of the CO_2 in the atmosphere, causing more acidic (lower pH) oceans. Continued ocean acidification and warming have potentially detrimental consequences for marine life and dependent coastal communities in the Caribbean islands. Source: University of Puerto Rico.

Sea level rise. Since the middle of 20th century, relative sea levels have risen by about 0.08 inches (2 mm) per year on average along the coasts of Puerto Rico and the USVI.[37,38] However, rates have been slowly accelerating since the early 2000s and show noticeable acceleration (by a factor of about 3) starting in about 2010–2011. This recent accelerating trend is in agreement with what has been observed along the southeastern U.S. seaboard, and rates of global and regional relative sea level rise are projected to continue to increase substantially this century, largely dependent on the amount of future greenhouse gas emissions. Under the Intermediate-Low, Intermediate, and Extreme scenarios, relative sea levels are projected to rise by about 0.8 feet, 1.2 feet, or 2.8 feet (24 cm, 37 cm, or 84 cm), respectively, by 2050 across the region compared to levels in 2000 and by about 1.6 feet, 3.6 feet, or 10.2 feet (0.5 m, 1.1 m, or 3.1 m), respectively, by 2100 (Figure 20.6).[38] Additionally, the region may experience more than the global average increase under the higher scenarios in response to changes in the Earth's gravitational field and rotation due to melting of land ice, ocean circulation, and vertical land motion.

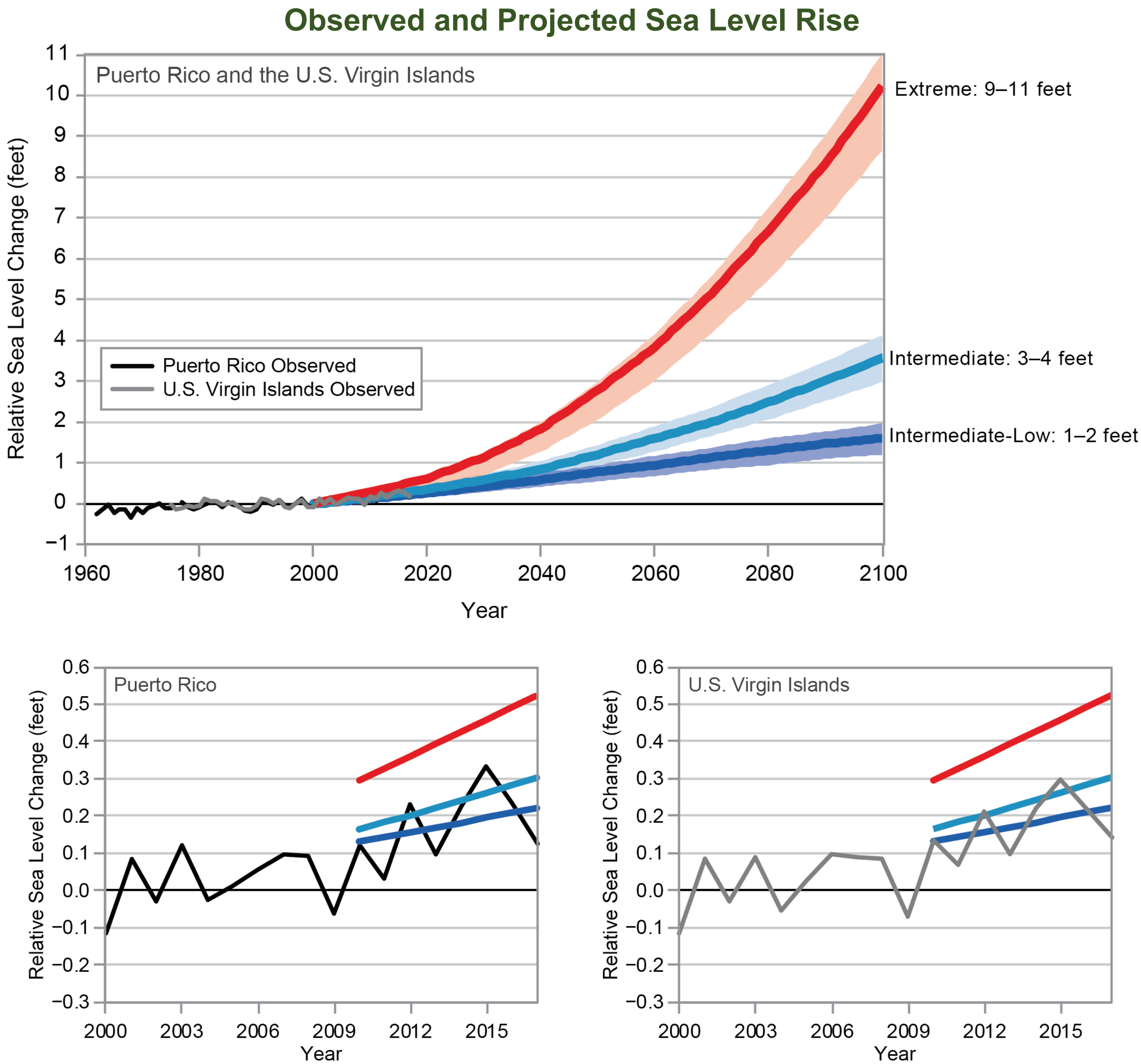


Figure 20.6: (top) Observed sea level rise trends in Puerto Rico and the U.S. Virgin Islands reflect an increase in sea level of about 0.08 inches (2.0 mm) per year for the period 1962–2017 for Puerto Rico and for 1975–2017 for the U.S. Virgin Islands. The bottom panels show a closer look at more recent trends from 2000 to 2017 that measure a rise in sea level of about 0.24 inches (6.0 mm) per year. Projections of sea level rise are shown under three different scenarios of Intermediate-Low (1–2 feet), Intermediate (3–4 feet), and Extreme (9–11 feet) sea level rise. The scenarios depict the range of future sea level rise based on factors such as global greenhouse gas emissions and the loss of glaciers and ice sheets. Sources: NOAA NCEI and CICS-NC.

Key Message 1

Freshwater

Freshwater is critical to life throughout the Caribbean. Increasing global carbon emissions are projected to reduce average rainfall in this region by the end of the century, constraining freshwater availability, while extreme rainfall events, which can increase freshwater flooding impacts, are expected to increase in intensity. Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers. Increasing variability in rainfall events and increasing temperatures will likely alter the distribution of ecological life zones and exacerbate existing problems in water management, planning, and infrastructure capacity.

Linkage Between Climate Change and Regional Risks

Freshwater availability is a function of rainfall, temperature, evapotranspiration (evaporation and transpiration from plants), land cover, watershed characteristics, water use and management, and water quality, and is dependent on the intensity, duration, frequency, and distribution of rainfall within the island. Availability is also affected by seasonal and annual variability in rainfall as well as long-term climate trends. Climate change will likely result in water shortages (due to an overall decrease in annual rainfall), a reduction in ecosystem services, and increased risks for agriculture, human health, wildlife, and socioeconomic development in the U.S. Caribbean.

Rainfall in the U.S. Caribbean is highly variable across space and time, complicating analyses of trends.[39] However, past occurrences of drought or excessive rainfall provide insights into vulnerabilities that may be indicative of the future. Droughts and extreme rainfall events in recent years have resulted in economic loss and social disruption. The most recent drought of 2014–2016 in Puerto Rico and the USVI resulted in severe losses to the agriculture sector, implementation of water rationing by the Puerto Rico Aqueduct and Sewer Authority, drying of wetlands, and reduced habitat quality for freshwater biota, including threatened and endangered species such as the Antillean manatee.[40]

Freshwater resources are primarily surface waters. In the USVI, desalination plants provide some of the public water supply. In Puerto Rico, management and sustainable use of water resources and infrastructure have been problematic for decades, particularly in terms of storage, distribution, and quality of the public water supply.[41,42] In 2013, 57.4% of all water produced was lost in distribution.[42] Recurring droughts and sedimentation-induced reductions in reservoir storage present a challenge to freshwater availability.[43] One of the principal sources of potable water for Puerto Rico, Loíza reservoir, has lost nearly 40% of its original storage capacity due to sedimentation.[44,45]

Future Climate Change Relevant to Regional Risks

The greatest risk to freshwater resources may be reduced availability due to drying trends.[46] Large uncertainty remains in terms of projected rainfall intensity, duration, and frequency. However, hydrologic model simulations indicate that major reservoirs in Puerto Rico could enter permanent supply deficit as early as 2025 under a higher emissions scenario (SRES A2) (see the Scenario Products section of App. 3) and by 2040 under a lower emissions scenario (SRES B1; Figure 20.7).[46]

Projected Change in Annual Streamflow

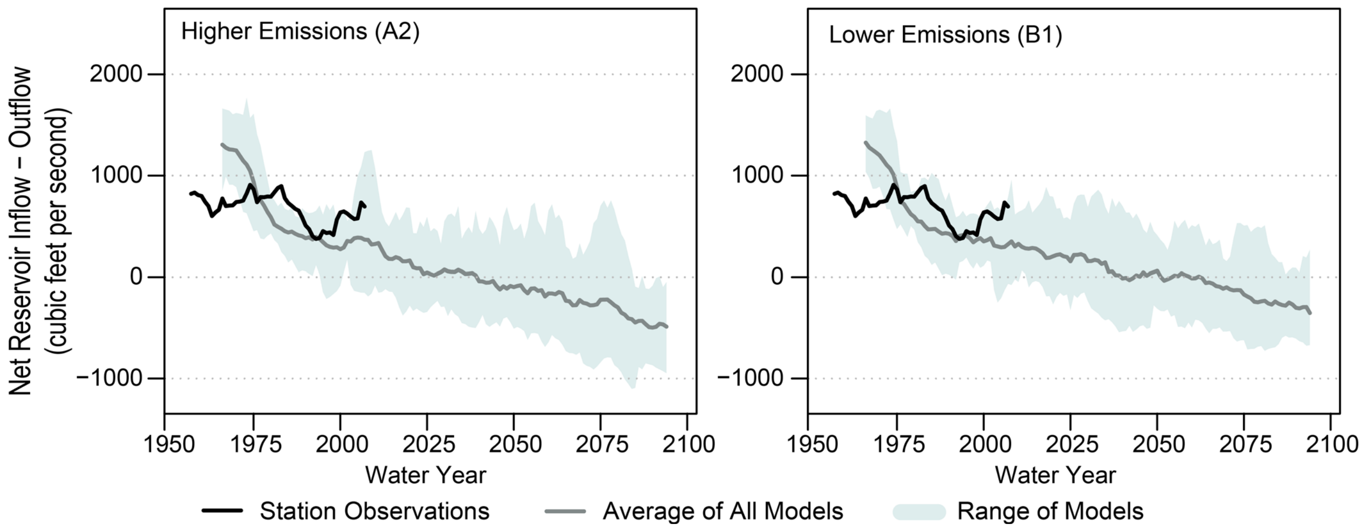


Figure 20.7: This figure shows ten-year moving averages of projected annual streamflow leaving Lago La Plata and Lago Loíza. Projections were developed using an estimation of water supply entering the reservoirs and an estimation of withdrawals. The former was developed using a range of global climate models (GCMs; shading indicates averages from all GCMs used in the study) and the mean of that range (gray line). The latter was developed using a conservative population growth rate. Annual streamflow is modeled under a higher emissions scenario (SRES A2; left panel) and a lower emissions scenario (SRES B1; right panel). The solid black line is the historical streamflow through 2012.[46] It is important to note these are the best estimates available for projected streamflow and use the older generation of GCMs, which project more drying for the region.[28] Source: adapted from Van Beusekom et al. 2016.[46]

Studies indicate that some locations within the Caribbean may experience longer dry seasons and shorter, but wetter, wet seasons in the future.[2,3,4,5,6,8] Extended dry seasons are projected to increase fire likelihood[9,10] and affect plant phenology (the timing of important biological events), as well as wildlife dependent on fruiting and flowering.[47] Excessive rainfall coupled with poor construction practices, unpaved roads, and steep slopes, which are typical of the Caribbean islands, can exacerbate erosion rates and reduce reservoir capacity, water quality, and nearshore habitat quality.

Rainfall also drives the distribution of ecological life zones in the U.S. Caribbean.[48] Projected decreases in rainfall foreshadow relative increases in dry life zones and the shrinkage and disappearance of wetter life zones. Ecological implications of these shifts include changes in biodiversity, carbon cycling, forest composition and structure, and nutrient and water cycling.[7] Vulnerable life zones include the unique rainforest habitats in the Luquillo Mountains of Puerto Rico (Figure 20.8).[8,49,50] Montane species are shifting their ranges upslope and may reach upper elevational limits as temperatures continue to climb.[51] Studies find that cloud levels in the dry season are consistently as low as, or lower than, in the wet season in the Luquillo Mountains, indicating that the cloud forest ecosystem may be more vulnerable to wet-season drought periods than previously assumed.[10]

Cloud Forests Are Vulnerable to Climate Change

Figure 20.8: Tropical montane cloud forests in the Luquillo Mountains of Puerto Rico are characterized by the frequent presence of clouds, reduced tree height, a high number of endemic and endangered species, and high water content of the soil due to reduced sunlight. Cloud forests around the world are vulnerable due to the warming and drying conditions that are expected with climate change.[52] Cloud forests on low mountains are especially vulnerable, as drying and warming conditions can increase the elevation at which clouds form, thereby reducing or possibly eliminating the cloud cover shrouding the mountain peaks.[53,54,55] Photo credit: Grizelle González, USDA Forest Service International Institute of Tropical Forestry.

Challenges, Opportunities, and Success Stories for Reducing Risk

Climate change projections provide new impetus to establish practices that reduce current risks to drought and excessive rain and, by inference, reduce future risks to new conditions. The United Nations Environment Programme has promoted rainwater harvesting in Caribbean Small Island Developing States (SIDS).[56,57] The Puerto Rico Technical Scientific Drought Committee also recommended the use of cisterns and other structural measures to capture rainwater in residential areas of the territory, encouraged their use on existing homes, and recommended making them mandatory for new projects.[40] These systems not only serve as sources for drinking water but also help in storm water management.[58,59,60]

Citizens of the USVI are required by law to be directly responsible for their own domestic water supply. The majority of USVI's residents depend on cistern water and use the public source only when they run out of their cistern water.[57]

Application of new technologies is vital if losses from water supply distribution systems are to be reduced. Public freshwater supplies are jeopardized by reservoir sedimentation, which can also be harmful to downstream ecosystems as sedimentation rates are reduced downstream. Improving sediment management practices, such as those identified from prior experiences,[61] can help sustain reservoir capacities and minimize environmental impacts.

Emerging Issues

Managing freshwater and balancing water use among sectors are emerging as two of the most important issues to the U.S. Caribbean islands. Increasing agricultural production will improve food security and the economy but will be challenging, as water availability is likely to decrease over much of the Caribbean.[62] Options for improving water-use efficiency in the agricultural sector include optimizing the management of water infrastructure, applying scientific methods for scheduling irrigation, determining crop water requirements for local crops, using crop suitability modeling to evaluate potential responses to climate change and extreme weather scenarios, plant-breeding for extreme conditions, and implementing methods to improve soil fertility, reduce erosion, and increase carbon storage (Ch. 27: Hawai'i & Pacific Islands, KM 1).[62,63]

Key Message 2

Marine Resources

Marine ecological systems provide key ecosystem services such as commercial and recreational fisheries and coastal protection. These systems are threatened by changes in ocean surface temperature, ocean acidification, sea level rise, and changes in the frequency and intensity of storm events. Degradation of coral and other marine habitats can result in changes in the distribution of species that use these habitats and the loss of live coral cover, sponges, and other key species. These changes will likely disrupt valuable ecosystem services, producing subsequent effects on Caribbean island economies.

Linkage Between Climate Change and Regional Risks

Corals are a major component of the coastal protection, fisheries, and tourism economy of Caribbean islands. Key Message 3 discusses the importance of coastal systems to island economies and the potential effects of climate change on these economies. As in many tropical island systems, coral reefs anchor one end of the ridge-to-reef continuum—a concept that recognizes the linkage of social, ecological, terrestrial, and marine components associated with island systems (Ch. 27: Hawai'i & Pacific Islands). Recognizing that the coral reef ecosystem includes mangrove and seagrass habitats, this section briefly discusses the role these habitats play in fisheries and the potential impacts climate change is likely to have on this role.

Ocean warming poses significant threats to the survival of coral species and may also cause shifts in associated habitats that compose the coral reef ecosystem (Ch. 9: Oceans, KM 1 and 3).[35] The primary observable response to ocean warming is bleaching of adult coral colonies, wherein corals expel their symbiotic algae in response to stress. Severe, repeated, or prolonged periods of high temperatures leading to extended coral bleaching can result in colony death. Ocean warming can also harm hard corals that form coral reefs by decreasing successful sexual reproduction, causing abnormal development, impairing coral larvae's attempts to attach to and grow on hard substrate, and affecting hard corals' ability to create their calcium carbonate skeleton. Ocean warming also increases the susceptibility of corals to diseases and is expected to increase the impact of pathogens that cause disease.[64] In 2005, a mass bleaching event, driven by 12 weeks of temperatures above the normal local seasonal maximum, affected the entire Caribbean region, resulting in the loss of 40%–80% of the coral cover in the region.[65]

Ocean acidification associated with rises in carbon dioxide (CO_2) levels also is likely to diminish the structural integrity of coral habitats, affecting fisheries and other marine resources (Figure 20.9).[35] One study concluded that calcification rates have decreased by about 15% based on examination of different species of calcification in planktonic foraminifera.[66] Uncertainty remains about the magnitude of decreases in calcification on coral reefs and some crustaceans and mollusks (such as queen conch). However, a small decline in calcification rates has the potential to alter the growth–erosion balance of reefs if the erosion of the hard structure of reefs becomes more frequent.[67] Ocean acidification effects could be further exacerbated by local processes in coastal zones, such as land-based transport of nutrients to nearshore waters.

The compounded risk of climate change with human-caused stressors increases vulnerability and accelerates habitat loss and degradation.[68] Where fringing (nearshore) and barrier reef systems have eroded, mangroves and seagrass may also decline due to the loss of protection from wave action afforded by reefs. The potential decline in seagrass and mangrove habitats would be compounded by the effects of coastal and in-water development on these habitats and on coral reefs, resulting in overall declines in nursery habitat for important fishery species like spiny lobster, queen conch, snappers, and groupers. The impacts of climate change, in general, on seagrass in the Caribbean is uncertain, but some studies suggest that photosynthesis could be inhibited at high temperatures.[69] Sea level rise may lead to a reduction in the area occupied by seagrass if waters become too deep for the plants to obtain enough light to photosynthesize. Sea level rise is also projected to result in a loss of mangrove habitat if low-lying coastal areas are not present or have already been developed on islands such that mangroves cannot colonize these areas as coastal waters get deeper.[70] Additionally, increases in the magnitude and frequency of storms result in impacts caused not only by waves and surge but also by increased rainfall and the associated transport of sediment and other land-based pollutants into nearshore waters. Mangrove and seagrass habitats filter storm water runoff, but large volumes of sediment transported downstream can overwhelm these systems, leading to burial of seagrass beds and partial burial of mangrove roots, thus affecting the ability of these habitats to reduce pollutant transport to coral reefs.

Caribbean reefs have experienced declines in important fishery species—such as the Caribbean spiny lobster and queen conch; predatory species, such as snappers and groupers; and important herbivores, like parrotfish—due to overexploitation.[71,72] Overexploitation is demonstrated by the exceedance of commercial annual catch limits (established by the Caribbean Fishery Management Council to protect depleted stocks) in 2013 in Puerto Rico and the USVI and in 2014 in Puerto Rico, leading to the establishment of additional regulatory measures.[73] In terms of annual economies, commercial fishing of reef fish provides an average of $9 million to Puerto Rico, $2.4 million to St. Thomas and St. John, and $3 million to St. Croix (in 2014 dollars).[73]

Studies show that major shifts in fisheries distribution, coupled with structural and compositional changes in marine habitats such as coral reefs due to climate change, adversely affect food security, shoreline protection, and economies throughout the Caribbean.[5,69,74,75,76] In the U.S. Caribbean region, where fishery resources are shared with other Caribbean islands, competition for fisheries resources are likely to increase as stock distribution changes due to climate change (Ch. 16: International, KM 4). Figure 20.10 shows the connections between climate change, marine habitats and species, and human communities. In the case of Puerto Rico, the coral reef ecosystems off the east coast of the main island (Fajardo area) and the islands of Culebra and Vieques were estimated as generating $192 million per year for recreation and tourism and $1 million in coastal protection services annually (in 2007 dollars, or $217 million and $1 million in 2015 dollars, respectively).[68] For the territory of USVI, reef-related tourism was estimated as generating $96 million per year, and coastal protection was estimated as providing $6 million annually to the local economy (in 2007 dollars, or $108 million and $7 million in 2015 dollars, respectively).[68]`

Climate Change Effects on Coral Reefs

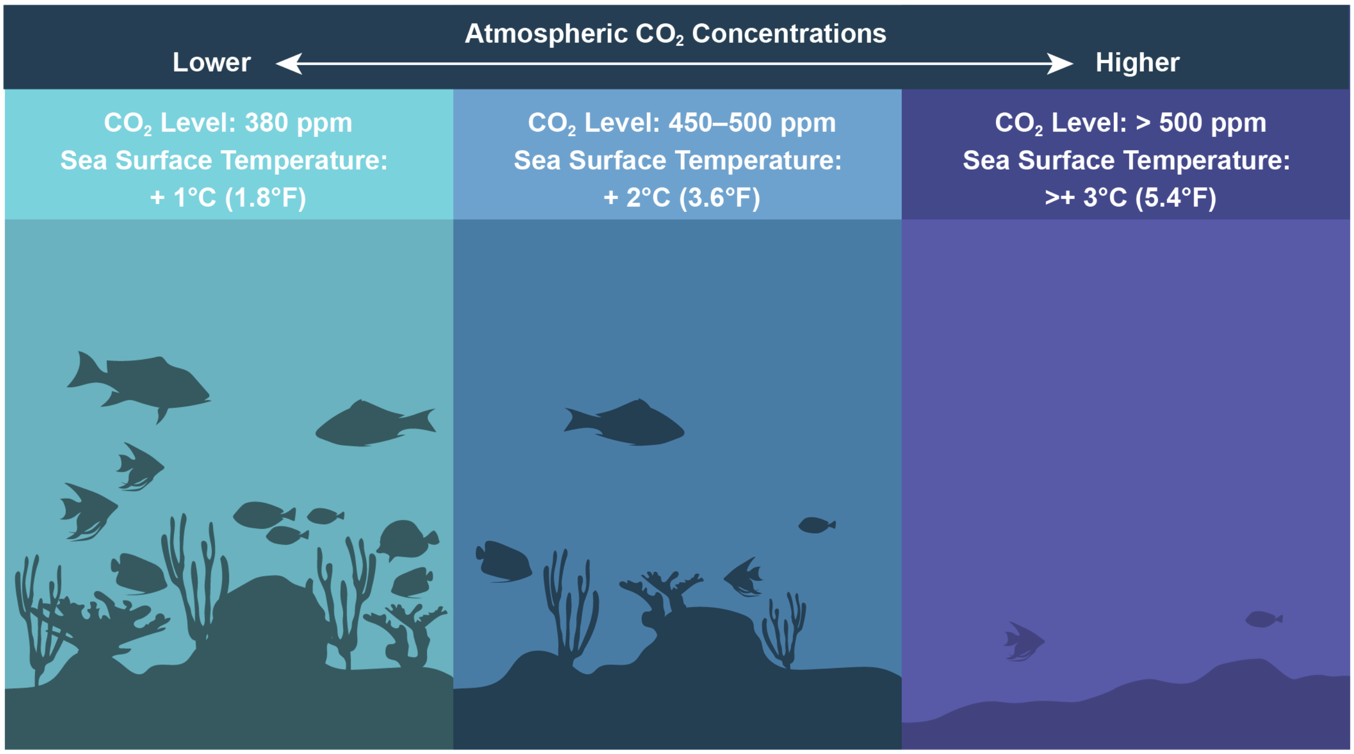


Figure 20.9: The diagram demonstrates how coral reef ecosystems in the U.S. Caribbean are likely to change in potentially warmer and more acidic waters caused by climate change, including elevated sea surface temperatures and elevated carbon dioxide (CO_2) levels. The severity of these impacts increases as CO_2 levels and sea surface temperatures rise. If conditions stabilized with concentrations of atmospheric CO_2 at 380 ppm (parts per million), coral would continue to be carbonate accreting, meaning reefs would still form and have corals. At 450–500 ppm, reef erosion could exceed calcification, meaning that reef structure is likely to erode and coral cover is likely to decline dramatically. Beyond 500 ppm, corals are not expected to survive.[77] Sources: NOAA and USFS.

Climate Change Impacts on Coral Reef Ecosystems and Societal Implications

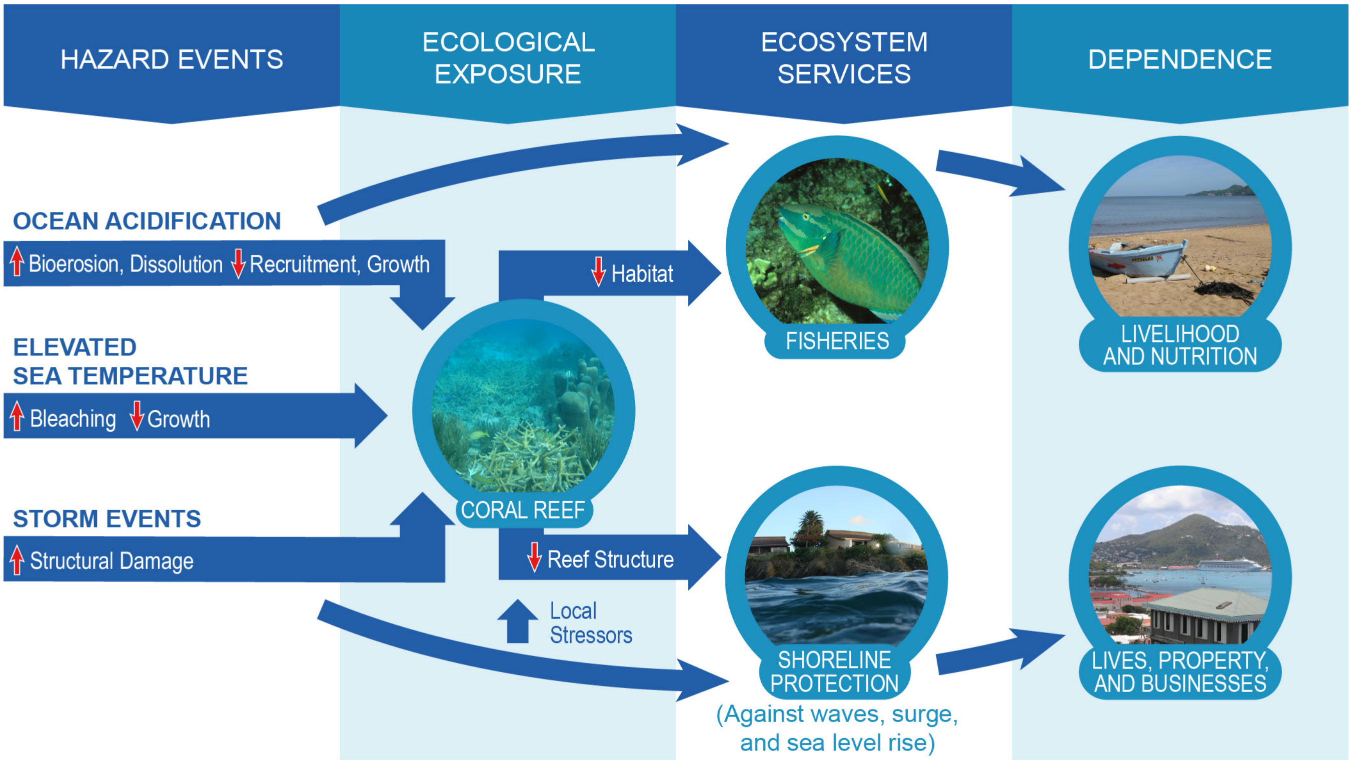


Figure 20.10: The figure shows the connections between climate-related impacts (ocean acidification and warming as well as severe storms), responses of marine habitats and species to these impacts, and, ultimately, the effects to ecosystem services (such as fisheries and shoreline protection) and, in turn, the human community. Specifically, the figure depicts how degradation of coral reefs due to climate change is expected to affect fisheries and the economies that depend on them as habitat is lost. The figure also shows how reef degradation decreases shoreline protection for local communities, which affects the economy and human populations more generally. Source: adapted from Pendleton et al. 2016.[78] Photo credits: NOAA.

Future Climate Change Relevant to Regional Risks

With high levels of greenhouse gas emissions (in other words, business as usual), mass coral bleaching in the Caribbean may occur at least twice a year within the next decade.[79] The increasing frequency of extreme heat events is highly likely to preclude reef recovery, considering that the region's reefs have yet to fully recover from the 2005 event. Moreover, the increase in average temperature will make corals more susceptible to extreme heat events and to coral disease, further contributing to declines in live coral cover in marine habitats.[64] One study suggests that coral reefs in Puerto Rico are expected to pass a critical ecosystem threshold in the first several decades of the century with coral cover loss of 95% by 2090 under a higher scenario (RCP8.5).[80]

Sea level rise is another climate-related stressor in the Caribbean. The rate of sea level rise in the region is expected to follow or exceed global projections. Sea level rise will likely have effects not only on marine communities by diminishing the amount of sunlight they receive but also on low-lying cays, which provide important habitat for seabirds and sea turtles. Coastlines on the larger islands and mainlands of the U.S. Caribbean will be submerged or greatly reduced in extent as sea levels rise. Coastal mangroves, squeezed between rising seas and coastal development, may be reduced in extent, diminishing the natural protection they provide against the action of waves and storm surge and limiting their role as wildlife habitat. Sea level rise is also expected to lead to a loss of seagrass if waters become too deep for them to photosynthesize. Photosynthesis will also be inhibited as sea surface temperatures continue to rise, which is likely to affect both seagrass and mangroves in addition to corals, as noted above.

The combined stress of sea level rise, increases in sea surface temperatures, and ocean acidification, along with increases in the severity and frequency of storms and associated transport of land-based pollutants into coastal and marine habitats, will likely lead to loss and degradation of these habitats. Future climate change effects on marine habitats will likely impact island economies due to changes in the availability of key fishery species such as queen conch, Caribbean spiny lobster, and species in the snapper and grouper complexes; declines in natural shoreline protection and associated impacts to coastal infrastructure and communities, as well as wildlife habitat; and loss of tourism associated with habitats such as coral reefs. Fisheries productivity is projected to decline while catch effort increases as fishers travel longer distances and spend more time on the water.[75] Potential losses of up to 90% of the coral reef recreation value in Puerto Rico are projected under most scenarios considered by the end of the century, due to the expected loss of coral reef habitat associated with climate change impacts.[80]

Challenges, Opportunities, and Success Stories for Reducing Risk

Climate change directly influences marine species' physiology, behavior, growth, reproductive capacity, mortality, and distribution, while indirectly influencing marine ecosystem productivity, structure, and composition.[74] As a result, fishery resources and essential habitats for commercially, recreationally, and ecologically important species are likely to be less resilient.

Several strategies meant to increase ecosystem resilience to local stressors (such as declines in water quality, overexploitation of fisheries, recreational use, and coastal and marine development) are being implemented in the Caribbean to lessen the potential impacts of climate change on marine resources. One such strategy is the establishment of protected areas in coastal and marine areas. Management of these areas may include limiting or prohibiting extractive uses, implementing conservation and restoration of coastal and marine habitats, and designating usage zones to minimize the impacts of recreational use on ecosystems. Another strategy is watershed planning to minimize the transport of land-based pollutants to nearshore waters, thus protecting marine habitats from declines in water quality caused by influxes of sediment, nutrients, and other contaminants. The NOAA Coral Reef Conservation Program, in partnership with federal and local agencies and local nongovernmental organizations, has sponsored the development and implementation of several watershed management plans in Puerto Rico and the USVI.[81]

Building the resilience of marine organisms, such as corals, is another strategy aimed at lessening the potential impacts of climate change on the marine ecosystem. Coral population enhancement through propagation (or coral farming) is a strategy meant to improve the reef community and ecosystem function, including for fish species that use this ecosystem (Figure 20.11). The selection and propagation of fragments and samples from coral colonies that have survived stressors such as bleaching events are emphasized as part of these efforts in an attempt to accelerate the otherwise uncertain recovery of these species.[82] This strategy has been used in the U.S. Caribbean and South Florida to recover species such as elkhorn and staghorn corals and species from the star coral complex—all of which are listed as threatened under the Endangered Species Act—without negatively affecting native populations of corals.

Coral Farming Can Increase the Extent and Diversity of Coral Reefs

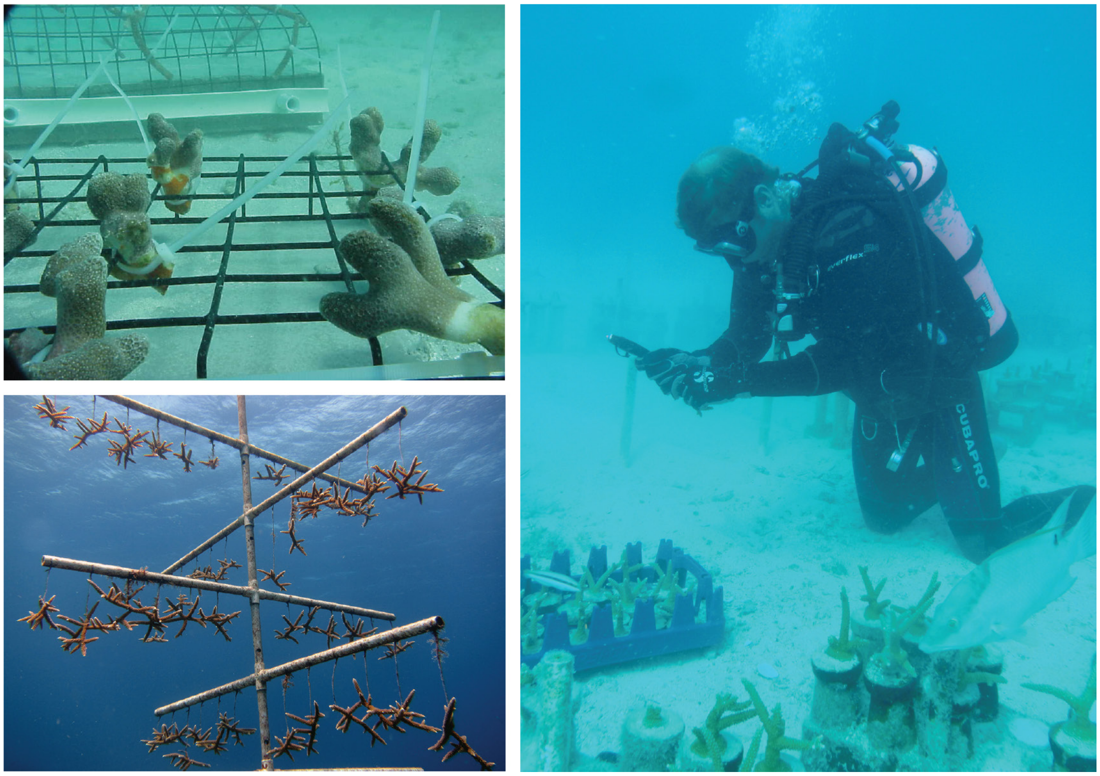


Figure 20.11: Examples of coral farming in the U.S. Caribbean and Florida demonstrate different types of structures used for growing fragments from branching corals. Coral farming is a strategy meant to improve the reef community and ecosystem function, including for fish species. The U.S Caribbean Islands, Florida, Hawai'i, and the U.S.-Affiliated Pacific Islands face similar threats from coral bleaching and mortality due to warming ocean surface waters and ocean acidification. Degradation of coral reefs is expected to negatively affect fisheries and the economies that depend on them as habitat is lost in both regions. While coral farming may provide some targeted recovery, current knowledge and efforts are not nearly advanced enough to compensate for projected losses from bleaching and acidification. Photo credits: (top left) Carlos Pacheco, USFWS; (bottom left) NOAA; (right) Florida Fish and Wildlife (CC BY-ND 2.0).

Emerging Issues

Integrating international monitoring networks of marine species and environmental conditions is critical to understanding the status and trends of wide-ranging marine resources. Areas like the Caribbean and the Pacific (Ch. 27: Hawai'i & Pacific Islands), where marine resources are key to socioeconomic well-being, benefit from monitoring programs that assess threats to reef health, ecosystem services, and reef-dependent communities. Research into the linkages between climate change and marine ecosystems is critical to enhancing the ability to predict future ecosystem responses to climate change and the associated socioeconomic consequences, as well as finding ways to mitigate those consequences.

Key Message 3

Coastal Systems

Coasts are a central feature of Caribbean island communities. Coastal zones dominate island economies and are home to critical infrastructure, public and private property, cultural heritage, and natural ecological systems. Sea level rise, combined with stronger wave action and higher storm surges, will worsen coastal flooding and increase coastal erosion, likely leading to diminished beach area, loss of storm surge barriers, decreased tourism, and negative effects on livelihoods and well-being. Adaptive planning and nature-based strategies, combined with active community participation and traditional knowledge, are beginning to be deployed to reduce the risks of a changing climate.

Linkage Between Climate Change and Regional Risks

A high concentration of population and critical infrastructure in low-lying coastal areas increases vulnerability to sea level rise and storm surge and magnifies the effects of coastal flooding and beach erosion. For example, most of the population in Puerto Rico (62%, or more than 2.2 million) lives in the 44 coastal municipalities, where a total of 1,019,300 housing units are also located.[83,84] It is also estimated that 401,145 people (11.5% of Puerto Rico's total population) live in areas subject to inundation, and 56,114 people live in areas susceptible to storm surge, also known as the coastal high hazard areas.[83] As sea level rises, storm surge and high energy wave action may cause shorelines to recede inland.[85] Approximately 60% of 3,808 beach transects studied along the coasts of Puerto Rico (799 miles) experienced erosion from the 1970s to 2010. Of those transects, 5% suffered very high erosion, with a beach loss of 3.97 feet to 6.56 feet per year.[86] Major loss of sand was identified in various municipalities of the north coast, including San Juan—the capital city and a center of economic activity, ports, and tourism—as well as Loíza and Dorado, which are cultural and tourist destinations. (For more information on effects from extremes and disaster events, see Key Message 5.)

The response of coastal systems to sea level rise is dependent on local natural and human factors.[87] Natural ecological systems can protect coastlines from erosion but can also be affected by sea level rise and other environmental changes. Coral reefs, mangroves, and sand dunes buffer coastlines from erosion and inundation, providing protective services. They reduce risk to people and infrastructure from wave damage and flooding. The coral reef–mangrove systems can reduce risk and provide fishery services if space is available for landward mangrove migration; however, this process can be hampered by coastal development. Beaches and coastal dunes provide wave energy dissipation and coastal asset protection yet are highly susceptible to wave action and erosion.

The U.S. Caribbean Economy

The U.S. Caribbean territories of Puerto Rico and the U.S. Virgin Islands have distinct differences in topography, language, population size, governance, natural and human resources, and economic capacity. However, both are highly dependent on natural and built coastal assets. Service-related industries account for more than 60% of the USVI's economy and cater to more than 570,000 tourists, as well as an additional 2.1 million cruise ship passengers who arrive to the island each year.[88] In 2013 in the USVI, tourists and cruise ship passengers spent $851 million and $381 million, respectively (in 2013 dollars; $877 and $392 million, respectively, in 2015 dollars). Approximately 3.7 million people visited Puerto Rico in 2016 as tourists, and an additional 1.3 million people arrived via cruise ships. Tourist and cruise ship passenger expenditures amounted to $3.8 billion and $202 million, respectively (in 2016 dollars; $3.8 billion and $200 million, respectively, in 2015 dollars).[89]

Beaches, affected by sea level rise and erosion, are among the main tourist attractions; consequently, these revenues from tourism are at risk due to limitations of access and deterioration to the coastal landscape. In addition, residents' recreational activities will likely be disrupted, as about 63% of Puerto Rican residents enjoy recreational activities such as swimming, bathing, or sunbathing on the beach.[90]

Operations of Puerto Rico's ports, the Luis Muñoz Marín (LMM) international airport, and the city of San Juan are currently at risk from extreme weather and climate-related events and will likely be even more vulnerable under projected sea level rise scenarios (Figure 20.12). In 2016, 93% of all passengers entering Puerto Rico through airports did so through the LMM airport.[91] The U.S. Caribbean's economy is also tied to climate impacts on Florida ports, as raw material for industries, food, clothes, and essential goods are shipped from Jacksonville, Florida, to the San Juan port and Isla Verde airport. As such, Florida's infrastructure vulnerability also affects the U.S. Caribbean.

Critical Infrastructure at Risk, San Juan Metro Area

Figure 20.12: Puerto Rico's Luis Muñoz Marín (LMM) international airport is already at risk from extreme weather and climate-related events and is expected to become more vulnerable in the future as a result of continuing sea level rise. Photo credit: Ernesto Díaz, Puerto Rico Department of Natural and Environmental Resources.

Cultural Heritage

Cultural and historic sites in the U.S. Caribbean region are threatened by sea level rise and storm surge. In the USVI, two significant early prehistoric sites, the Aklis and Great Pond archaeological sites, are directly threatened by sea level rise.[92] In Puerto Rico, effects on cultural heritage resources at risk due to climate change include impaired access to coastal resources like fishing, degraded ecotourism attractions, and loss of public access to beaches.[93] One of Puerto Rico's most notable cultural sites, the San Juan National Historic Site (El Morro), faces challenges from climate change, including sea level rise and coastal erosion.[94]

Critical Infrastructure, Property, and Real Estate

Sea level rise will likely increase threats to private, commercial, and residential property, as well as associated service infrastructure. Over 8,000 structures in Puerto Rico's low-lying areas would be affected by an increase in sea level of 1.6 feet (0.5 m). A sea level increase of 6.5 feet (2 m) would affect more than 50,000 structures located along the coast, causing approximately $11.8 billion in losses (in 2017 dollars).[83]

Critical infrastructure in the region is vulnerable to the effects of sea level rise, storm surge, and flooding. As an example, if sea levels rise 6.5 feet (2 m), which could occur during this century under the Intermediate-High to Extreme scenarios,[38,95] Puerto Rico and the USVI are projected to lose 3.6% and 4.6% of total coastal land area, respectively. Were such a rise to take place, Puerto Rico's critical infrastructure near the coast would be negatively impacted, including drinking water pipelines and pump stations, sanitary pipelines and pump stations, one wastewater treatment plant, and six power plants and associated substations.[96] In the USVI, infrastructure and historical buildings in the inundation zone for sea level rise include the power plants on both St. Thomas and St. Croix; schools; housing communities; the towns of Charlotte Amalie, Christiansted, and Frederiksted; and pipelines for water and sewage.

Challenges, Opportunities, and Success Stories for Reducing Risk

In Puerto Rico, the Department of Natural and Environmental Resources (DNER) commissioned the development of five climate change community-based adaptation plans for selected coastal municipalities.[97] Through an active community participation process, which included surveys and participatory mapping, these plans evaluated the risks and vulnerabilities posed by climate change and developed recommendations and adaptation strategies that will serve as guidance for municipal governments, communities, and local businesses (Figure 20.13).[97]

The USVI has released a guidance document to promote resilient coastal and marine communities through Ecosystem-based Adaptation (EbA). EbA reduces risk through the protection and restoration of natural areas like mangroves, dunes, and wetlands. High-risk areas were identified through analysis of social vulnerability, risk exposure, and adaptive capacity. Eleven areas throughout the USVI were selected as optimal to implement EbA options, as they faced high-risk exposure, high sensitivity, and low adaptive capacity. When considering climate effects and adaptation in the Caribbean, traditional knowledge from those members of the community maintaining the most intimate relationships with the land and natural systems is key to the early stages of the planning process. Traditional fishing, subsistence agriculture, and plant harvesting practices may provide a better understanding of how Caribbean Indigenous knowledge systems have sustained generations in the past and can benefit future generations.[98]

Assessing Vulnerability with Communities

Figure 20.13: Culebra's Mayor and community members worked on the participatory maps to identify risks, important natural resources, infrastructure, and important services to the community in Culebra. This exercise allowed them to gather information about issues in the territory that are important to the community but not commonly reflected in maps. Photo credit: Vanessa Marrero, Puerto Rico Department of Natural and Environmental Resources.

Natural and nature-based shoreline responses are used as stabilization techniques against erosion and can provide habitat for coastal species. Wetlands, dunes, and mangroves experience less damage from severe storms and are more resilient than hardened shorelines, and they also provide multiple benefits such as habitat for fish and other living organisms, as well as support recreational and commercial activities.[88] Mangroves alone can help reduce wave energy, erosion, and damage caused by large storms.[99] The U.S. Fish and Wildlife Service and the Puerto Rico DNER have funded wetland and dune restoration projects at various sites along the coast of Puerto Rico as nonstructural solutions to reduce coastal flooding and beach erosion.

Emerging Issues

Adaptive planning and nature-based strategies are gaining increased attention in Puerto Rico, as they are more accessible to coastal communities and can be cost effective. Also, stabilization and excavation of vulnerable cultural sites throughout the USVI can serve to protect or salvage cultural resources from the effects of climate change.[92]

Key Message 4

Rising Temperatures

Natural and social systems adapt to the temperatures under which they evolve and operate. Changes to average and extreme temperatures have direct and indirect effects on organisms and strong interactions with hydrological cycles, resulting in a variety of impacts. Continued increases in average temperatures will likely lead to decreases in agricultural productivity, changes in habitats and wildlife distributions, and risks to human health, especially in vulnerable populations. As maximum and minimum temperatures increase, there are likely to be fewer cool nights and more frequent hot days, which will likely affect the quality of life in the U.S. Caribbean.

Linkage Between Climate Change and Regional Risks

Records from weather stations in Puerto Rico indicate that the annual number of days with temperatures above 90°F has increased over the last four and a half decades (Figure 20.14). A number of extreme temperature events occurred in Puerto Rico during the summers of 2012–2014, when most days exceeded 90°F. This period included the hottest months on record and the longest continuous period of days over 90°F.[11] Higher temperatures drive increased energy demand to cool buildings and indoor environments. San Juan's record heat episode in 2012 drove record-level energy consumption. During that time, stroke and cardiovascular disease were the primary causes of death due, in part, to the elevated summer temperatures in the municipalities of San Juan and Bayamón (Ch. 14: Human Health, KM 1).[11,12]

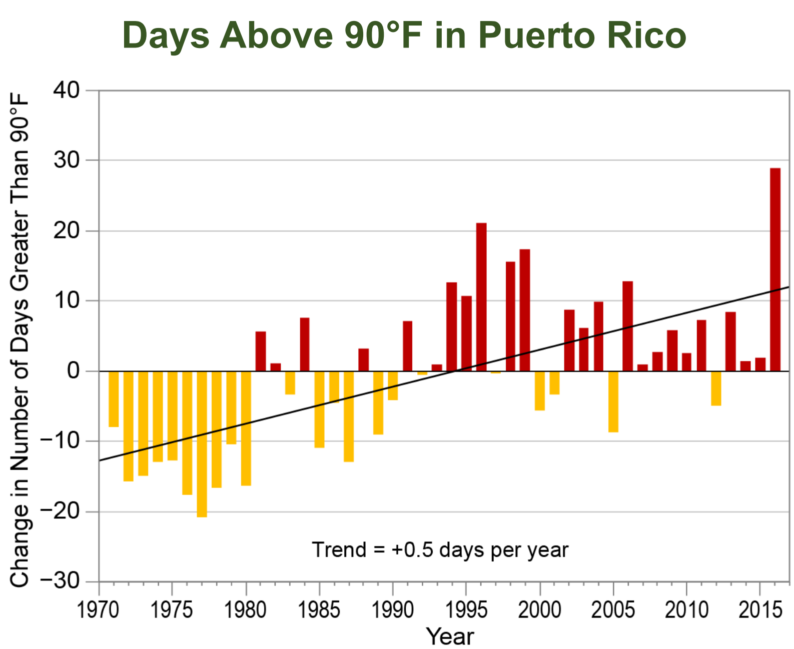


Figure 20.14: This figure illustrates the deviation from the long-term (1971–2016) average annual number of days exceeding 90°F, based on data from eight climate stations in Puerto Rico. Source: University of Puerto Rico. *This caption was revised in June 2019. See Errata for details: https://nca2018.globalchange.gov/downloads*

Heat stress can exacerbate preexisting health conditions and lead to an increase in human mortality.[100,101] Time of year, repetition, duration, time between events, and adaptation of individuals are important determinants of the health outcomes during extreme heat episodes. Vulnerability to heat is a function of exposure and personal sensitivity, which depends on an array of individual factors and may influence the ability to cope with extreme temperatures.[102]

Urban areas are particularly vulnerable to extreme heat events, given the concentration of built structures, traffic, and other factors that drive the urban heat island (UHI) effect.[103,104] Since the middle of the last century, urbanization and population growth have increased the UHI effects in San Juan. Such effects are becoming even more life threatening with a growing and more vulnerable aging population. Heat vulnerability index maps show that the hottest and most vulnerable areas correspond to highly built areas, including within and around the LMM Airport, seaports, parking lots, and high-density residential areas, while cooler areas correspond to vegetated landscapes and urban bodies of water (such as lagoons and wetlands).[102]

The role of agriculture in Puerto Rico and the USVI is both economic and cultural. The economic role of agriculture has diminished in recent decades compared to the mid-20th century. Currently, less than 1% of Puerto Rico's gross domestic product (GDP) and approximately 1% of the USVI's GDP is due to agriculture.[13,89] Recent revitalizations in agricultural productivity are vulnerable to climate change. At risk are food security, rural livelihoods, and agroecological services. Increases in average temperature and extreme heat events will likely have detrimental effects on agricultural operations throughout the U.S. Caribbean region.[13,14] Climate change affects cattle ranchers and dairy farmers in the U.S. Caribbean by reducing productivity of rangeland, causing a shortage of nutritional feed, increasing heat stress on animals, and increasing energy costs for cooling.[105] High temperatures and resultant heat stress reduce animal productivity and increase the proliferation and survival of parasites and disease pathogens. Warming reduces the ability of dairy cattle to produce milk and gain weight and can lower conception rates.[105]

Tropical cropping systems are often more vulnerable to climatic shifts and anomalies for a number of reasons. Many farmers throughout the tropics, including in the U.S. Caribbean, are considered small-holding, limited resource farmers.[1,15] This terminology refers to farmers who own small parcels of land (fewer than 2–5 acres) and often lack the resources and/or capital to adapt to changing conditions.[15] Many important tropical crop species, such as coffee, evolved within relatively narrow temperature bands and are more sensitive to variation in rainfall and temperature than are crop species native to temperate regions.[24]

Finally, rising temperatures will generally increase regional sea surface temperatures, which tends to increase the maximum intensity that hurricanes in the region can achieve.[33] This can lead to stronger hurricanes and more active hurricane seasons in general, which the Caribbean region is especially vulnerable to, as evidenced by the 2017 hurricane season (see Box 20.1).

Future Climate Change Relevant to Regional Risks

Cooling degree days (CDDs), used as a proxy for future air conditioning energy demands, are projected to increase over time and to more than double in Puerto Rico by the end of century (Ch. 4: Energy, KM 1).[7] The warmer south coast is projected to have the highest increase in CDDs in the first half of the century, while the San Juan metropolitan area is projected to have its highest increases in the second half of the century, suggesting higher energy demands in the island's largest metropolitan area by the end of the century.[7]

Warming, along with drying, is projected to affect the terrestrial ecosystems in the region. The ecological life zones of Puerto Rico are projected to shift from rain and wet zones to moist and dry zones based on the projected drying. By the middle of this century, under most scenarios considered, all life zones in Puerto Rico are projected to shift to tropical zones.[7] Environmental suitability for species in the region would be altered by life zone shifts, which may lead to biodiversity redistribution in the region. Environmental factors, especially climatic variables, were shown to have higher importance than land-use history on forest species composition in Puerto Rico and the USVI.[106] The projected changes in the amount and spatial variability of climatic variables will likely affect the composition and spatial redistribution of species.

Climate change adaptation strategies and national (as well as international) discussions and agreements have focused more on direct socioeconomic implications and less on changes in natural ecosystems; nonetheless, climate-induced species redistribution affects ecosystem functioning, human well-being, and the dynamics of the climate change itself and represents a substantial challenge for human society.[107] Species respond to changes in environmental conditions by tolerating the changes, adapting to the new conditions, facing extinction, or moving, which changes their distributions.[108] Warming forces species to move toward higher latitudes and altitudes.[109] On small islands in the Caribbean with limited latitudinal ranges, species' adaptive movement is limited to tracking changing temperatures toward higher altitudes.

Challenges, Opportunities, and Success Stories for Reducing Risk

Green and blue infrastructure are, respectively, the natural terrestrial vegetation and water-related components of an urban or other landscape. They provide many beneficial ecosystem services for surrounding microclimates.[102,110,111] Urban planning efforts in coastal cities are placing greater emphasis on the use of green infrastructure and water bodies for cooling urban environments. Planners in low-lying cities are also incorporating adaptable spaces that can accommodate occasional flood waters while providing services such as parks or urban open space[112] that can also help mitigate the UHI effect. In agriculture, the rapid expansion of electronic and worldwide communications is bringing old and new adaptation practices to a new generation of practitioners as they deal with multigenerational problems of water management and heat stress in crops and livestock.[13]

Emerging Issues

Cumulative effects on urban populations, agricultural sectors, and the natural environment add complexity to developing scenarios and prioritizing actions to reduce risks related to climate change. New alliances, collaborations, and governmental structures may be necessary to address these complex challenges.

Key Message 5

Disaster Risk Response to Extreme Events

Extreme events pose significant risks to life, property, and economy in the Caribbean, and some extreme events, such as flooding and droughts, are projected to increase in frequency and intensity. Increasing hurricane intensity and associated rainfall rates will likely affect human health and well-being, economic development, conservation, and agricultural productivity. Increased resilience will depend on collaboration and integrated planning, preparation, and responses across the region.

The Caribbean is highly vulnerable to disaster-related risks.[113] The U.S. Caribbean region experiences hurricanes, extreme rainfall, and droughts. The most extreme of these events have caused significant disruptions in Caribbean island livelihoods, including casualties and substantial economic losses. Current demographic and economic characteristics of Puerto Rico and the USVI—and their innate vulnerabilities as islands—result in greater sensitivity to these events, therefore imposing greater burdens in terms of response and recovery compared to many places in the continental United States.

Tropical cyclones (hurricanes and tropical storms), floods, and droughts are the most frequent and damaging extreme events in Puerto Rico. More than 50 extreme events related to floods, droughts, tropical storms, and winter swells have been declared emergencies and disasters since the mid-1990s.[114] Disaster declarations have occurred on a yearly basis since 2001.

Over the years, extreme events have caused billions of dollars in property and crop damages in Puerto Rico and the USVI. Tropical cyclones cause the most severe disruption and economic damage. In 2017, damages caused by Hurricanes Irma and Maria prompted a humanitarian crisis in the U.S. Caribbean by causing the collapse of the region's main energy, water, transport, and communication infrastructures (see Box 20.1). The estimated damages for Hurricane Maria alone totaled between $27 and $48 billion for the Caribbean region, with Puerto Rico estimates ranging from $25 to $43 billion (in 2017 dollars).[115] Total casualties caused by these hurricanes have proven difficult to establish. In Puerto Rico, estimates range from 64 to more than 1,000 deaths, although the evidence base is still evolving in this area.

Box 20.1: 2017 Atlantic Hurricane Season Impacts

The 2017 Atlantic hurricane season had devastating impacts across the Caribbean region (Figure 20.15) and reemphasized the exposure and vulnerabilities of the Small Island Developing States (SIDS) in the region.[116] During the unusually active 2017 hurricane season, there were 17 named storms (wind speeds of 39 mph or higher), 9 of which impacted one or more Caribbean SIDS. Twenty-two of the 29 Caribbean SIDS (including islands that are United Nation members and non–U.N. Associate Members of Regional Commissions) were impacted by at least one named storm, and a large number of SIDS experienced catastrophic impacts from major hurricanes (wind speeds of 111 mph or more). Five SIDS were impacted by three storms, 13 by two storms, and 4 by one storm. Eleven SIDS experienced tropical storm force winds (39 mph or higher wind speeds), 11 experienced hurricane force winds (74 mph or higher wind speeds), and 9 experienced direct landfall of a major hurricane.[116]

Of the 29 SIDS, only 7 were not significantly affected by the 2017 storms: Guyana, Jamaica, Suriname, Aruba, Bermuda, Cayman Islands, and Curaçao. Antigua and Barbuda, Cuba, Dominica, Saint Kitts and Nevis, Anguilla, British and U.S. Virgin Islands, Guadeloupe, Puerto Rico, Saint Maarten, and Turks and Caicos were all affected by Saffir–Simpson Category 4 and 5 hurricanes (winds of 130 mph or higher). The impacts and costs, in terms of lives and property damage, during the 2017 Atlantic hurricane season are still being calculated. In this age of satellite technology, hurricane warnings are generally timely, and mortality rates during local hurricane passage have been minimized, but post-event mortality numbers can grow quickly due to lack of electrical power, potable water, food, and access to adequate healthcare, among other factors (Ch. 14: Human Health, KM 1 and 2).[116,117] The death toll in Puerto Rico, for example, has been estimated to have grown by a factor of about 1700% in the three months following Maria's landfall on the island,[116] due in part to the lack of electricity and potable water, as well as access to medical facilities and medical care.

The health impacts across the Caribbean SIDS span a large range, including physical injury from wind and water during hurricane passage and during post-event rescue and cleanup efforts, heat-related injury due to loss of access to air conditioning and fans, inability to manage chronic disease due to loss of access to electrical power or medical services, and increased exposure to vector-borne diseases and diseases from contaminated water. Mental health impacts are also notable, as most survivors experience a high degree of psychological trauma during and after hurricane events (Ch. 14: Human Health, KM 1).[116]

Critical infrastructure in the region suffered catastrophic damages as a consequence of Hurricanes Irma and Maria. These hurricanes caused the complete failure of Puerto Rico's power grid[118] and the loss of power throughout the USVI. Telecommunication infrastructure suffered major damages in the aftermath of the 2017 hurricanes, severely disrupting the communication capabilities of both Puerto Rico and the USVI.[119] Over 70% of potable water infrastructure was also severely affected in Puerto Rico due to Hurricane Maria's impacts, primarily from direct damages to infrastructure and loss of electricity.[118]

Hurricanes Irma and Maria caused catastrophic damage to crops and infrastructure across farms in Puerto Rico and the USVI. In Puerto Rico, losses surpassed $2 billion in crops alone (in 2018 dollars), with damages to infrastructure adding much more to the total.[120] In the USVI, farms, ranches, and infrastructure, including government agriculture offices, experienced sizable damages; however, there are no official estimates of the economic value of the losses caused by the storms.

Box 20.1: 2017 Atlantic Hurricane Season Impacts, *continued*

Hurricane Maria caused severe damage to the milk and poultry industries in Puerto Rico. Over $4 million (in 2018 dollars) was lost in the poultry industry due to chicken mortality during the storm or conditions afterward (lack of water, shelter, or feed).[120] Similarly, many in the milk industry lost barns, food for cows, or power, leading to an inability to sustain operations.[121] Further, due to a lack of electricity, many residents were reluctant to purchase fresh chicken or milk, which affected the markets. Hundreds of thousands of residents are estimated to have left the islands in the aftermath of Hurricane Maria,[122] which is likely to affect the long-term demand for agricultural products.

Based on information in NOAA's ResponseLink, in the USVI, 479 vessels were displaced, and almost 4,000 orphaned containers, propane cylinders, marine batteries, and other waste from these vessels had to be removed from coastal waters after the hurricanes. In Puerto Rico, 376 vessels were displaced, and approximately 27,000 gallons of waste oil had to be recovered from these vessels and coastal waters after the hurricanes. Coral reefs and other marine habitats suffered impacts from transport of these vessels and associated debris into these habitats, as well as from debris transported in rivers and streams into nearshore waters. Hurricanes Irma and Maria also caused impacts to corals and other marine habitats due to bottom swells and wave action. Coral farms being used to grow Endangered Species Act–listed corals as part of reef restoration efforts were largely lost from sites around Puerto Rico and St. Croix, where they had been in place for years.

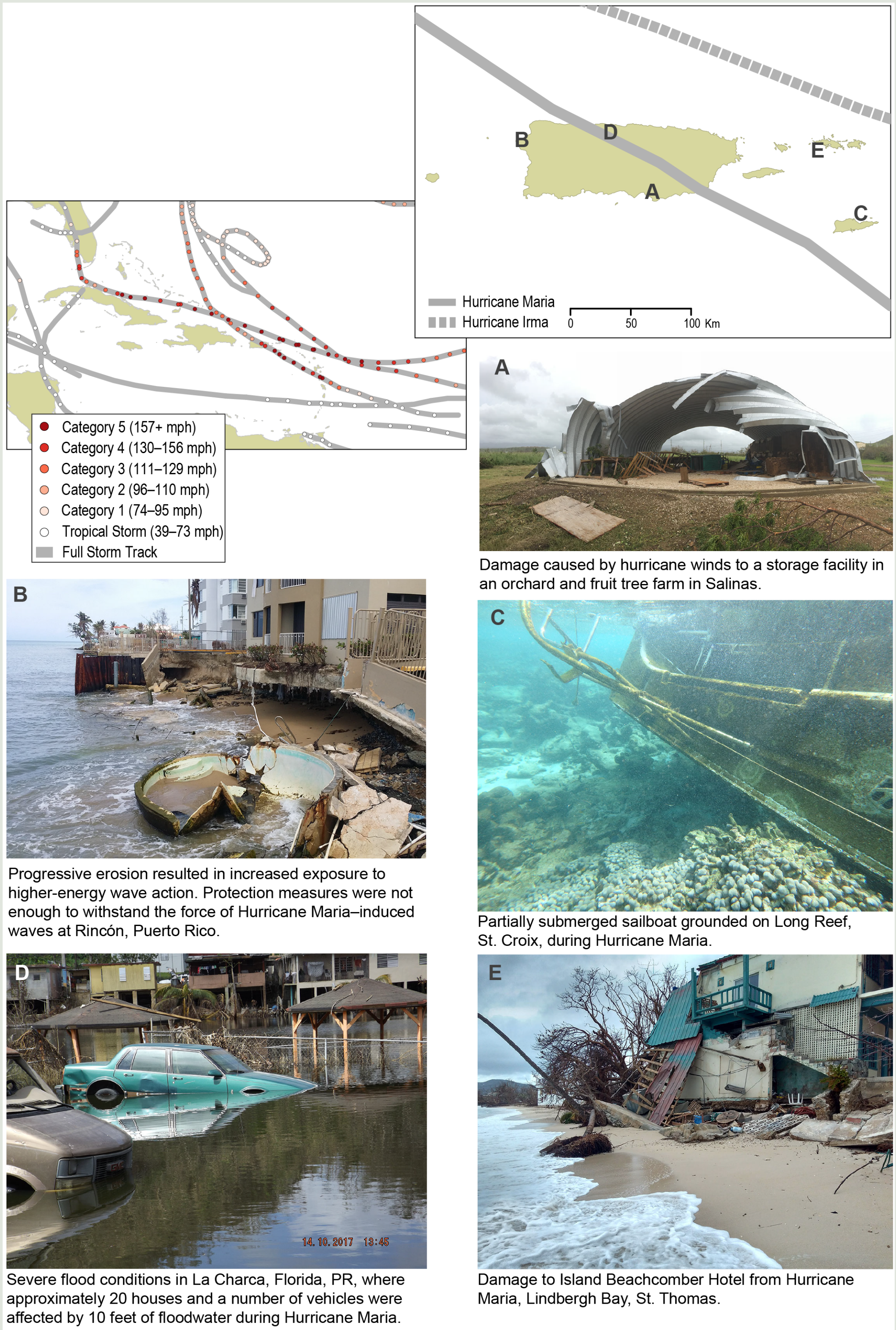
NOAA and its local and federal partners have been working on rapid assessments around the islands to determine the extent of damage to marine habitats in order to focus on habitat restoration and recovery efforts. Surveys in Puerto Rico from October to December 2017 looked at 30 high-value reef sites, of which 20 were identified as having moderate to major impacts needing emergency restoration. Damages included large coral heads being overturned or tossed into sand areas where they cannot grow successfully, extensive burial and breakage of corals from waves and storm surge, and physical impacts from grounded vessels and debris. Surveys in waters off Christiansted, St. Croix, found physical impacts to seagrass beds associated with barge and other vessel groundings due to Hurricane Maria. Whether marine habitats impacted by the hurricanes are left to recover naturally or experience some level of restoration, there are potential short-term impacts to ecosystem services such as fisheries and coastal protection while these habitats return to their pre-hurricane state.

The Caribbean lies in a region where the natural climate system acts in a way that compounds the effect that warm ocean temperatures have on hurricanes.[123] In particular, when ocean temperatures are unusually warm, other environmental factors that affect hurricanes tend to be optimized. This is not the case for regions along the U.S. mainland coast, where warmer waters tend to cause other factors to inhibit hurricanes.[124] There are also disparities between the United States' resources to respond to local hurricane impacts and those of the Caribbean SIDS. Furthermore, any impacts that may be exacerbated by global and regional climate change tend to disproportionately affect regions that are geographically small and relatively short on resources.[125]

The challenges of effective disaster response in the U.S. Caribbean region are daunting and formidable.[116] The 2017 Atlantic hurricane season provided a window into the vulnerabilities of the region and the difficulties in responding to hurricane impacts. As the response to the 2017 hurricane season continues in the region, sustained dialog among the range of stakeholders whose interests and areas of expertise are involved can improve strategies regarding response actions and coordination of response based on lessons learned in 2017 and 2018.

Box 20.1: 2017 Atlantic Hurricane Season Impacts, *continued*

Hurricane Impacts in 2017



A: Damage caused by hurricane winds to a storage facility in an orchard and fruit tree farm in Salinas.

B: Progressive erosion resulted in increased exposure to higher-energy wave action. Protection measures were not enough to withstand the force of Hurricane Maria–induced waves at Rincón, Puerto Rico.

C: Partially submerged sailboat grounded on Long Reef, St. Croix, during Hurricane Maria.

D: Severe flood conditions in La Charca, Florida, PR, where approximately 20 houses and a number of vehicles were affected by 10 feet of floodwater during Hurricane Maria.

E: Damage to Island Beachcomber Hotel from Hurricane Maria, Lindbergh Bay, St. Thomas.

Figure 20.15: In September 2017, the U.S. Caribbean region was impacted by two major hurricanes: Irma (Category 5) and Maria (Categories 4 and 5). This figure shows the hurricanes' tracks across both the Caribbean and (inset) the U.S. Caribbean region, as well as (A–E) some of the impacts felt throughout the region. Sources: (tropical cyclone tracks) NOAA NCEI and ERT, Inc. Photo credits: (A) Ricardo Burgos; (B) Ernesto Díaz, Puerto Rico DNER; (C) Michael Doig, NOAA; (D) Joel Figuero; (E) Greg Guannel, The University of the Virgin Islands.

Damages from Hurricanes Irma and Maria in Puerto Rico caused the longest-lasting power outage in U.S. history to date (Figure 20.16).[126] Communications for Puerto Rico and the USVI were largely disabled following the hurricanes, with a respective 88% and 69% of cellular communication infrastructure out of service.[119] For Puerto Rico, preliminary estimates suggest that economic losses to businesses due to wind damage for Hurricane Maria totaled $4.9 billion (in 2017 dollars, $4.8 billion in 2015 dollars).[127] Alongside economic loss and infrastructure damage, hurricane impacts also caused severe disturbances to terrestrial and marine ecosystems, including sensitive coral reef colonies in the region (see Box 20.1).

Historical events much less severe than those in 2017 have resulted in significant damages as well. In 1995, Hurricane Marilyn resulted in losses equivalent to 122% of the USVI's gross domestic product. From 2010 to 2016, hurricanes produced a loss of about $39 million (in 2015 dollars) to Puerto Rico's agricultural sector alone.

Over the past 20 years, floods in urban areas caused by extreme precipitation have frequently disrupted human and economic activities.[128] On July 18, 2013, a record 9 inches of rain fell in San Juan, Puerto Rico, in less than 24 hours,[129] affecting multiple residential and commercial areas. The resulting floods caused the temporary closure of the LMM International Airport, disrupting the movement of people and goods. In November 2016, heavy rains and associated flooding resulted in agricultural losses of approximately $13 million (in 2015 dollars) in Puerto Rico.[130]

Droughts are one of the most frequent climate hazards in the Caribbean. Since the 1950s, at least seven major droughts have occurred in the U.S. Caribbean.[131,132] Since 2000, there have been five moderate droughts in Puerto Rico that lasted, on average, 8.6 weeks (Figure 20.17). The most recent major regional drought of 2014–2016, classified as extreme, affected Puerto Rico and the USVI, as well as other islands in the region. At its peak, this drought covered more than 60% of Puerto Rico's land area.[133] Conditions resulted in water rationing for 1.2 million people and over $14 million in agricultural losses for 2015, primarily in livestock, grazing lands, bananas, and plantains.[40] While the onset and end of a drought are hard to determine, records of the U.S. Drought Monitor suggest that it takes only weeks of abnormally dry conditions before the declaration of a meteorological drought in Puerto Rico.[134]

Hurricane Maria Damage

Figure 20.16: Residential and vessel damages caused by Hurricane Maria in 2017, at (left) Palmas del Mar and (right) Punta Santiago, Humacao, Puerto Rico. Photo credits: (left) Ernesto Díaz, Puerto Rico DNER; (right) Vanessa Marrero, Puerto Rico DNER.

Maximum Extent of Drought

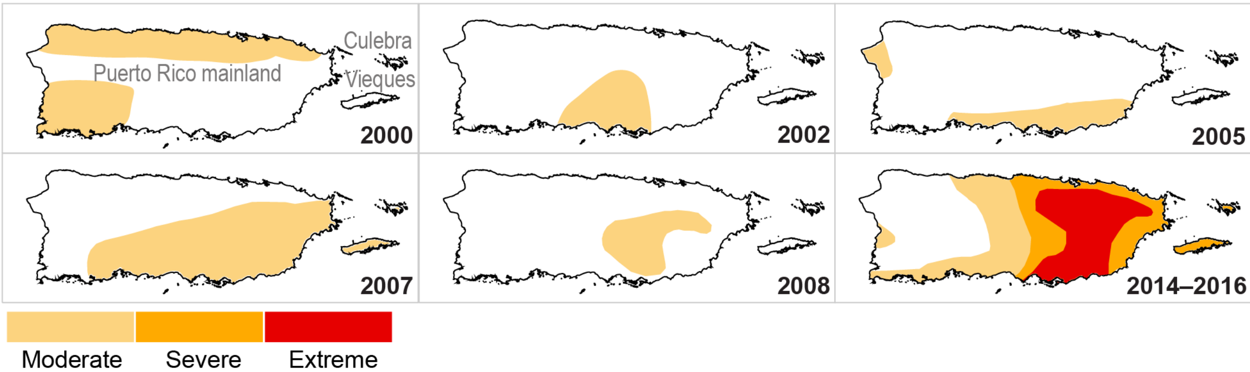


Figure 20.17: These maps show the maximum extent of each registered drought between 2000 and 2016 by the U.S. Drought Monitor. While six drought events were registered, the most severe of these occurred between 2014 and 2016, with extreme conditions covering the eastern half of the main island of Puerto Rico. The five events prior to 2014 were registered as moderate drought and were short-lived in comparison. Source: USDA Forest Service.

Future Climate Change Relevant to Regional Risks

While there is still much uncertainty in global climate model predictions of tropical cyclone formation,[135] climate models project an increase in the frequency of strong hurricanes (Categories 4 and 5) in the Atlantic Basin, including the Caribbean.[33] Drought projections for Puerto Rico suggest an increase in both drought intensity and frequency due to increases in both average and extreme temperatures and decreases in precipitation.[7]

Challenges, Opportunities, and Success Stories for Reducing Risk

The challenges for the U.S. Caribbean region in formulating disaster risk responses to extreme events lie in its geographical, social, and economic vulnerabilities. Puerto Rico and the USVI face common challenges, such as distance from continental resources, scarcity of land resources, increasing pressures on coastal and marine resources, high volume of food and fuel imports, and limited human resources.[1,25] Distance from the continental United States increases the region's vulnerability due to limited access to resources in times of need. Current fiscal and economic challenges of the region, coupled with an increasing elderly population, create additional challenges for the islands' governments to prepare for, respond to, and recover from climate-related disasters.

Improvements in data collection of extreme events and cost analyses of disasters have enhanced the resilience capacity of the U.S. Caribbean by supporting decision-making processes, particularly for drought events (see Box 20.4). Policymakers and disaster risk managers, as well as the general public, benefit from accurate data to support planning for disaster risk reduction. At present, current and historical data on the effects associated with extreme events are limited and not readily accessible for government officials and disaster risk managers.

Collaborative action has proven to be a successful strategy to manage and address the impacts from climate-related disasters.[136] Puerto Rico has actively provided humanitarian and technical support to other Caribbean nations and U.S. states during climate-related disasters and emergencies for at least 20 years. In Puerto Rico, collaborative actions among state and federal agencies, academics, and climate experts enabled improved preparation for and management of the 2014–2016 drought. Efficient coordination and collaboration among agencies prompted a largely effective governmental response to the disaster risk reduction challenges, while also promoting greater public education and awareness about extreme events (see Box 20.4).

Key Message 6

Increasing Adaptive Capacity Through Regional Collaboration

Shared knowledge, collaborative research and monitoring, and sustainable institutional adaptive capacity can help support and speed up disaster recovery, reduce loss of life, enhance food security, and improve economic opportunity in the U.S. Caribbean. Increased regional cooperation and stronger partnerships in the Caribbean can expand the region's collective ability to achieve effective actions that build climate change resilience, reduce vulnerability to extreme events, and assist in recovery efforts.

Shared Risks and Opportunities

Caribbean countries and territories share broad similarities in characteristics related to climate vulnerability, including low availability of resources, high debt rates, coastal populations, remoteness, and dependence on imports and global markets.[137] The recent impacts of Hurricanes Irma and Maria in 2017 brought to light the high vulnerability of Caribbean islands to natural disasters and the potential benefits of adopting long-term resilience measures. Increased regional cooperation and strengthening partnerships between Puerto Rico, the USVI, and the wider Caribbean countries can be achieved through collaborative climate research; by performing regional assessments of vulnerabilities, risks, and mitigation potential via joint efforts in adaptation planning and education; and by designing early warning systems to support strategic decision-making. These efforts are likely to increase resilience and the adaptive capacity of Caribbean countries by leveraging capabilities and resources and may help to speed up disaster recovery, reduce the loss of life, enhance food security, and improve economic opportunity in the region. The period following climate-related disasters can provide the opportunity to reduce future risks, when political attention is heightened and key decisions are being made on response, recovery, and planning. Being proactive and building back better is a simple idea, but its implementation has diverse challenges.[138] Recovery is not a neat linear progression with a clear end point but is rather a part of an ongoing process of development and change with attendant uncertainties and hurdles, including financing, personnel, and incentives for collaboration across Caribbean islands.[16,138,139]

New and sustained cooperation mechanisms between U.S. territories and Caribbean countries would likely increase the participation of Puerto Rico and the USVI in regional initiatives addressing climate adaptation and disaster risk reduction.

Effectiveness of Cross-Regional Collaboration for Building Resilience

There is a history of regional efforts on climate change assessment and governance in the Caribbean (Figure 20.18). Joint regional efforts to address climate challenges include the implementation of adaptation measures to reduce natural, social, and economic vulnerabilities, as well as actions to reduce greenhouse gas emissions. The Caribbean Small Island Developing States (SIDS) have articulated national climate change adaptation policies and implementation plans using processes similar to the UN Framework Convention on Climate Change guidance for preparation of national adaptation programs of action.

Climate Research and Risk Management Organizations

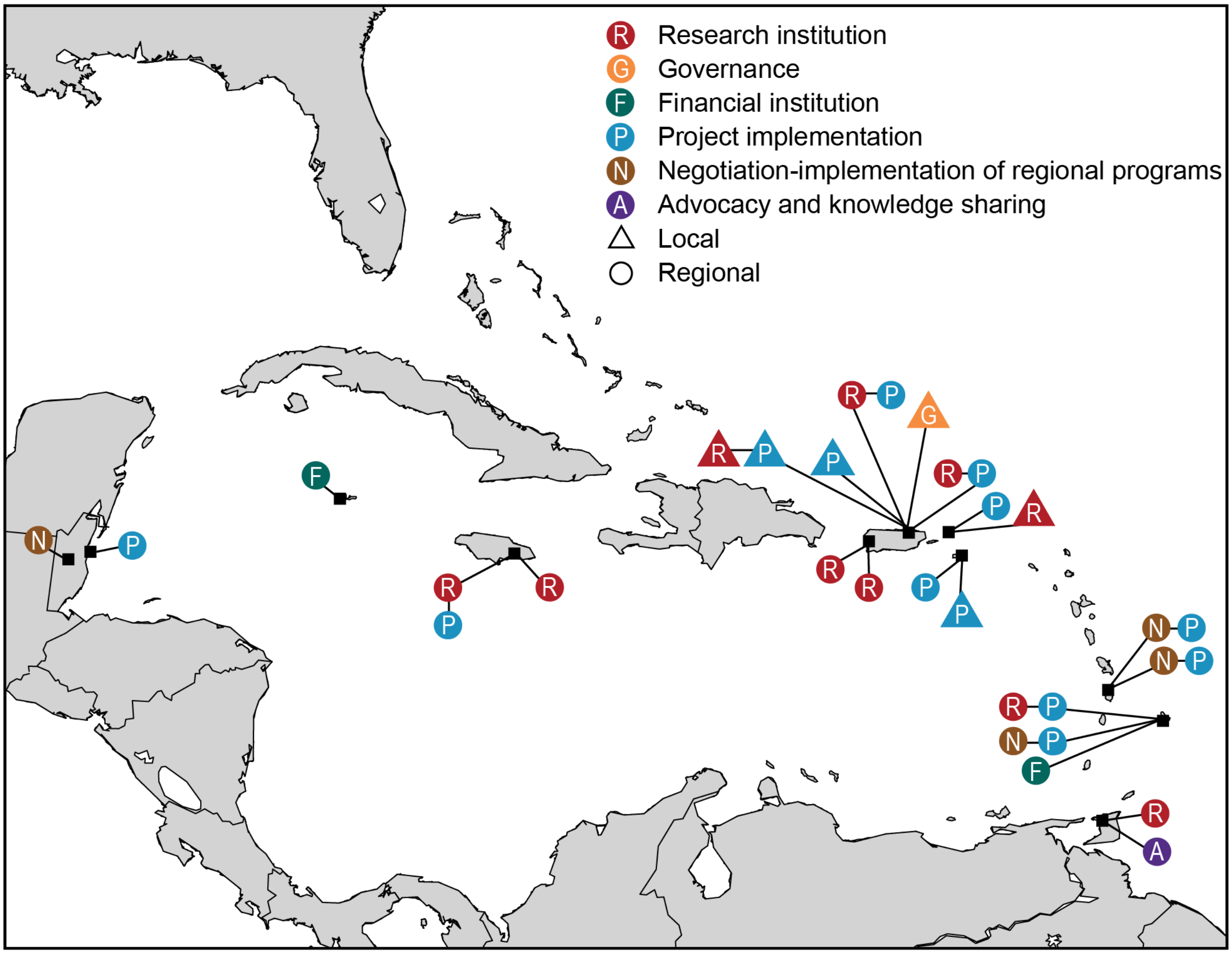


Figure 20.18: Some of the organizations working on climate risk assessment and management in the Caribbean are shown. Joint regional efforts to address climate challenges include the implementation of adaptation measures to reduce natural, social, and economic vulnerabilities, as well as actions to reduce greenhouse gas emissions. See the online version of this figure at http://nca2018.globalchange.gov/chapter/20#fig-20-18 for more details. Sources: NOAA and the USDA Caribbean Climate Hub.

Two regional entities specifically focused on developing and improving information, services, and planning to support climate risk management are the Caribbean Community Climate Change Centre (5Cs) and the Caribbean Institute for Meteorology and Hydrology (CIMH; see Boxes 20.2 and 20.3). The 5Cs is headquartered in Belize and is the main organization improving the framework and activities for addressing climate change in the Caribbean region.

The 5Cs projects include development and training in the use of analytical tools (for example, CCORAL; see Box 20.4), translating the outputs from global climate models for application at the scale of small islands, deployment of climate and coral reef monitoring equipment, provision of policy guidance for mainstreaming climate change considerations into regional development activities, preparation of a Regional Framework for Achieving Development Resilient to Climate Change[140] and its accompanying Implementation Plan, and the construction of desalination facilities powered by solar photovoltaic systems as solutions to water scarcity. The CIMH is an institution of the Caribbean Community (CARICOM) and is the technical arm of the Caribbean Meteorological Organization, a member of the UN World Meteorological Organization. The role of the CIMH is to assist in improving and developing climate services and to provide awareness of the benefits of meteorology and hydrology for economic and environmental well-being. Both the 5Cs and CIMH have engaged with U.S. territories in anticipating and reducing risks and supporting adaptation actions.

Common to most Caribbean countries and territories are the needs to 1) assess risks; 2) enable people and actions at regional, national, and local scales; and 3) assess changes in ecosystems and species to inform decision-making on habitat protection under a changing climate (Ch. 28: Adaptation, Figure 28.1).[16,17] The CARICOM regional strategy and the framework for transformation are clear steps in that direction and encompass goals that are shared by Puerto Rico and the USVI.

Box 20.2: United States Virgin Islands and 5Cs Partnership on Vulnerability Assessment

The 5Cs, in conjunction with the National Oceanic and Atmospheric Administration (NOAA), developed a Vulnerability and Capacity Assessment Methodology inventory (Ch. 16: International, KM 4), which was used and modified under the European Union–Global Climate Alliance Programme (2011–2015) in several Caribbean countries. The 5Cs–NOAA method was combined with the approach derived from a local planning guidebook on preparing for climate change developed under the NOAA Regional Integrated Sciences and Assessments program.[141] This combined approach led to a Caribbean-specific methodology that has been successfully applied in Antigua and Barbuda, Saint Lucia, Saint Kitts and Nevis, and Grenada.[142,143] Common challenges across the region include relatively small islands with diverse microclimates, locations, and levels of exposure to climate-related risks; the expanse of human settlement and critical facilities located along vulnerable coastlines; inadequate forward planning; and a heavy dependence on imports of commodities, equipment, and energy, which leads to extreme vulnerability to external economic shocks (Ch. 16: International, KM 1). These best-case examples provide a template for the vulnerability assessment that is currently being executed in the USVI under the Climate Change Adaptation Planning Assessment and Implementation project.

Box 20.3: CIMH, NOAA, and the 5Cs Partnership to Deliver Climate Services

In 2010, CIMH, in partnership with NOAA and the 5Cs, reestablished the Caribbean Regional Climate Outlook Forum to serve as the convening mechanism for regional engagement, early warning information, climate impacts, and responses.[16] Products resulting from this include the Caribbean Regional Drought Monitor and Climate Impacts Report.[144,145] Based on successes in the Caribbean Regional Outlook Forum, CIMH is leading the multisectoral Consortium of Sectoral Early Warning Information Systems Across Climate Timescales (EWISACTs). The EWISACTs agreement makes the Caribbean the first region to formally create and implement a joint commitment between climate-sensitive sectors and a public climate services provider to support climate-resilient risk management and development.

Box 20.4: Collaboration and Tools for Cross-Country Capacity Building and Decision-Making

The Caribbean Climate Online Risk and Adaptation tooL (CCORAL) is a planning tool that can help countries make climate-resilient decisions and take actions in response to a changing climate. (http://www.caribbeanclimate.bz/caribbean-climate-chage-tools/tools/)

The **Caribbean Catastrophe Risk Insurance Facility** is the world's first index-based parametric insurance mechanism. It is a partnership of 17 Caribbean countries and the World Bank. (https://www.ccrif.org/)

The **Caribbean Challenge Initiative** was launched in 2008, with support of The Nature Conservancy. Puerto Rico and the USVI later joined participating governments committed to conserving at least 20% of their nearshore marine and coastal environments by 2020 and to ensuring that these areas are managed through a long-term finance structure. (http://caribbeanchallengeinitiative.org/)

Reducing Risks and Supporting Adaptation: Gaps, Opportunities, and Benefits

The U.S. Caribbean region has potential to improve adaptation and mitigation actions by fostering stronger collaborations with Caribbean initiatives on climate change and disaster risk reduction. The U.S. Caribbean islands are not members of CARICOM. However, the Government of Puerto Rico established a memorandum of understanding with the 5Cs to work collaboratively in climate adaptation and mitigation initiatives. Such agreements provide mechanisms to foster cooperation and build capacity in the region beyond the capabilities of any single island, leveraging greater support to address common challenges. U.S.-based centers and activities can benefit from and contribute to regional resilience. Key among these are the U.S. Department of Agriculture's Caribbean Climate Hub, the U.S. Department of the Interior's Climate Adaptation Science Centers, and NOAA's Caribbean initiative, which is supported by NOAA's Climate Program Office and NOAA's Office for Coastal Management.

Acknowledgments

Technical Contributors

Mariano Argüelles
Puerto Rico Department of Agriculture

Gabriela Bernal-Vega
University of Puerto Rico

Roberto Moyano
Estudios Técnicos, Inc.

Pedro Nieves
USVI Coastal Zone Management

Aurelio Mercado-Irizarry
University of Puerto Rico

Dominique Davíd-Chavez
Colorado State University

Rey Rodríguez
Puerto Rico Department of Agriculture

USGCRP Coordinators

Allyza Lustig
Program Coordinator

Apurva Dave
International Coordinator and Senior Analyst

Christopher W. Avery
Senior Manager

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Traceable Accounts

Process Description

The majority of our Key Messages were developed over the course of two separate author meetings. The first occurred March 9–10, 2017, and the second on May 3, 2017. Both meetings were held in San Juan, Puerto Rico; however, people were also able to join remotely from Washington, DC, Raleigh, North Carolina, and the U.S. Virgin Islands (USVI). In addition, the author team held weekly conference calls and organized separate Key Message calls and meetings to review and draft information that was integral to our chapter. To develop the Key Messages, the team also deliberated with outside experts who are acknowledged as our technical contributors.

Key Message 1

Freshwater

Freshwater is critical to life throughout the Caribbean. Increasing global carbon emissions are projected to reduce average rainfall in this region by the end of the century (*likely, high confidence*), constraining freshwater availability, while extreme rainfall events, which can increase freshwater flooding impacts, are expected to increase in intensity (*likely, medium confidence*). Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers (*very likely, high confidence*). Increasing variability in rainfall events and increasing temperatures will likely alter the distribution of ecological life zones and exacerbate existing problems in water management, planning, and infrastructure capacity (*likely, medium confidence*).

Description of evidence base

The average global atmospheric carbon dioxide (CO_2) concentration has increased from 378 parts per million (ppm) in 2005 to over 406 ppm during April of 2017. The rate of increase over this period appears to be constant, and there is no indication that the rate will decrease in the future.[146] Several climate change studies have concluded that owing to increased atmospheric CO_2 and the consequent global climate change, rainfall will likely decrease in the region between now and the end of the century (e.g., Meehl et al. 2007, Biasutti et al. 2012, Campbell et al. 2011, Cashman et al. 2010[2,3,4,5]). Neelin et al. (2006)[147] and Scatena (1998)[148] have predicted increasingly severe droughts in the region in the future. Several downscaling studies, which specifically considered Puerto Rico, predict a reduction in rainfall by the end of the century[6,7,34] and constraints on freshwater availability. Furthermore, Taylor et al. (2018)[149] used the most recent generation of global climate models and demonstrated that when global warming increases from 1.5°C to 2°C above the preindustrial values (1861–1900), the Caribbean experiences a shift to predominantly drier conditions. Small watersheds that feed reservoirs are typical of the Caribbean region, and they are less able to serve as a buffer for rainfall variability. Small watersheds exhibit variable drainage patterns, which in turn affect evapotranspiration, groundwater infiltration, and surface water runoff. Drainage patterns in watersheds are also affected by the specific geometry, configuration, and orientation in relation to the average direction of wind over the region, as well as the morphology of rivers. With a projected reduction in rainfall up to 30% on average for the island by the end of the century,[7] certain watersheds will likely be less able to buffer rainfall variability and will likely see water deficits in the near future. Increasing variability in rainfall events and increasing temperatures will likely exacerbate existing problems in water management, planning, and infrastructure capacity.

Streamflow is estimated using hydrologic models that are calibrated to networks of stream gauges and precipitation measurements. Reservoirs are considered in a permanent supply deficit if the annual streamflow leaving these reservoirs falls below zero after estimating withdrawals for human consumption, evapotranspiration, and rainfall. Projections of when deficit conditions could occur (circa 2025) are estimated using climate models.[46]

Saltwater intrusion associated with sea level rise will reduce the quantity and quality of freshwater in coastal aquifers. In Puerto Rico, groundwater quality can change when the water table is below sea level in coastal areas or when the intensity of pumping induces local upconing of deeper, poor-quality water.[43] Upconing is the process by which saline water underlying freshwater in an aquifer rises upward into the freshwater zone due to pumping.[150] When the water table is below sea level, the natural discharge of groundwater along the coast is reversed and can result in the inland movement of seawater or the upconing of low-quality water.[151,152] Diminished aquifer recharge and, to a lesser extent, increased groundwater withdrawals during 2012–2015 resulted in a reduction in the freshwater saturated thickness of the South Coast Aquifer. With sea level rise, groundwater quality will likely deteriorate even further in coastal aquifers in Puerto Rico.

Major uncertainties

As global changes continue to alter the hydrological cycle across the region, water resources are expected to be affected in both quantity and quality. There is still uncertainty as to the extent and severity of these global changes on small island nations such as Puerto Rico and the USVI, despite notable advancements in downscaled modeling exercises. Current climatological observations have presented an overall increase in mean annual precipitation across Puerto Rico.[153] However, climate model projections point toward an overall decrease in annual mean precipitation toward 2050 and an increase in rainfall intensity for extreme rainfall,[6,7,28,30,34,154] including rainfall associated with hurricanes. There is more uncertainty regarding the frequency and duration to changes in extreme rainfall within the region.[7,28,34]

Selected CMIP3 (Coupled Model Intercomparison Project, phase 3) and CMIP5 global climate models (GCMs) capture the general large-scale atmospheric circulation that controls seasonal rainfall patterns within the Caribbean[155] and provide justification that these GCM projections can be further downscaled to capture important rainfall characteristics associated with the islands.[156] Systemic dry biases exist, however, in the GCMs.[155] And many GCMs fail to capture the bimodal precipitation pattern in the region.[28] The CMIP3 generation of GCMs that do capture the bimodal rainfall pattern predict extreme drying at the middle and end of this century.[7,28] The CMIP5 generation of GCMs also projects drying by the middle and end of the century, but the magnitude of drying is not as large. Local and island-scale processes could affect these projected changes, since the land surface interacts with and affects both precipitation and evaporation rates.[157]

Description of confidence and likelihood

There is *high confidence* that freshwater availability will *likely* be constrained by the end of the century and *medium confidence* that extreme rainfall events will *likely* increase in intensity. There is *high confidence* that sea level rise will *very likely* cause saltwater intrusion impacts on coastal freshwater aquifers. There is *medium confidence* about *likely* changes to ecological life zones but *low confidence* about the distributional effects on the existing terrestrial ecosystems in the region.

Key Message 2

Marine Resources

Marine ecological systems provide key ecosystem services such as commercial and recreational fisheries and coastal protection. These systems are threatened by changes in ocean surface temperature, ocean acidification, sea level rise, and changes in the frequency and intensity of storm events. Degradation of coral and other marine habitats can result in changes in the distribution of species that use these habitats and the loss of live coral cover, sponges, and other key species (*very likely, high confidence*). These changes will likely disrupt valuable ecosystem services, producing subsequent effects on Caribbean island economies (*likely, medium confidence*).

Description of evidence base

In 2006, the National Marine Fisheries Service (NMFS) listed elkhorn and staghorn corals as threatened species under the Endangered Species Act, with persistent elevated sea surface temperatures and sea level rise being two of the key factors influencing the listing decision.[158] The Acropora Biological Review Team (2005) found that the number of hurricanes affecting reef ecosystems in the Caribbean has increased over the past two decades (2 hurricanes in the 1970s, 6 in the 1980s, and 12 in the 1990s). Sea surface temperature is expected to continue rising, and this implies an increasing threat to elkhorn and staghorn corals from bleaching-induced mortality and possibly an exacerbation of disease effects. In 2014, NMFS listed an additional 5 species of Atlantic/Caribbean corals (lobed, mountainous star, boulder star, pillar, and rough cactus) as threatened and reevaluated the listing of elkhorn and staghorn corals, confirming them as threatened species; it also listed 15 Indo-Pacific coral species as threatened,[159] with two of the key factors being ocean warming and ocean acidification. Brainard et al.[159] found that ocean warming and related effects of climate change have already created a clear and present threat to many corals that will likely continue into the future and can be assessed with certainty out to 2100. Increases in human population densities and activity levels in the coastal zone are expected to continue, meaning the vulnerability of these populations and infrastructure will likely continue increasing with climate change.[160] Direct measurements at the Bermuda Atlantic Time-series Study station shows that surface ocean acidity has increased by about 12% and aragonite saturation (Ω_{arg}) has decreased by about 8% over the past three decades.[161] These values agreed with those reported across the Caribbean[162] and Atlantic regions[18,161] using regional and global numerical marine carbonate system models.

Many coastal regions already experience low surface seawater pH and Ω_{arg} conditions (localized or coastal ocean acidification) due to processes other than CO_2 uptake. As a result, the effect of ocean acidification on coastal zones can be several times higher and faster than typically expected for oceanic waters.[163]

Caribbean coral reefs in the Bahamas, Belize, Bonaire, and Grand Cayman are already experiencing significant reductions in carbonate production rates, with 37% of surveyed sites showing net erosion.[164] Friedrich et al. (2012).[66] concluded that calcification rates may have already dropped by about 15% within the Caribbean with respect to their preindustrial values.

Major uncertainties

The link between climate stressors such as increasing sea surface temperatures and bleaching response and increasing prevalence of disease in corals is postulated. There is some scientific evidence indicating a link, but it is hard to make definitive conclusions. Effects of climate change on fisheries in the Caribbean have not been as well studied as the effects on marine habitats, particularly coral reefs.[74,165] Similarly, the social consequences of climate change and associated declines in marine fisheries and the effects on coastal communities reliant on coral reef fishery species have not been as well studied.[166]

Uncertainty with respect to ocean acidification is dominated by uncertainty about how ecosystems and organisms will respond, particularly due to multiple interactions with other stressors.

The value of the loss of ecosystem services to ocean acidification is unknown. Such losses are attributable to the degradation of ecosystems that support important economic marine species such as coral, conch, oysters, fish larvae, urchins, and pelagic fish in the Caribbean. There is strong evidence for decreasing carbonate production, calcification rates, coral cover, and biomass of major reef-building species throughout the Caribbean region. However, there is still not enough evidence to conclude that all these decreased ecosystem processes are due to ocean acidification.

There are only a few studies on ecosystem and organism responses to climate stressors (such as ocean warming) that consider ocean acidification in the Caribbean. For instance, low pH values could affect nursery areas of commercially important species such as tuna, presenting a source of vulnerability for the economy, but studies are scarce. Ocean acidification could also affect the food web dynamics at lower trophic levels and have physiological effects at larval stages that would likely cascade upward, affecting coral and fish recruitment.

The effects of ocean acidification on coral reefs, shellfish, fish, and marine mammals will likely cause an economic effect on fisheries, coastal protection, and tourism in the Caribbean. Ocean acidification can exacerbate the current global warming effects on coral reefs, and it will likely continue deteriorating reef conditions and cause ecological regime shifts from coral to algal reefs.[77,167] The primary effect on reef communities will probably be a reduction in their capacity to recover from acute events such as thermal bleaching.

Sea level rise is currently the most immediate and well-understood climate-related threat to mangroves.[70] It is not clear how mangroves will respond to elevated CO_2, and some studies suggest increases may actually be beneficial to mangroves.[70] Similarly, in the Caribbean where temperatures are already high, increasing temperatures, as well as declines in rainfall and corresponding increases in soil salinity during periods of drought, will likely increase plant water stress and reduce productivity. There have been limited studies on the effects of climate change on seagrass beds; therefore, these effects remain uncertain.[69] Sea level rise that results in reduced sunlight due to increased water depths can lead to the loss of seagrass beds from deeper waters. As discussed previously, the loss or degradation of these habitats, which are part of the coral reef ecosystem and serve as nursery habitat for important nursery species, will likely contribute to declines in fishery productivity due to climate change.

Description of confidence and likelihood

There is *high confidence* that increasing ocean temperatures, changes in ocean acidity, and changes in the frequency and intensity of storms are *extremely likely* to affect coastal and marine resources. Large storm events within the past decade have resulted in significant effects on marine resources, particularly coral habitats and organisms that rely on them. There is *medium confidence* in predictions that coral habitats will *likely* continue to decline throughout the Caribbean, with associated effects on resources dependent on these habitats; although, scientific studies are still needed in terms of climate change effects on fisheries resources, particularly for species that are found in offshore waters or are pelagic. Changes in coral habitats are already occurring as evidenced by massive coral bleaching events (including a three-year global-level bleaching event from 2015–2017) and the increase in these events. Such changes in bleaching events are due to rising sea surface temperatures. There is *high confidence* that there have been changes in ocean pH and *medium confidence* on the ecological effects. Due to the lack of studies on the social consequences of climate change and associated losses of resources such as fisheries, there is *medium confidence* that effects on coastal and marine resources resulting from climate change will affect island economies. These effects can be a result of changes in availability and condition of fishery resources, loss of reefs and other coral communities that serve as coastal barriers, and effects on tourism due to loss of the resources that are primary attractions for visitors.

There is *medium confidence* in the ecological effects that will result due to changes in ocean pH. The CO_2 system of seawater is well understood and established. As such, the understanding of the basic equilibria governing the process of ocean acidification dates back to at least 1960[168] and represents a foundational understanding of modern chemical oceanography. The ecological consequences of human-induced changes to the system (that is, ocean acidification) is, however, a considerably new field. Both themes were assessed considering recent findings and based on adequate observed local data (for example, atmospheric pCO_2 [carbon dioxide partial pressure] values are based on measurements of weekly air samples from St. Croix, the USVI, the United States, and Ragged Point, Barbados), complemented with empirical models. Projected changes in climate for the Caribbean islands were based on the future projections of fossil fuel emissions driven by reasonable models from the Intergovernmental Panel on Climate Change (IPCC).[169] Additional empirical species response data would be useful for increasing the understanding of expected effects of ocean acidification on species and habitats in the Caribbean.

Key Message 3

Coastal Systems

Coasts are a central feature of Caribbean island communities. Coastal zones dominate island economies and are home to critical infrastructure, public and private property, cultural heritage, and natural ecological systems. Sea level rise, combined with stronger wave action and higher storm surges, will worsen coastal flooding and increase coastal erosion (*very likely, very high confidence*), likely leading to diminished beach area (*likely, high confidence*), loss of storm surge barriers (*likely, high confidence*), decreased tourism (*likely, medium confidence*), and negative effects on livelihoods and well-being (*likely, medium confidence*). Adaptive planning and nature-based strategies, combined with active community participation and traditional knowledge, are beginning to be deployed to reduce the risks of a changing climate.

Description of evidence base

The Key Message and subsequent narrative text are based on the best available information for the U.S. Caribbean. There are not many studies on or projections for sea level rise for the U.S. Caribbean. Therefore, evidence of sea level rise used for this report comes from the U.S. Army Corps of Engineers' (USACE) Sea Level Change Curve Calculator.[95] To calculate the Intermediate and High scenarios, the USACE uses modified National Research Council (NRC) curves, the most recent IPCC projections, and modified NRC projections with local rate of vertical land movement.[95] The four NOAA estimates integrate data ranging from tide gauge records for the lowest scenario to projected ocean warming from the IPCC's global sea level rise projections combined with the maximum projection for glacier and ice sheet loss for 2100 for the highest scenario. The sea level rise analysis mainly focuses on data from two tide gauges chosen to be representative of the region, one in San Juan, Puerto Rico, and the other in Charlotte Amalie, USVI. There are two others in the region that provide sea level trend data located in Magueyes, Puerto Rico, and Lime Tree Bay, USVI.

Additional evidence that sea level is rising is well documented in Chapter 9: Oceans and in the *Climate Science Special Report*. There are also numerous empirical examples of sea level rise and its effects in Puerto Rico and the USVI, where beaches have been reduced by erosion, roads have been lost, and access to schools has been affected.

Major uncertainties

Sea level rise is already occurring. However, the uncertainty lies in how much of an increase will take place in the future and how coastal social and ecological systems will respond. There are various models and projections to estimate this number, but it is influenced by many unknown factors, such as the amount of future greenhouse gas emissions and how quickly glaciers and ice sheets melt. Another major uncertainty lies in humans' abilities to combat or adapt to these changes. The scale at which people and cities will be affected depends on the actions taken to reduce risk. Lastly, the experience of sea level rise on each coast and community is different, depending on land subsidence or accretion, land use, and erosion; thus, the severity of effects might differ based on these factors.

Due to the levels of uncertainty surrounding the projections, we focused much attention on the highest scenarios, as fewer consequences exist for planning in terms of the higher scenario (RCP8.5).

Description of confidence and likelihood

Sea levels have already risen and will likely continue to rise in the future. Based on current levels of greenhouse gas emissions, glacial melt, and ice sheet loss, there is *high confidence and likelihood* in these sea level rise projections.

Key Message 4

Rising Temperatures

Natural and social systems adapt to the temperatures under which they evolve and operate. Changes to average and extreme temperatures have direct and indirect effects on organisms and strong interactions with hydrological cycles, resulting in a variety of impacts. Continued increases in average temperatures will likely lead to decreases in agricultural productivity, changes in habitats and wildlife distributions, and risks to human health, especially in vulnerable populations. As maximum and minimum temperatures increase, there are likely to be fewer cool nights and more frequent hot days, which will likely affect the quality of life in the U.S. Caribbean. (*High Confidence*)

Description of evidence base

In warm tropical areas like Puerto Rico and the USVI, higher summertime temperatures mean more energy is needed to cool buildings and homes, increasing the demand for energy. Heat episodes are becoming more common worldwide, including in tropical regions like the U.S. Caribbean. Higher frequency, duration, and intensity of heat episodes are triggering serious public health issues in San Juan. Heat poses a greater threat to health and well-being in high-density urban areas. Land use and land cover have affected local climate directly and indirectly, facilitating the urban heat island (UHI) effect, with potential effects on heat-related morbidity and mortality among urban populations.

Major uncertainties

Warming is evident. A remaining scientific question is how ecological and social systems that have established themselves in a particular location can adapt to higher average temperatures.[170] Islands such as Puerto Rico are particularly vulnerable because of heat events associated with changes in both terrestrial and marine conditions. Although there is evidence suggesting that mortality relative to risk increases in San Juan due to extreme heat,[12] this association is not completely understood on tropical islands like Puerto Rico and the USVI. Addressing such hazards can benefit from new strategies that seek to determine linkages between human health, rapid and synoptic environmental monitoring, and the research that helps improve the forecast of hazardous conditions for particular human population segments or for other organisms.

Description of confidence and likelihood

There is *high confidence* that increasing temperatures threaten the health and well-being of people living in the U.S. Caribbean, especially in high-density urban areas where the UHI effect places further stress on city populations.

Key Message 5

Disaster Risk Response to Extreme Events

Extreme events pose significant risks to life, property, and economy in the Caribbean, and some extreme events, such as flooding and droughts, are projected to increase in frequency and intensity (*flooding as likely as not, medium confidence; droughts very likely, medium confidence*). Increasing hurricane intensity and associated rainfall rates (*likely, medium confidence*) will likely affect human health and well-being, economic development, conservation, and agricultural productivity. Increased resilience will depend on collaboration and integrated planning, preparation, and responses across the region (*high confidence*).

Description of evidence base

On both Puerto Rico and the USVI, disaster events have caused billions of dollars in property and crop damages.[171] Over the years, disaster-induced casualties have declined in both territories. Tropical cyclones, particularly hurricanes, continue to generate the most severe economic damage across the U.S. Caribbean. Floods and droughts are challenging to manage for both territories, and these challenges may be exacerbated by climate change induced shifts in precipitation regimes.

Climate modeling for tropical cyclone activity in the Atlantic Basin, including the Caribbean region, points toward an increase in the frequency of more intense hurricanes.[135] An increase in days with more than 3 inches of rain per 24-hour period is projected for Puerto Rico, based on statistically downscaled CMIP3 climate models.[28] Changes in precipitation patterns are expected for Puerto Rico in the periods 2030–2050 and 2100, pointing toward an overall decrease in mean precipitation for different climate change scenarios.[7,28,30,34]

While continental droughts typically affect vast regions, droughts affecting Puerto Rico and the USVI tend to vary significantly in extent and severity over smaller distances.[132] Statistically downscaled climate projections for Puerto Rico suggest an increase of drought intensity (measured as the total annual dry days) and extremes (measured as the annual maximum number of consecutive dry days) due to an increase in mean and extreme temperatures and a decrease in precipitation.[7]

An increase in mean atmospheric temperature has been observed across the U.S. Caribbean islands, particularly on Puerto Rico. An analysis of the observed temperatures across several NOAA weather stations in Puerto Rico showed rising temperature trends between 1970 and 2016.[172] Following the principles established by the international Expert Team on Climate Change Detection and Indices,[173] temperature extremes and trends were identified, indicating significant increases in rising annual temperatures and an increase in extreme heat episodes.

Major uncertainties

There are still uncertainties as to how these projected changes in tropical Atlantic cyclone activity will affect the frequency distribution of extreme precipitation events. While an increase in days with more than 3 inches of rain per 24-hour period has been projected based on statistically downscaled CMIP3 models,[28] more recent generations of GCMs do not show this increase in extreme rainfall events, and this adds uncertainty. Results from two dynamically downscaled climate models using the most recent generation of GCMs for the region do not show increases in the frequency of extreme events.[34]

At present, data pertaining to the costs and effects that are associated with extreme events and disasters are very limited and not readily accessible for government officials, disaster risk managers, or the general public. In the future, more accessible data could facilitate opportunities for more thorough analyses on the economic costs of extreme events for the U.S. Caribbean.

Description of confidence and likelihood

There is *high confidence* that increasing frequency of extreme events threatens life, property, and economy in the region, given that the U.S. Caribbean's vulnerable populations and fragile economies are continually exposed to climate extremes. There is *medium confidence* that the frequency and intensity of the most extreme hurricanes and droughts will likely increase. There is *high confidence* that extreme events will *likely* continue to affect human health and well-being, economic development and tourism, conservation, agriculture, and danger from flooding. There is *high confidence* that future recovery and cultural continuity will depend on significant and integrated resilience planning across the region, focusing on collaborative actions among stakeholders.

Key Message 6

Increasing Adaptive Capacity Through Regional Collaboration

Shared knowledge, collaborative research and monitoring, and sustainable institutional adaptive capacity can help support and speed up disaster recovery, reduce loss of life, enhance food security, and improve economic opportunity in the U.S. Caribbean. Increased regional cooperation and stronger partnerships in the Caribbean can expand the region's collective ability to achieve effective actions that build climate change resilience, reduce vulnerability to extreme events, and assist in recovery efforts (*very likely, high confidence*).

Description of evidence base

Cross-regional and international cooperation is a mechanism that will likely reduce climate vulnerability and risks in the U.S. Caribbean, because it builds capacity and leverages resources in a region that has low adaptive capacity, due in part to the high costs of mitigation and adaptation relative to gross domestic product.[1,17,145] There are several efforts among the islands focused on coordination, information exchange, and approaches for risk assessment and management in the Caribbean region.[142,143,144,145] There are emerging opportunities for improving these partnerships and capacity across the region.

Major uncertainties

There is high certainty that Caribbean island states are being affected by climate change, but the rate and degree of effects vary across countries due to the differences in environmental and socioeconomic conditions. Examples of regional cooperation efforts to share knowledge, conduct collaborative research, and develop joint projects have increased the adaptive capacity in the region; however, sustaining such efforts across the region remains a challenge. As efforts for regional coordination, cooperation, and information exchange evolve, evidence of the benefits of collaboration can be better assessed.

Description of confidence and likelihood

There is *high confidence* that climate change will *likely* result in serious water supply shortages and in increased risks for agriculture production, human health, wildlife, and the socioeconomic development of Puerto Rico, the USVI, and the wider Caribbean region. The effects of climate change in the Caribbean region are *likely* to increase threats to life and infrastructure from sea level rise and extreme events; reduce the availability of fresh water, particularly during the dry season; negatively affect coral reef ecosystems; and cause health problems due to high temperatures and an increase in diseases.

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