Working Group 1: Geophysical and Chemical Scientific Knowledge

Observed Trends and Future Projections

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1. INTRODUCTION

1.1 About Puerto Rico

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

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

Climate has played a key role in shaping Puerto Rico, a small and varied island with 3,435 square miles, The main island accounts for 99 percent of Puerto Rico's area; the interior of the main island is mountainous with a peak elevation at Cerro Punta of 1,338 meters (4,390 feet) above mean sea level. Vieques and Culebra islands to the east are populated year-round, while Mona, Monito and Desecheo to the west, and Caja de Muertos to the South are natural reserves. The tropical climate ensures year-round warm temperatures, with an island-wide mean annual temperature near 25^{o}C (77^{o}F). Temperatures do vary however, between the warmer coast and inland mountains, with average annual temperatures between 26 and 27^{o}C (78 ^{o}F and 80.6 ^{o}F) in San Juan and the other lowland areas as opposed to the mean annual temperatures in the mountainous interior that are below 20°C (68 ^{o}F). Precipitation also varies across the island based on interactions between the island's topography, urban population, and vegetation cover, and the dominant easterly trade winds. These interactions lead to high spatial variability in annual precipitation across the island. Total annual precipitation ranges from over 4000 mm in the rainforest of El Yunque to 800 mm in the dry forests of Guánica.

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

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

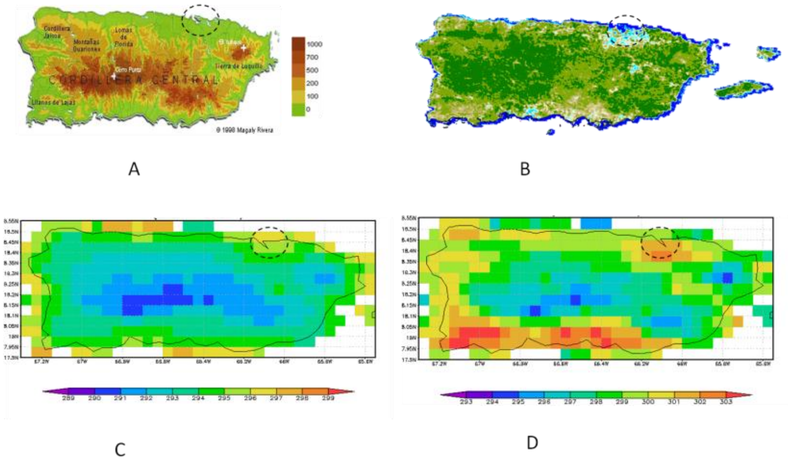


Figure 2 (A) Elevation map of Puerto Rico, and (B)Satellite vegetation land cover with areas of substantial urbanization in light blue; (C) Mean night (left) and (D) day-time (right) surface temperature at 5km resolution from infrared satellite over past decade. San Juan area is circled. Scales in degrees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

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

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

After hurricane Georges the National Weather Service reported enormous damage to Puerto Rico's utility infrastructure. Electricity was lost to 96% of the island 1.3 million customers, while water and sewer service was lost to 75% of the islands 1.83 million customers. It was estimated that at least 50% of the electrical poles and cables were damaged. Many roads were impassable by floods or destruction. A large number of road signs were twisted and destroyed, while electric post and cables were strewn on the ground, along with trees and foliage. Damage to roads was estimated at $21, 995,975. Telephone service was affected as 8.4% of telephone customers lost their service.

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

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

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

1.2 Report Organization

The members of Working Group 1: Geophysical and Chemical Scientific Knowledge are all highly respected in their fields of physics, chemistry, oceanography, climatology, hydrology, geology, engineering and meteorology both locally and abroad. The reviewers of this report were local experts from Puerto Rico, from the continental United States, and from overseas such as other Caribbean islands and the United Kingdom. Through a number of small sub-working group meetings, large working groups meetings, full PRCCC meetings, and a conference in San Juan, *Climate Change in the Caribbean 2011: Puerto Rico and the U.S. Virgin Islands*, the members meet in-person to discuss the report compilation, data analyses, and peer-reviewed published studies. However, the majority of report writing and discussions occurred via email and dropbox research library correspondences. Additional correspondences occurred via the PRCCC listserv, the PR-CC-L. The Working Group 1 report is organized by geographic scale – in that we start by discussing the global climate changes we are seeing and expecting to see in the future and narrowing down in scale through the Caribbean climatology and trends and finally to Puerto Rico's observed trends and projected changes. The logic for this order was stressed by Working Group members in that when discussing large coupled atmospheric and oceanic phenomena it is important to look at Puerto Rico's climate conditions in the context of the greater Caribbean and North Atlantic regions. In the report, each of the climate parameters analyzed (air and sea surface temperature, precipitation, extreme events, storms and hurricanes, sea level rise, and ocean acidification) are described specific to Puerto Rico in terms of their historically observed trends and the projections based on multiple sources. The information compiled is from literature review using a variety of databases as well as through the networks of our PRCCC members and from efforts to reach out to other Caribbean scientists and experts. As such some relevant studies may not have been received. The Working Group members and the PRCCC as a whole recognize that the information contained in this report is the best available knowledge as of July 2012 and will need to be continuously edited and expanded over the years as new and improved information becomes available.

Important Note: Climate change projections are based on simulations by Dr. Mark Jury with University of Puerto Rico, international climate modeling groups that have submitted their data to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), as well as other impact assessments from the Caribbean that have been conducted after the IPCC AR4 in 2007. The expertise of climatologists, oceanographers, meteorologists, biogeochemists, and physicists have further informed and refined the historic trends and climate projections summarized in this report. Impact assessments for the Caribbean basin have been conducted by the United Nations Development Program (UNDP), the Caribbean Community Climate Change Center (5C's), and in the peer-reviewed independent literature, as well as by the U.S. Global Climate Research Program's 2009 report, *Global Climate Change Impacts in the United States* (Karl et al. 2009) – which is the first official U.S. climate assessment to include Puerto Rico and other small island states.

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

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

2. CHANGES IN GLOBAL CLIMATE

2.1 Climate is Always Changing

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

2.2 The World is Warming

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

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

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

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

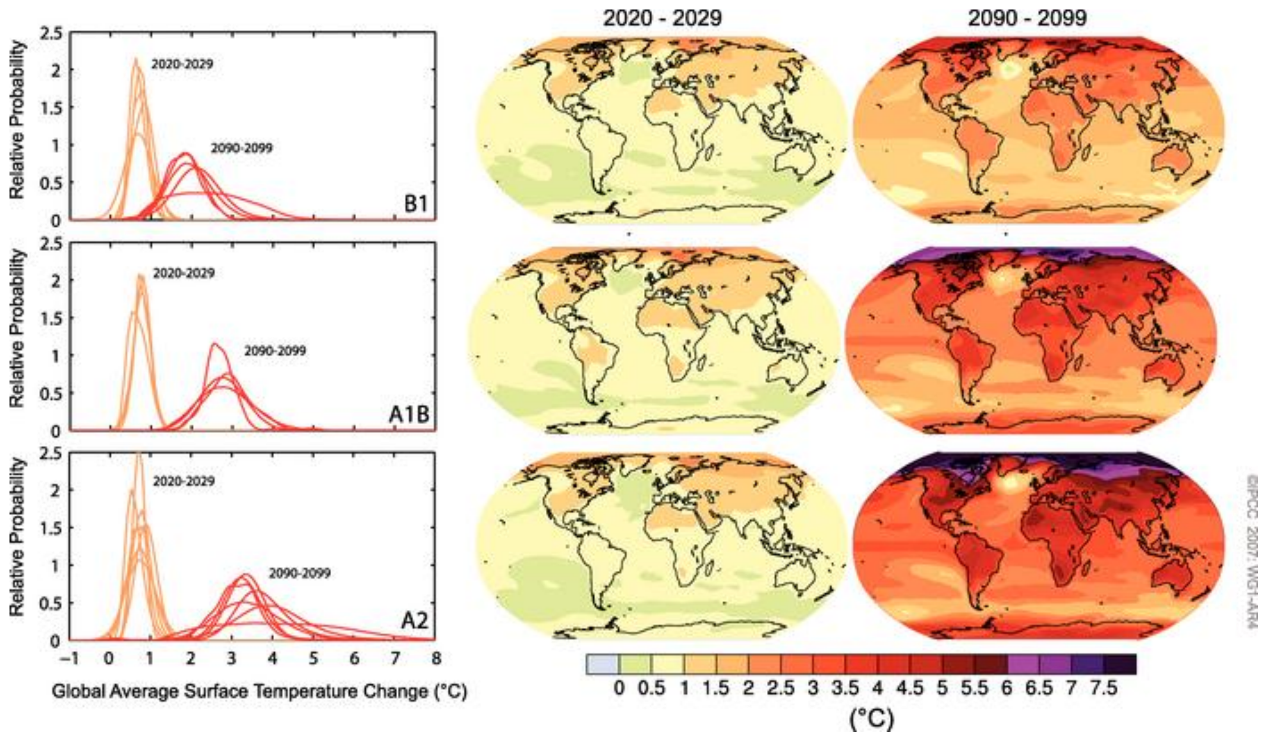


Figure 3 Projected surface temperature changes for the early and late 21st century relative to the period 1980–1999. The central and right panels show the AOGCM multi-model average projections for the B1 (top), A1B (middle) and A2 (bottom) SRES scenarios averaged over the decades 2020– 2029 (centre)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

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

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

3. CHANGES IN CARIBBEAN CLIMATE

3.1 Caribbean Climatology

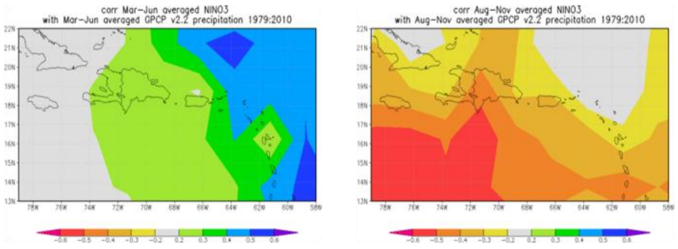
The climate of the Caribbean is characterized as sub-tropical with relatively dry winters and wet summers (Taylor and Alfaro 2005). The dominant large-scale atmospheric influence on the climate is the North Atlantic subtropical high (NAH). Island orography and elevation are significant modifiers of the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

3.2 Precipitation Variability in the Caribbean

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

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

Additionally, as shown in figure 4, there is spatial variability across the Caribbean in response to the ENSO phase. The warm phase of ENSO, or El Niño, tends to increase rainfall in the eastern Caribbean in early summer, while it reduces rainfall in the western Caribbean in late summer. The effect on winter rains is minor except near Florida. (Enfield and Alfaro 1999) showed that opposing SST anomalies in the tropical Atlantic further enhance the ENSO influence on Caribbean rainfall. Tropical cyclone activity diminishes over the Caribbean during El Niño summers due to upper westerly wind shear over the central Atlantic (Gray 1984).



A B

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

The effect of ENSO on the climate of the Caribbean is also influenced by another important mode of climatic variability, the North Atlantic Oscillation (NAO). The NAO is characterized by opposing variations of barometric pressure between Iceland and the Azores. These oscillations in turn can modulate the influence of ENSO (Giannini et al. 2001). A positive NAO phase implies a stronger than normal North Atlantic High which amplifies the drying during a warm ENSO. On the other hand, a negative NAO phase amplifies the precipitation in early summer following an El Niño.

3.3 Recent Climatic Trends in the Caribbean

According to the 2001 National Climate Assessment, average annual air temperatures in the Caribbean islands increased by more than 0.6°C or 1.0°F over the 21st century ((USGCRP) 2001). Similarly, IPCC AR4 found that, for the Caribbean islands, average annual temperatures have increased by more than 0.5°C over the period 1900-1995; the seasonal data are consistent with this overall trend. Observed trends in precipitation in the Caribbean are less clear. Whilst Neelin et al. (2006) identified a small but statistically significant drying trend during the months of June, July, and August (JJA) in recent decades, Peterson et al. (2002) found no statistically significant trends in mean precipitation (Neelin et al. 2006b). However, recent changes in the Caribbean climate were examined using the Climate Explorer statistical analysis tool and in addition have been previously analyzed for the ocean environment in (Jury 2011) (figure 5). NEED TO TALK ABOUT WHAT THE RESULTS OF THESE TWO ANALYSES SHOWED. ARE THESE RESULTS BASED ONLY ON JURY 2011. OR BOTH? OR SOMETHING ELSE? The linear trend analysis shows more warming (figure 5a) and drying in the eastern Caribbean (figure 5b), according to NCEP reanalysis data that include station, ship and satellite data interpolated by a weather forecast model. For Puerto Rico, the NCEP reanlaysis indicates a positive trend of 0.01°C yr^{-1} for surface air temperature and a negative trend of -0.02 mm $day^{-1}yr^{-1}$ for precipitation since 1948. Both trends are significant above the 95% confidence level. Trends in different seasons are similar.

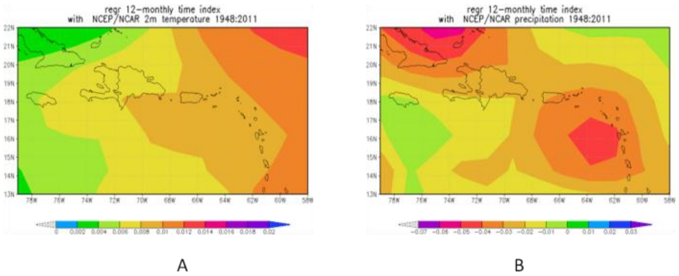


Figure 5 Linear trends in surface air temperature (A, °C/yr) and rainfall (B,mm/day/yr) from NCEP reanalysis. Note rain scale is reversed.

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

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

Donnelly and Woodruff's (2007) proxy reconstruction of the past 5,000 years of intense hurricane activity in the western North Atlantic suggests that hurricane variability has been strongly modulated by El Niño during this time, and that the past 250 years has been relatively active in the context of the past 5,000 years (Donnelly and Woodruff 2007). Nyberg et al. (2007) suggest that major hurricane activity in the Atlantic was anomalously low in the 1970s and 1980s relative to the past 270 years. As with Donnelly and Woodruff, their proxy measures were located in the western part of the basin (near Puerto Rico), and in their study, hurricane activity was inferred indirectly through statistical associations with proxies for vertical wind shear and SSTs. According to the U.S. Global Change Research Program, Atlantic tropical storm and hurricane destructive potential as measured by the Power Dissipation Index (which combines storm intensity, duration, and frequency) has increased. This increase is substantial since about 1970, and is likely substantial since the 1950s and 60s, in association with warming Atlantic sea surface temperatures. There have been fluctuations in the number of tropical storms and hurricanes from decade to decade and data uncertainty is larger in the early part of the record compared to the satellite era beginning in 1965. Even taking these factors into account, it is likely that the annual number of tropical storms, hurricanes and major hurricanes in the North Atlantic have increased over the past 100 years, a time in which Atlantic sea surface temperatures also increased. The evidence is not compelling for significant trends beginning in the late 1800s as uncertainty in the data increases as one proceeds back in time. There is also evidence for an increase in extreme wave height characteristics over the past couple of decades, associated with more frequent and more intense hurricanes (USGCRP 2008).

What is difference between global warming and climate change?

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

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

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

Where can I find more information?

United States Global Change Research Program
www.globalchange.gov

NOAA National Climatic Data Center site on Global Warming:
www.ncdc.noaa.gov/oa/climate/globalwarming.html

NASA GISS recent research website:
www.giss.nasa.gov/research

Global Change Master Directory
gcmd.gsfc.nasa.gov/Resources/pointers/glob_warm.html

3.4 Future Caribbean Climate

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

According to the IPCC AR4, over the coming century projected temperature increases for the Caribbean are projected to be slightly below the global average of 2.5 - 4°C (4.5 – 7.2°F) by 2100 (IPCC 2007), but slightly above the tropical average. Also, most IPCC AR4 models projected decreases in annual precipitation and a few increases, varying from -39 to + 11%, with a median of -12%. The annual mean decrease is projected by the IPCC AR4 to be spread across the entire region. December, January, February in the Greater Antilles is expected to see increased precipitation and June, July, Ausust to see a region-wide decrease (IPCC 2007). A number of research groups in Puerto Rico, the Caribbean, and elsewhere have begun to study future climate scenarios to identify possible impacts on the region. Such studies help define the range of possible future change and illuminate ways in which these changes will impact human and natural systems. This report section summarizes the results of a literature review performed from September 2010 to June 2012 by Working Group 1 of published and unpublished studies to compile currently available information on climate change and impacts for the Caribbean, the Greater Antilles, and Puerto Rico.

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

3.5 Previous Modeling Efforts for the Caribbean

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

In 2003 the Caribbean Modelling Initiative used a regional, simplified climate model, PRECIS (Providing Regional Climates for Impact Studies), to evaluate possible future regional climatic changes in the Caribbean (Campbell et al. 2010a). PRECIS is a dynamical downscaling model driven by the HADAM3P GCM and ECHAM GCMs but can be forced at its boundaries by other GCMs. It has a resolution of up to 25km and can be used for any part of the Globe. Using IPCC SRES Scenarios A2 (high emissions) and B2 (low emissions) they simulated historic conditions (i.e., 1970-present) and future (i.e., end of century) conditions and reported absolute or percent change between the present and future. They found that irrespective of scenario the Caribbean was expected to warm (warming between 1°C and 5°C; 1.8°F and 9 °F) with greater warming under A2 (high emissions) scenario. The warming was consistent with projections for other parts of the globe and far exceeds natural variability (fig 6).

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

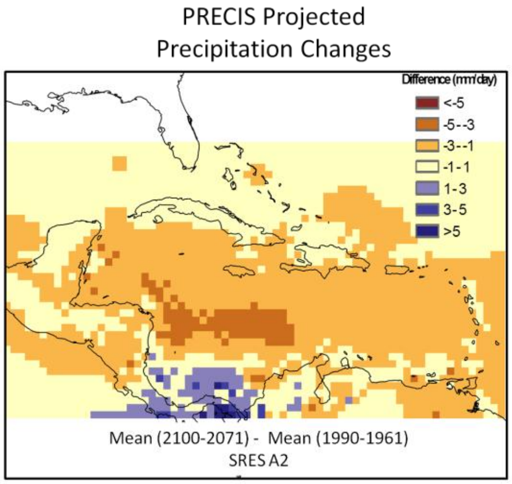


Figure 7: PRECIS Projected Precipitation Changes for SRES A2

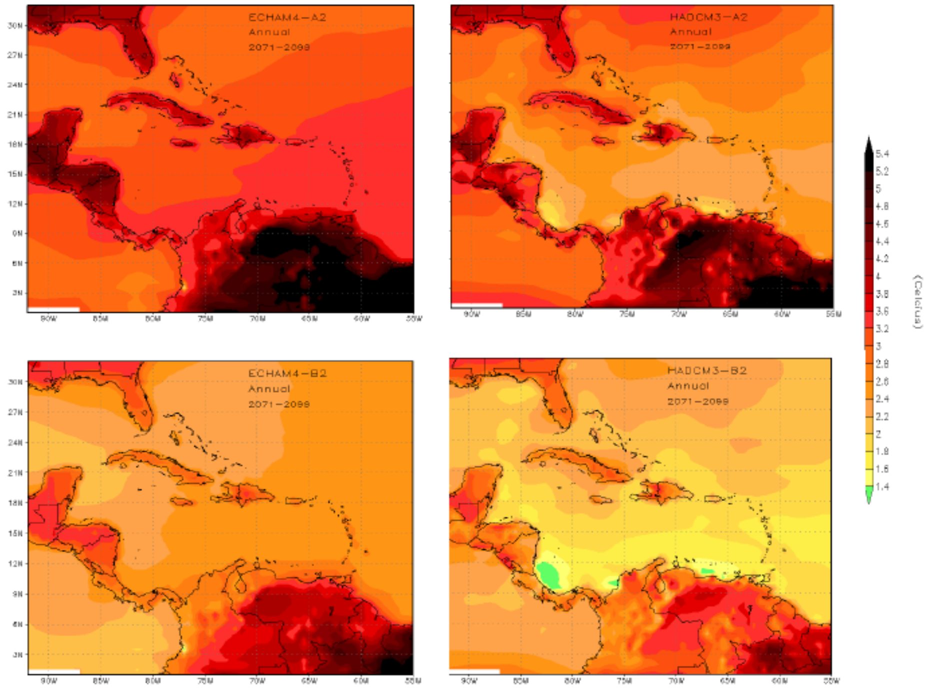


Figure 6 Mona Climate Studies Group found that irrespective of scenario the Caribbean was expected to warm (warming between 1°C and 5°C) with greater warming under A2 (high emissions) scenario. The warming was consistent with projections for other parts of the globe and far exceeds natural variability.

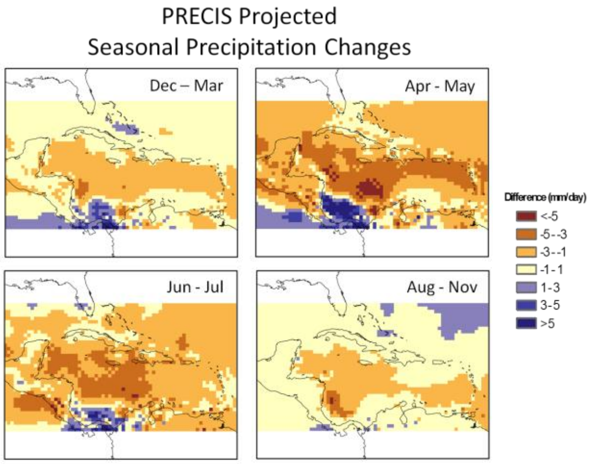


Figure 8: PRECIS projected seasonal precipitation changes for the Caribbean

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

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

3.5.3 University of Oxford and United Nations Development Program (2009)

Simpson et al. (2009) used 14 GCMs to create climate projections for 3 emissions scenarios (A1B, A2, and B1) for the 15 CARICOM countries of the Caribbean. Under these scenarios, the results indicate average air temperatures will rise in the future in all seasons. Typical projected temperature increases in CARICOM countries are consistent with global trends (i.e. the Caribbean region largely tracks projected global temperature changes). However, the temperature increase is less in coastal regions and islands with greater warming over landmasses. This is related to the thermal inertia of the ocean and the greater internal heat capacity of water compared to land. All countries warm by at least 0.7°C (1.26 ^{o}F) by the time global temperatures have increased 2.0 ^{o}C (3.6 ^{o}F) above historic conditions (figure 9). According to these projections, there is little uncertainty that the trend of temperature is upwards, the main uncertainties are in the timing and extent.

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

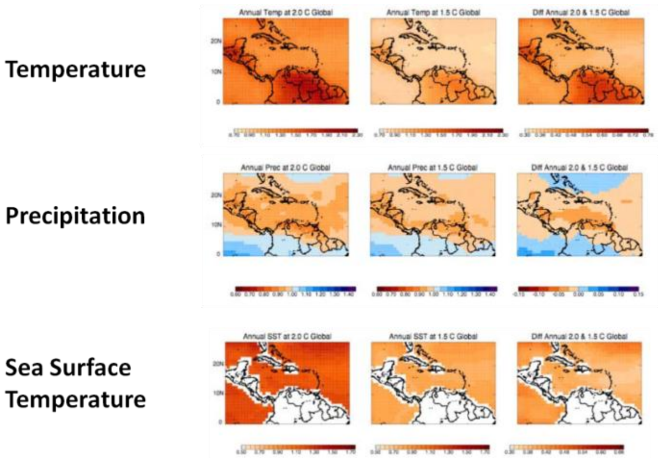


Figure 9: Changes in regional average annual temperatures (top), precipitation (middle), and sea surface temperatures (bottom) compared to present day values at thresholds of 2.0°C and 1.5°C and differences between the two; note different scales. Precipitation projections show fractional changes in total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

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

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

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

3.5.5 Caribbean Community Climate Change Center (2010)

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

3.5.6 Puerto Rico Climate Change Council (2011)

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

Overall the higher emissions scenario projects more warming and less precipitation for the region. The average warming for the Antilles is 2.8^{o}C (5.04 ^{o}F) for the A2 scenario versus 1.7^{o}C (3.06 ^{o}F) for the B1 emissions stabilization scenario. The median precipitation projection indicates drying for most of the region with the exception of some areas in the southern Caribbean near the Panamanian Isthmus. The mean change for the median projection for the A2 scenario is a decrease of 15.8% compared to the 1961-1990 average precipitation and the mean change for the B1 scenario is a decrease of 8.5%.

Given the uncertainty in precipitation projections, the results shown in Figure 12 are noteworthy in that the 80th percentile projection (that is, leaving out the 20% of model results that showed the greatest future drying) shows a consensus amongst the models for drying in the Caribbean by the end of the century (for the high emissions scenario). Baisutti et al. (2012) show similar results using a slightly lower emission scenario (A1b). They tie the regional drying to the broader dynamical response of the tropical circulation to greater relative increases in SST in the tropical Pacific and Atlantic compared to the sub-tropical Caribbean (figure 13).

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

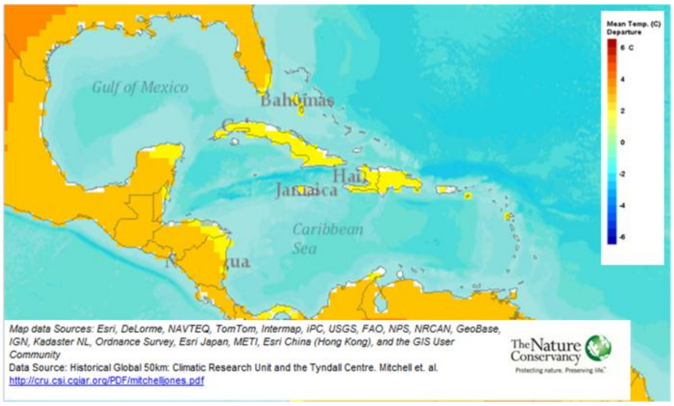


Figure 10 ClimateWizard visualization of ensemble median output for average projected temperature change from 2070-2099 compared to 1961 – 1990. Ensemble projection is for the IPCC A2 SRES Emission Scenario.

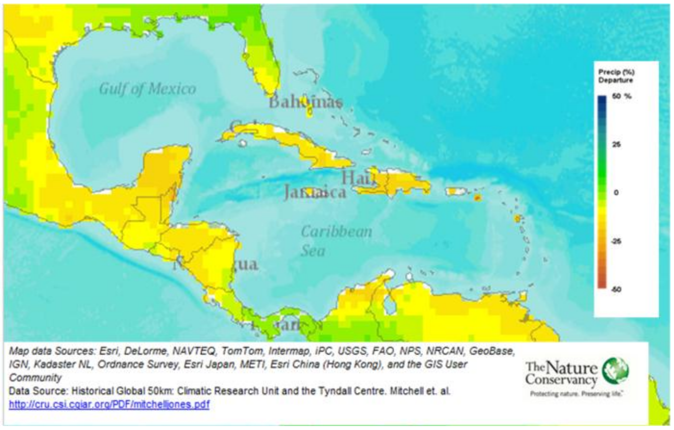


Figure 11 Same as Figure 10 except shows the median projection for percent departure from mean annual precipitation from 1961-1990.

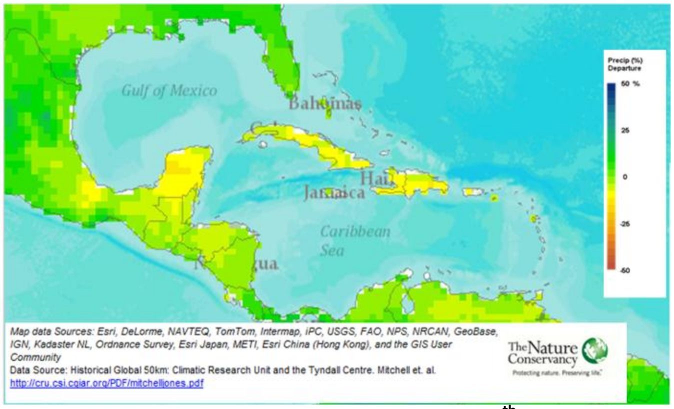


Figure 12 Same as Figure 11 except shows the 80th percentile projection for percent departure from mean annual precipitation from 1961-1990.

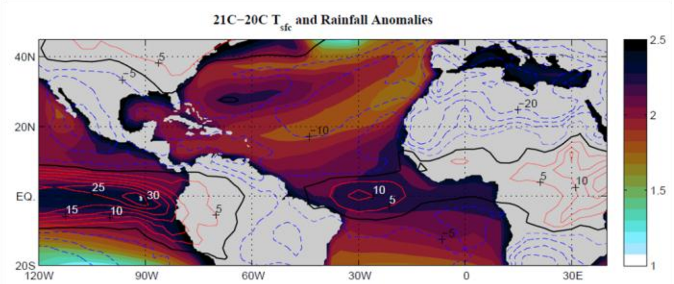


Figure 13 Ensemble mean temperature (shaded colors) and precipitation (colored contours) differences between the periods 2075-2099 and 1975-1999 for the A1b emissions scenario. Temperature changes are shown in degrees Celsius and precipitation changes are given in percent change from 20th century values.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

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

Table 1 Summary of six Caribbean modeling studies for climate change projections described in the text, including the PRCCC.

3.6 Knowledge Gaps and Future Research Needs for Caribbean Climate Change Studies

All previous studies have recommended a more detailed analysis of projections, together with research to downscale the information from the global models. Doing so would provide improved spatial detail and develop more specific information regarding the uncertainties associated with certain parameters, such as rainfall. Future research should also examine changes in the most intense climate events, such as those that produce heavy rainfall. Additional and updated dynamical downscaling studies could improve understanding of the local and regional processes that drive precipitation events. Larger ensemble experiments such as perturbed physics experiments using single GCMs or simplified climate models could improve efforts to quantify uncertainty (and perhaps reduce uncertainties) in key physical parameters (e.g. ENSO, SST). Statistical downscaling could also improve projections of well-simulated climate variables such as surface air temperatures and sea surface temperatures.

4. PUERTO RICO’S CLIMATE

This section discusses the observed climatology of the island and expands on the summary of climatic trends in Puerto Rico using information from (Bush 1995), Lugo et al. (2011), Mendez (2010), Jury et al. (2011), and the NOAA National Weather Service. The Jury analysis conducted for the PRCCC uses the NOAA GHCN station network over Puerto Rico (figure 14a) and the Mendez (2010) analysis is based on 36 precipitation stations and 16 temperature stations in Puerto Rico (figure 14b).

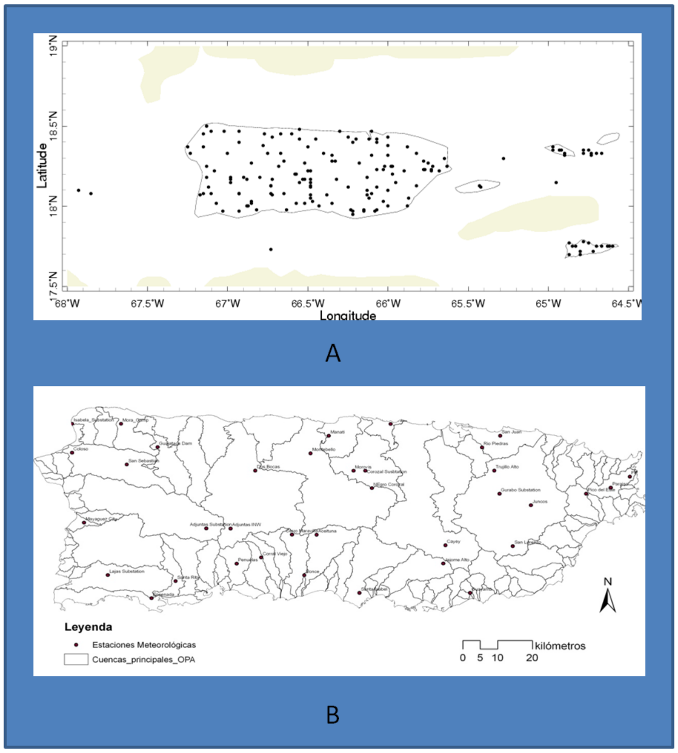


Figure 14: (a) NOAA GHCN station network over Puerto Rico and adjacent islands used in the PRCCC analysis; (b) Stations used in the Mendez (2010) analysis

Puerto Rico is part of the Antilles island chain that between the Atlantic Ocean and the Caribbean Sea. This chain extends in a southeasterly arc toward the island of Trinidad and South America. Puerto Rico lies within the northeast trade wind belt and experiences a sub-tropical maritime climate typical of Caribbean islands, with warm temperatures and high summer precipitation (Daly et al. 2003, López-Marrero and Villanueva Colón 2006). Mendez (2010) estimated an island-wide average temperature of 24.9ºC (76.8ºF) over the period 1948-2007 based on 16 stations. Variability for all stations was below 2.5%. The stations which have recorded the highest annual average temperature are Fajardo (26.2ºC; 79.2 ºF), San Juan (26.8ºC; 80.2ºF) and Gurabo Substation (26.7ºC; 80ºF). The coolest average annual temperatures are observed at high elevation stations (Pico del Este (18.6ºC; 65.5ºF), Adjuntas Substation (21.5ºC; 70.7ºF) and Cayey (22.9ºC;73.2ºF)) where local data indicates that temperature decreases approximately -0.6ºC (-1.1ºF) per 100m (328.1 ft) of elevation. The NOAA National Climatic Data Center has climatological normals and all time records across Puerto Rico and the U.S. Virgin Islands and shows that for a shorter time period (1981- 2010) than the Mendez (2010) analysis San Juan’s annual average high was 87.6º F (30.9º C), Fajardo’s was 87.2º F (30.7º C), and Gurabo’s was 87.7º F (30.9º C).

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

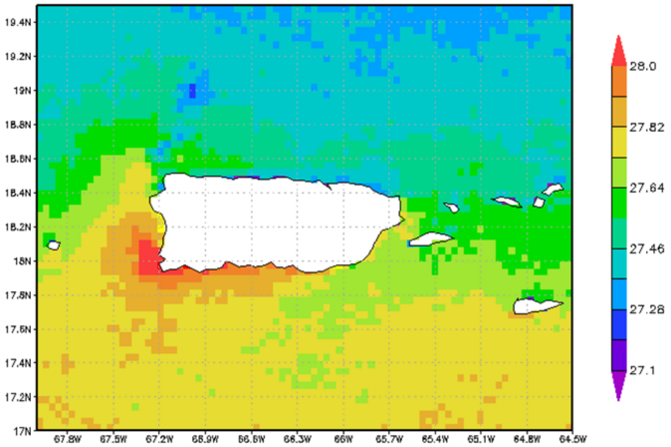


Figure 15 WHERES RIGHT? (left) Mean sea surface temperatures around Puerto Rico at 4 km resolution from NOAA

satellite in the past decade. (right) Mean 1-100 depth averaged currents from SODA ocean reanalysis.

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

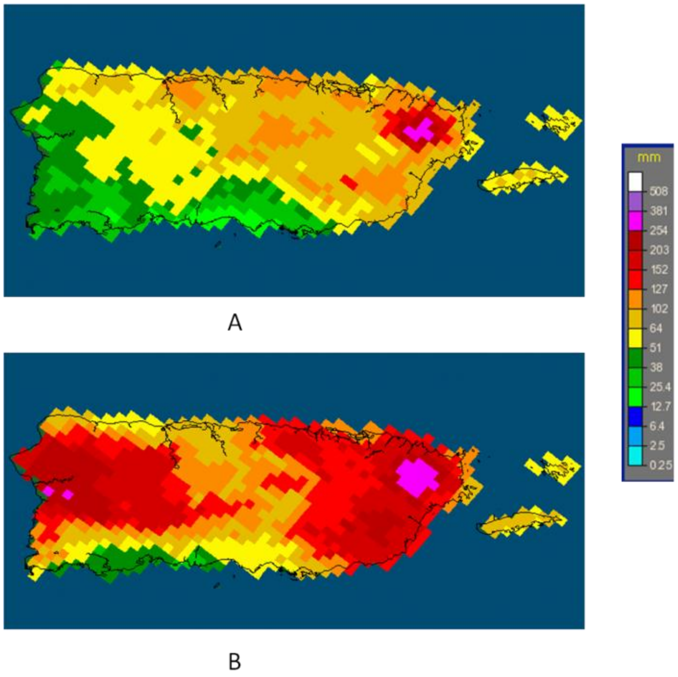


Figure 17: Mean monthly January (a) and July (b) rainfall at 1 km resolution from weather radar in the past decade.

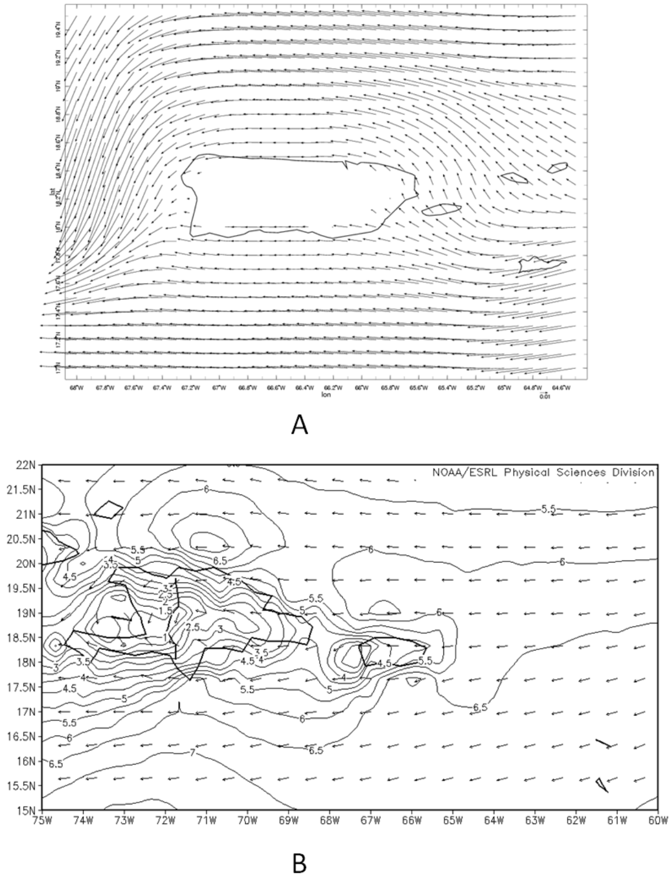


Figure 16: (A) prevailing winds around Puerto Rico; (B) 30-yr mean wind pattern from high resolution reanalysis model (NARR), with isotachs in m/s.

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

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

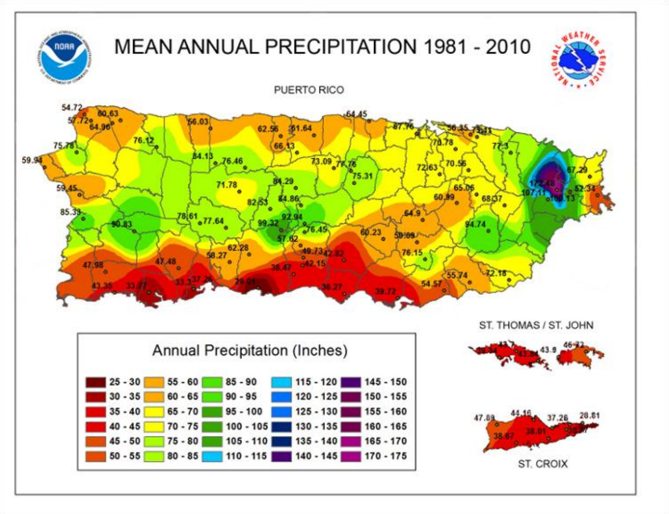


Figure 18: Mean Annual Precipitation from 1981-2010, courtesy of NOAA National Weather Service San Juan Office.

Although the total amount of precipitation varies considerably, the seasonal cycle of precipitation is similar across all regions of the island. Typically the dry season is from December to March, with February being the driest month (figure 19a). A seasonal maximum in precipitation occurs in the month of May (figure 19b) followed by decreasing amounts in June and July before rising, reaching a fall peak in the months of October and November (figure 19c). Trade wind showers in the dry season are present over the northeastern half of the island while the southern coast is generally drier (Figure 16a; January weather radar rainfall). Figure 20 shows the frequency of stations reporting each month as either the driest month or the wettest month (Mendez 2010).

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

The rainfall distribution is punctuated by hurricanes, tropical storms, and westerly troughs (Busch et al. 1995). In July-August fast moving African easterly waves and hurricanes pass near Puerto Rico, but in September-October these same systems slow down and cause localized flooding almost every year. Puerto Rico lies directly in the Caribbean hurricane belt. The hurricane season lasts from June through November, with a peak in August and September. Additionally, Puerto Rico is visited by a tropical depression (*onda tropical)* on the average of once every 2.5 years (Busch et al. 1995).

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

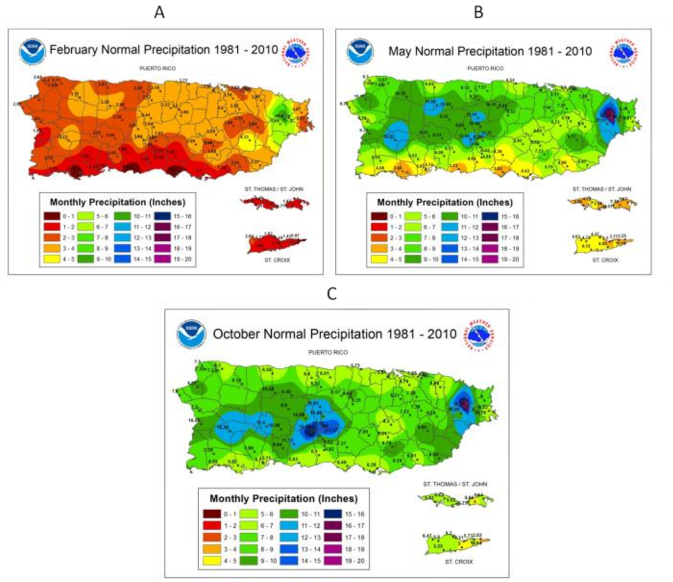


Figure 19: Normal Precipitation for 1981-2010 for months of (a) February, (b) May, and (c) October, courtesy of NOAA National Weather Service San Juan Office.

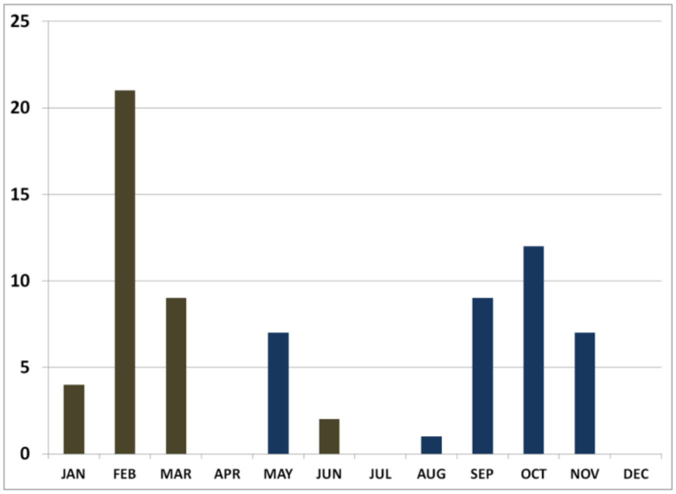


Figure 20: Frequency of stations (n=36) reporting each month as either the driest month (brown) and wettest month (blue). Based on analysis in Mendez (2010).

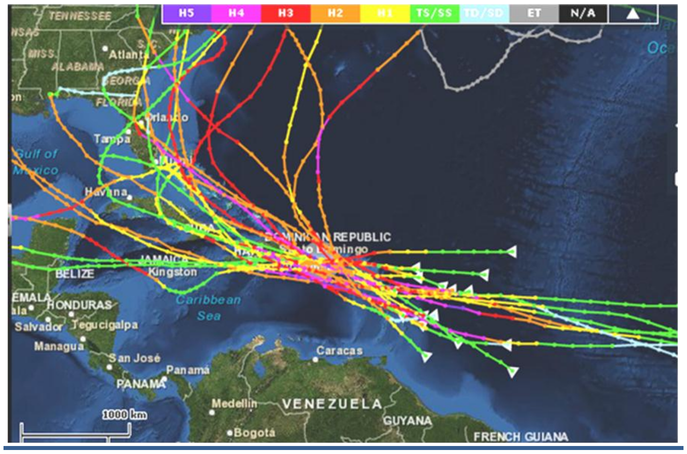


Figure 21: Tracks of all category 3,4,5 hurricanes passing within 100 nm of Puerto Rico in July-October season since 1860, based on NOAA hurdat data.

Analysis Methods from Dr. Mark Jury for the PRCCC

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

Table Description of Gridded Products

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

5. HISTORIC TRENDS AND CLIMATE PROJECTIONS BY PARAMETER

This section discusses the observed, historical trends and projected changes of the island for seven climate parameters (air temperature, precipitation, extreme events, sea surface temperature, sea level, and ocean acidity) and uses data from CariCOOS, NOAA, IPCC, and PRCCC partner analyses. The information is summarized in Tables 2,3, and 4. Climate trend information differs from the known climatology or “climate normals” of Puerto Rico that were previously described, in that climate trends can be used to detec climate changes. Climate normals were not designed to be metrics of climate change as they are long-term averages versus long-term changes. More simply, the climate trends described here in section 5 are the historic observations of how we may be departing from the known climate normals of Puerto Rico that were described in section 4 and what changes we are expecting to see in the near future (years 2050 to 2100).

5.1 Air Temperature

5.1.1 Observed Air Temperature Trends in Puerto Rico

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

Using gridded products (see box on previous page), Dr. Mark Jury mapped the linear trend of surface air temperature with two different datasets using the Climate Explorer statistical analysis tool. There is faster warming in the east in the longer dataset (1901 - 2009), and faster warming over the center of the island in the shorter dataset (1979 - 2009). Temperature trends are significant above 98% confidence level. Trends are similar in different seasons (figure 22). Climate Forecast System Reanalysis Temperature trends, figure 23, shows that the central (elevated) parts of Puerto Rico have a faster rate of warming than the coast. Air temperatures in the trade wind inversion (~850 hPa, 1500m) over Puerto Rico are rising faster than the global average. This is due to an accelerated Hadley circulation, with a trend of sinking motions over the Caribbean and rising motion over South America as indicated by the trend analysis of NCEP reanalysis data in Figure 24. The additional sinking motion causes heating by compression at the bottom of the layer, so the trade wind inversion has strengthened. The rate of warming in the 1-2 km layer is 3 x greater than surface air temperatures.

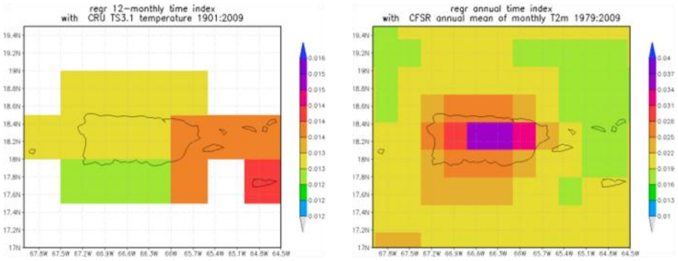


Figure 22: Linear trends in surface air temperature for CRU3 station interpolated observations (left, C/yr) and from CFS reanalysis (right C/yr).

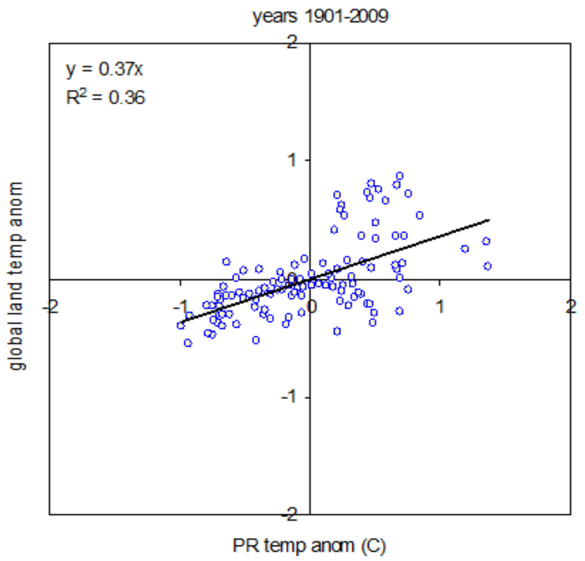


Figure 23: Climate Forecast System Reanalysis Temperature trends shows that the central (elevated) parts of Puerto Rico have a faster rate of warming than the coast

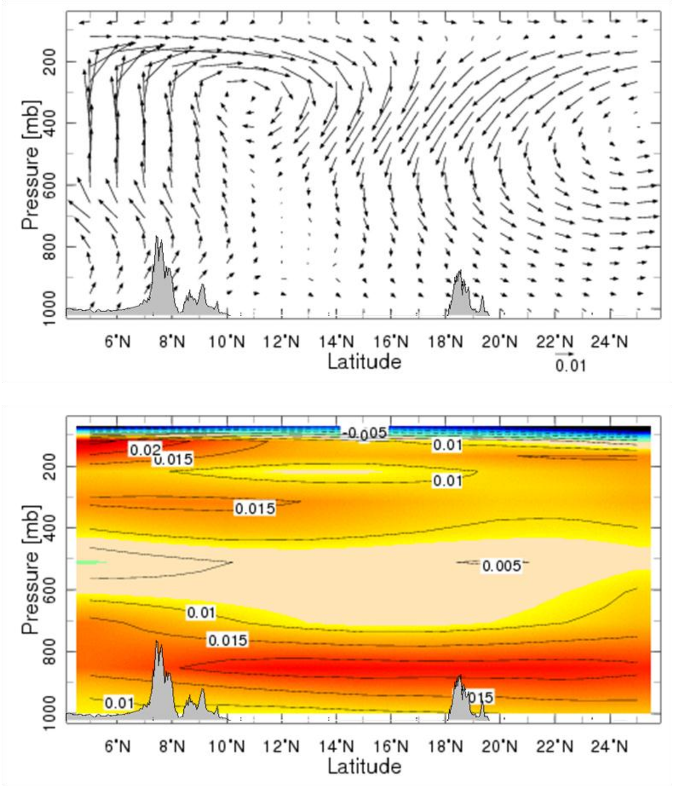


Figure 24: The analysis is of linear trends in the meridional atmospheric Hadley circulation (top, m/s /yr) and air temperature (C/yr), as N-S height sections across Puerto Rico from NCEP reanalysis 1948-2009. Adapted and updated from Jury and Winter (2009).

Both global and local changes can drive temperature trends. Historic temperature trends in Puerto Rico based on station data include large-scale influences of global climate change as well as land cover change as reflected in increasing daily minimum temperatures (Duchon 1986). In Puerto Rico, there is some indication that the enhanced coastal warming may be at least in part due to the urban heat island effect (Velazquez-Lozada et al. 2006; Gonzalez and Comarazamy 2009). Stations located in San Juan show that both maximum and minimum temperatures are on the rise in heavily urbanized areas where there is conversion of natural vegetation to urban dewellings (Gonzalez and Comarazamy 2009). Velazquez-Lozada et al. (2006) also found warming in the San Juan metropolitan area, with a trend of 0.06°C/yr from 1960-2000. Throughout the tropics, population movements, urban growth, and industrialization are causing conditions that result in elevated temperatures within urban areas when compared to that in surrounding rural areas, a phenomenon known as the urban heat island (UHI) (Murphy et al. 2010). Murphy et al. (2010) demonstrated that San Juan experiences greater temperature when compared to the surrounding forested and open, rural areas by as much as 4.7^{o}C (8.5^{o}F). Using projections of future development and temperatures theysuggest that if the present pattern of development continues, over 140 km^{2} of land that showed no signs of the urban heat island effect in 2000 will have an average annual temperature increase between +0.4 and +1.55^{o}C (+0.72 and 2.79^{o}F) by 2050. Furthermore, more than 130 km^{2} of land area with a current UHI between +0.4 and +1.4^{o}C (+0.7^{o}F and +3.5^{o}F) in 2000 will have an average UHI greater than +1.55 ^{o}C (+2.79^{o}F) by 2050 (Murphy et al. 2010).

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

5.1.2 Projected Changes in Temperatures

The CMIP5 coupled general circulation model projections that will be used in the next IPCC assessment report (AR5) are now available (Taylor et al. 2011b). These models have increased resolution and dynamic vegetation, compared with the earlier CMIP3 models used in the IPCC AR4 assessment, reported in the earlier section of this report. These models have been evaluated for the Caribbean and for Puerto Rico. While they perform reasonably well for many features of the observed climate, certain models better match the annual cycle of climate due to better representation of Antilles Island wind shadows which generate larger amplitude seasonal and diurnal cycling. Most of the CMIP5 models, like their predecessors, are biased towards a North Atlantic high pressure cell that is too strong - with trade wind evaporation causing below normal sea surface temperatures east of Puerto Rico. In this analysis of CMIP5 models, use is made of an all-model ensemble average based on the 'rcp6 forcing' scenario. This assumes an approximate doubling of CO_2 by the end of this century, consistent with the earlier CMIP3 A1B scenario, a 'middle of the road' projection.

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

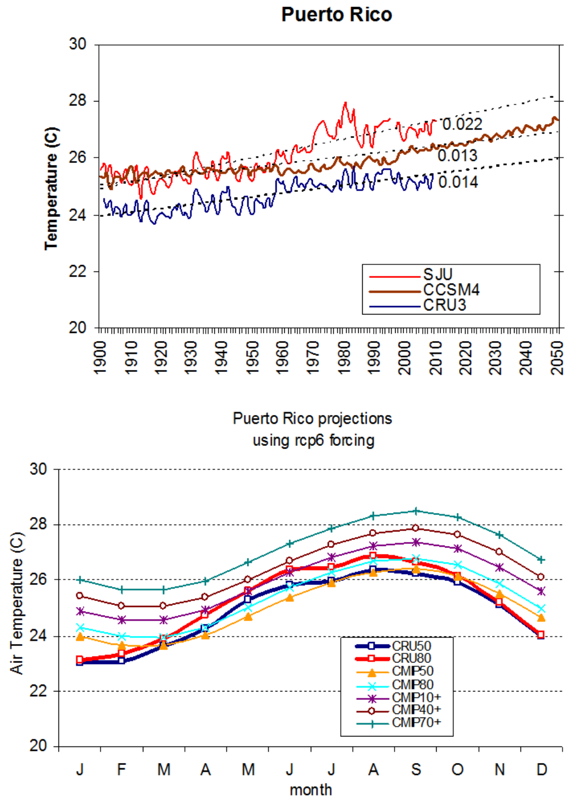


Figure 25: Comparison of surface air temperature from area-averaged observation product CRU3, San Juan station and CMIP5 coupled model CCSM4 projection with rcp6 scenario. Puerto Rico area is defined as 18-18.5N, 67-65W. Linear trends for area averages show a 0.012-0.014C/yr temperature increase. San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

Station Data and Limitations

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

5.1.3 Knowledge Gaps and Future Research Needs

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

5.1.4 Summary of Observed and Projected Temperatures for Puerto Rico

Over the 20th century, average annual air temperatures in the Caribbean islands have increased by more than 0.6°C or 1.0°F. In Puerto Rico, station analyses show significant increases in annual and monthly average temperatures and a rise of 0.012^{o}C/yr to 0.014^{o}C/yr (0.022 to 0.025^{o}F/yr) was observed from 1900 to present. Therefore, Puerto Rico does follow the larger-scale trend in warming, although some locations on the island are warming faster than others. Urban heat islands exist in Puerto Rico where temperatures are higher in developed areas than in rural, vegetated areas. For instance, San Juan's observed temperature trend is higher than the rest of the island at 0.022^{o}C/year (0.04^{o}F/year) since 1900. If this trend continues, San Juan's average annual temperature will have increased to 27°C (80.6^{o}F) in 2050 (as compared to 25.5°C or 77.9^{o}F in 1950). There is consensus on continued warming into the future amongst all modeling experiments. Over the coming century, projected temperature increases for the Caribbean are projected to be slightly below the global average of 2.5 - 4°C (4.5 – 7.2°F) by 2100, but slightly above the tropical average. Projected temperature increases are expected to be significant by late century at all locations. Projections for the Caribbean show a greater than >1.5°C rise in annual average temperature by 2100, with greatest warming over Cuba, Jamaica, Hispañiola, Central America and northern South America, where the increase is >2°C across all seasons. Projections for Puerto Rico show as little as 0.02^{o}C/year warming through 2050, in other words at least 0.8 ^{o}C (1.44^{o}F) by mid-century, and as much as 2-5^{o}C (3.6-9^{o}F) by the year 2100.

5.2 Precipitation

5.2.1 Observed Precipitation Trends in Puerto Rico

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

While no clear trend exists for the entire island, there is evidence for changes in the spatial distribution of rainfall. Although the analysis by Mendez (2010) found mixed trends in annual precipitation, there was an indication that the southern region of Puerto Rico, which is also the driest region, had positive trends in annual rainfall while the western and a portion of the northern region showed decreases (figure 26). Seasonal trends were also observed: a majority of stations (72.2%) showed negative trends in summer (June, July, August) precipitation and a majority of stations (72.9%) showed positive trends in winter (January, February, March). However, no temporal trends are observed for spring or autumn precipitation (Mendez 2010) (figure 27).

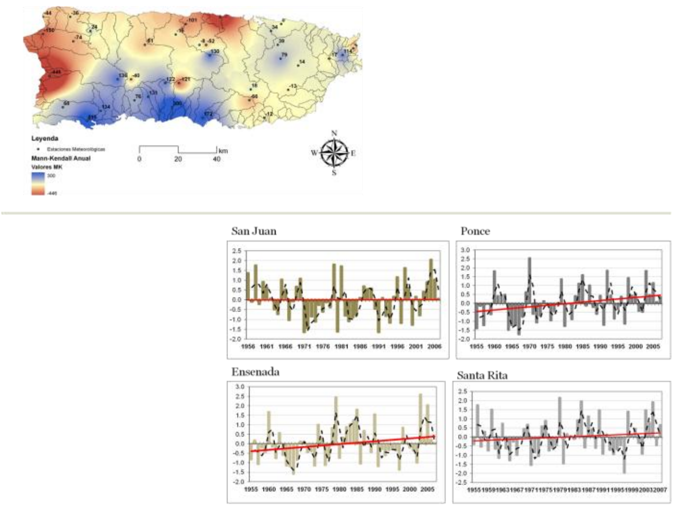


Figure 26: Precipitation trends for Puerto Rico (Mendez 2010)

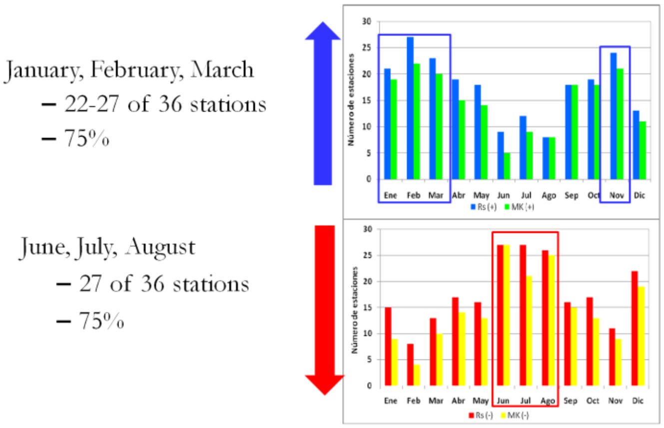
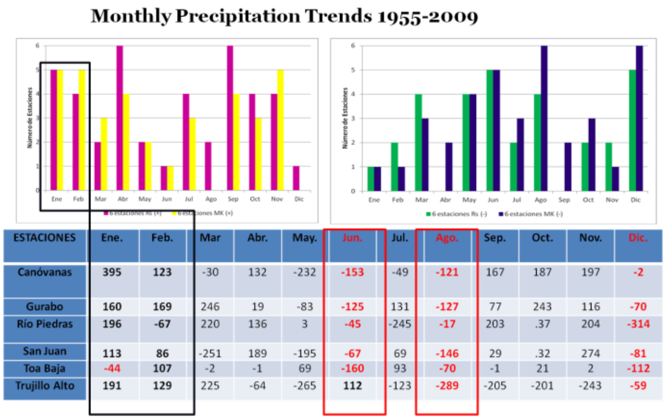


Figure 27: Data from rain gauges show that winter months (top) have experienced increasing rainfall while rainfall has been decreasing during the summer months (bottom).

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


Monthly Precipitation Trends 1955-2009

ESTACIONES	Ene.	Feb.	Mar	Abr.	May.	Jun.	Jul.	Ago.	Sep.	Oct.	Nov.	Dic.
Canóvanas	395	123	-30	132	-232	-153	-49	-121	167	187	197	-2
Gurabo	160	169	246	19	-83	-125	131	-127	77	243	116	-70
Río Piedras	196	-67	220	136	3	-45	-245	-17	203	.37	204	-314
San Juan	113	86	-251	189	-195	-67	69	-146	29	.32	274	-81
Toa Baja	-44	107	-2	-1	69	-160	93	-70	-1	21	2	-112
Trujillo Alto	191	129	225	-64	-265	112	-123	-289	-205	-201	-243	-59

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

Conversely, other datasets exhibit drying trends throughout the year. Linear trends in observed rainfall in the CRU3 observed and CFS reanalysis datasets were mapped per grid cell (figure 29) by Dr. Mark Jury for the PRCCC. Decreases of -0.01 mm/day/yr are noted in the longer CRU3 record while significantly faster drying trends are evident in the shorter CFS reanalysis (-0.1mm/day/yr). These decreases are found to be similar in all seasons, as opposed to the analysis by Mendez (2010) showing an increase in precipitation during winter months. Linear trends in river run-off from independent USGS records show a -1.27 mm/yr decline, though landuse change plays a large role in river run-off (figure 30).

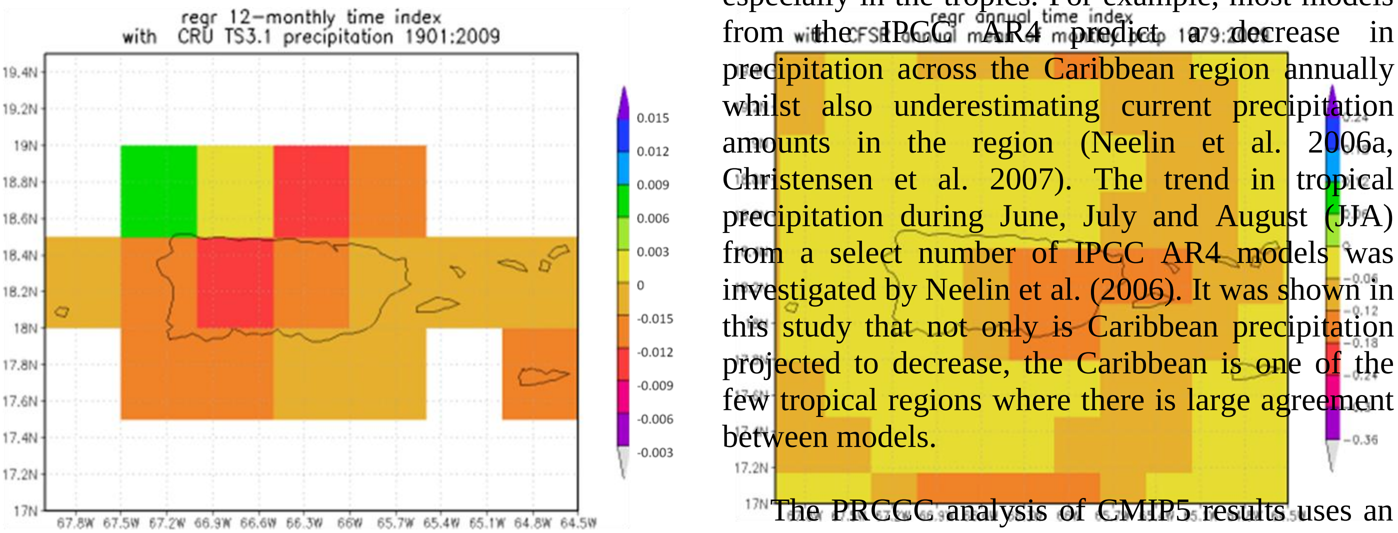


Figure 29: Linear trends in rainfall (mm/day/yr) in the CRU3 observations (left) and CFS reanalysis (right). There is a weak drying trend in both long and short records that exceeds 90% confidence. Note scale is inverted.

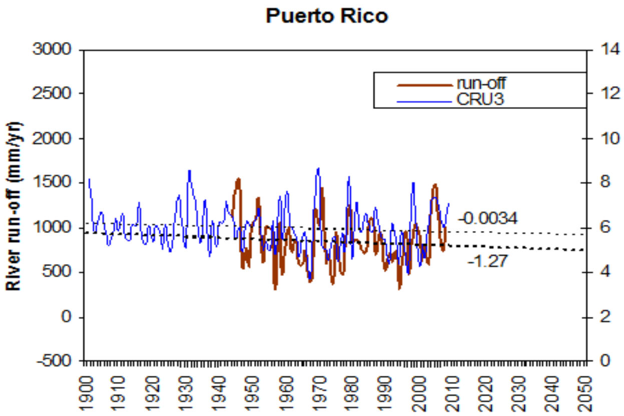


Figure 30: Comparison of annual river run-off from US Geological Survey observations and rainfall from area-averaged observation product CRU3.

5.2.2 Projected Precipitation Changes in Puerto Rico

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

The PRCCC analysis of CMIP5 results uses an all-model ensemble average based on the ‘rcp6 forcing’ scenario. This assumes an approximate doubling of CO_2 by the end of this century, consistent with the earlier CMIP3 A1B scenario, a ‘middle of the road’ projection. The annual cycle of precipitation from observations and two CMIP5 models is analyzed in the period 1980-2010 below (figure 31). In addition the observed trend of annual rainfall over the 20th century and in one CMIP5 model projection is studied. Past and future trends are similar, there is a decrease of rainfall of -0.0012 to -0.0032 mm/day /yr.

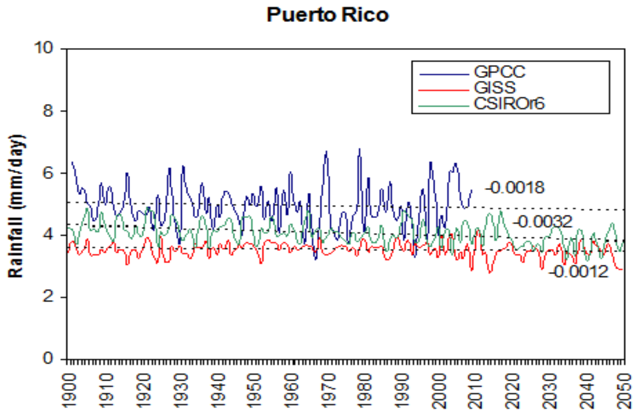


Figure 31: Comparison of annual rainfall from area-averaged observation product GPCC, and two CMIP5 coupled models: GISS and CSIRO with rcp6 scenario.

The CMIP5 coupled general circulation model projections that will be used in the next IPCC assessment (AR5) are now available (Taylor et al. 2011a). These models have increased resolution and dynamic vegetation, compared with the earlier CMIP3 models used in the IPCC AR4 assessment, reported in the earlier section of this report. These models have been assessed for validity in the Caribbean and for Puerto Rico. While they perform reasonably well for many features of the observed climate, certain models better match the annual cycle of climate due to better representation of Antilles Island wind shadows which generate larger amplitude seasonal and diurnal cycling. Most of the CMIP5 models, like their predecessors, simulate the North Atlantic high pressure cell as too strong - with trade wind evaporation causing below normal sea surface temperatures east of Puerto Rico. In this analysis of CMIP5 models, use is made of an all-model ensemble average based on the 'rcp6 forcing' scenario. This assumes an approximate doubling of CO_2 by the end of this century, consistent with the earlier CMIP3 A1B scenario, a 'middle of the road' projection. Figure 35 shows the results of observed trend analysis of the San Juan weather station as well as model outputs of precipitation from an area-averaged observation product CRU3 and from the CMIP5 coupled model CCSM4 projection with the rcp6 scenario. The analysis shows that the historic trends of precipitation for the whole of Puerto Rico is -0.001 mm/day/yr and will continue through 2050 (figure 32).

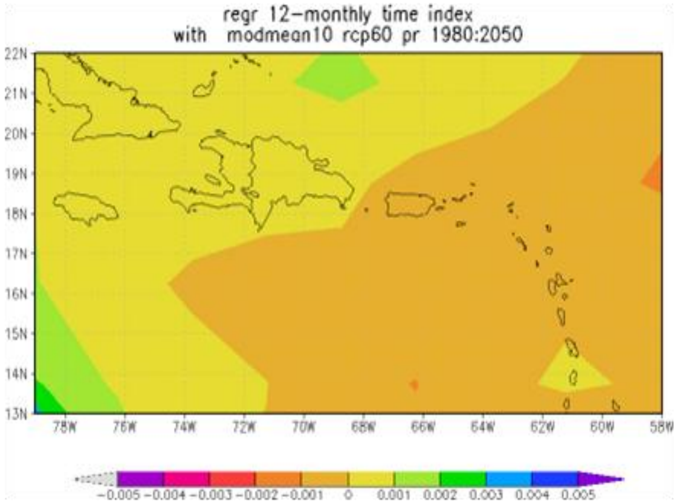


Figure 32: Linear trends in rainfall (mm/day/yr) predicted from CMIP5 model ensemble average using the rcp6.0W/m^2 forcing scenario in the period 1980-2050. The trend over Puerto Rico is -.001mm/day/yr. Trends in different seasons are similar.

5.2.3 Knowledge Gaps and Future Research Needs

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

5.2.4 Summary of Observed and Projected Precipitation Changes

Observed trends in precipitation in the Caribbean as a whole are unclear from the literature. Most models from the IPRCC fourth assessment report predict a decrease in precipitation across the Caribbean region. An analysis for the PRCCC shows that since 1948 the Caribbean Basin has seen decreasing precipitation (-0.01 to -0.05 mm/day/yr), with a greater drying trend for the Eastern Caribbean. Specifically for Puerto Rico, one analysis of weather station data for the period 1948 to 2007 found no clear trends in total annual rainfall for the island as a whole, while another analysis showed decreases in rainfall from -0.01 to -0.1 mm/day/yr. Regionally within the island, there are indications that the southern region of Puerto Rico has experienced positive trends in annual rainfall while the western and a portion of the northern region showed decreases. Additionally, seasonal trends with observed showing negative trends in summer and positive trends in winter. In order to simulate future climate change, global climate models need to accurately represent observed climate. There is a lot of uncertainty in the magnitude of precipitation changes in the Caribbean, though a majority of GCMs used in the IPCC fourth assessment report show future decreases in precipitation are likely. Model projections range from -78 to -10% (with a few GCMs showing +30%) and current evidence suggests drier conditions are more likely than wetter for Puerto Rico, a contrast to the global precipitation signal. Specifically the PRCCC analysis found that past and future trends are similar, a decrease of rainfall of -0.0012 to -0.0032 mm/day /yr, that are projected to continue through 2050.

What is the IPCC and USGCRP?

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

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

5.3 Extreme Weather Events

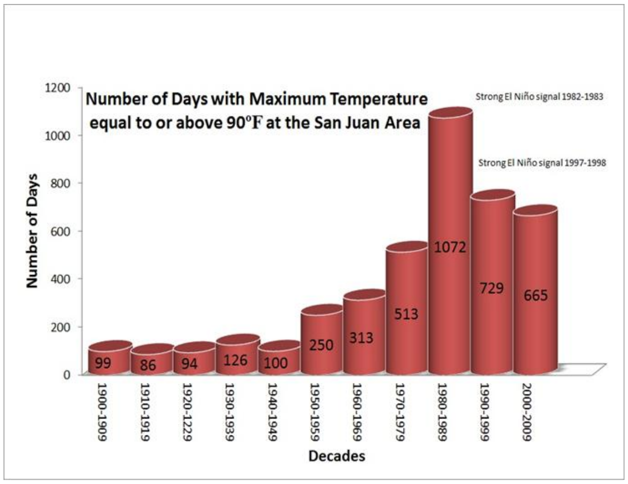
Extremes are a natural part of even a stable climate system, but because social-ecological systems have adapted to their historical range of extremes, the majority of events outside this range have primarily negative impacts and therefore it is highly important to assess observed trends and projected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

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

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

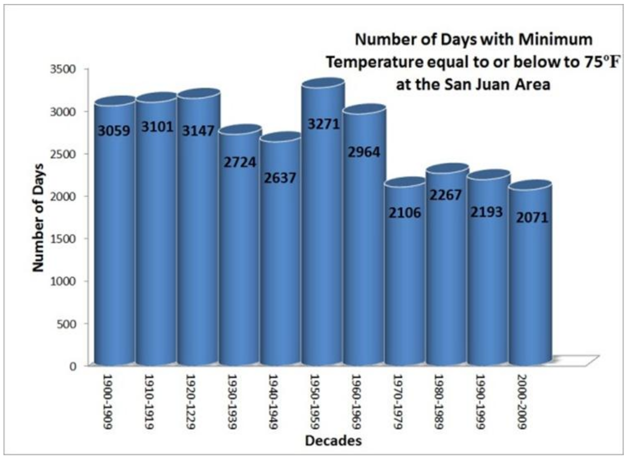
5.3.1 Extreme Temperatures in Puerto Rico

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



Source: NOAA National Weather Service Office, San Juan

Figure 33: Number of Days with Maximum Temperature equal to or above 90^{0}F in the San Juan Area



Source: NOAA National Weather Service Office, San Juan

Figure 34: Number of Days with Minimum Temperature equal to or below to 75^{0}F in the San Juan Area.

During the 80's and 90's, the frequency of hot days is notably higher due to the presence of El Niño conditions across the Pacific basin. This increase in greater frequency of hot days is consistent with an analysis done by the U.S. Global Change Research Program. They found that the number of very warm nights in Puerto Rico has increased by 15 or more per year for Puerto Rico from 1950 to 2004 (USGCRP 2008). In terms of minimum temperatures, the NOAA National Weather Service's 113 yr record shows a lower frequency of days with temperature equal to or below 75 ^{o}F (23.9 ^{o}C) has been observed as well (figure 34). The signal of the urban heat island effect is included in the decrease of days with minimum temperature equal to or below 75 °F. An urban heat island is a metropolitan area which is significantly warmer than its surrounding rural areas. The temperature difference usually is larger at night than during the day.

5.3.2 Extreme Precipitation in Puerto Rico

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

One of the clearest precipitation trends in the United States is the increasing frequency and intensity of heavy downpours. The amount of rain falling in the heaviest downpours has increased approximately 20 percent on average across North America, the Hawaiian Islands, and Puerto Rico in the past century, and this trend is very likely to continue, with the largest increases in the wettest places (USGCRP 2009). In fact, from 1958 to 2007, Puerto Rico experienced a 37% increase in very heavy precipitation (USGCRP 2009). The San Juan metropolitan area has seen greater than 15% increase in more frequent rainfall events greater than 78mm of rain per 24 hours (3 in/24hrs) from 1955 to 2009. 70 episodes were observed in the 1970s, 55 episodes in 1980, 38 episodes in 1990, and 80 episodes in 2000 (not including 2010), according to the San Juan ULTRA Project (figure35).

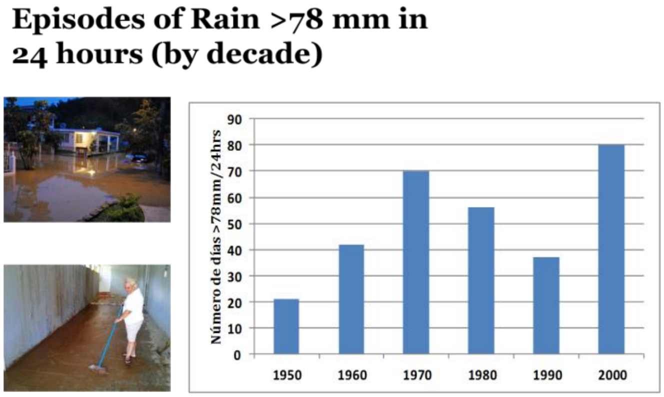


Figure 35: Episodes of rain over 78 mm in 24 hours by decade from 1950-2000

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

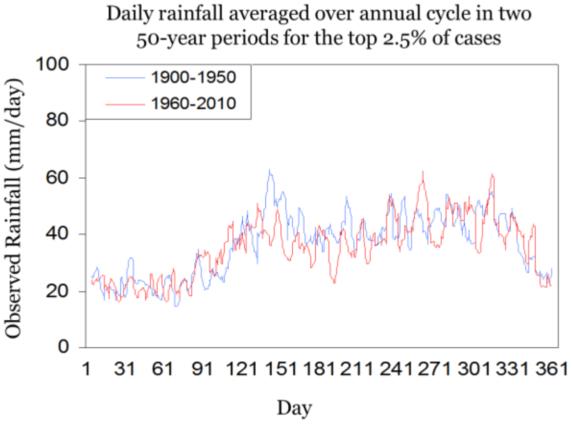


Figure 36: Daily rainfall averaged over annual cycle in two 50yr periods using data combined from Mayaguez, Manati and Manuabo for top 2.5% of cases. Notice the decrease in May floods (days 121-151).

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

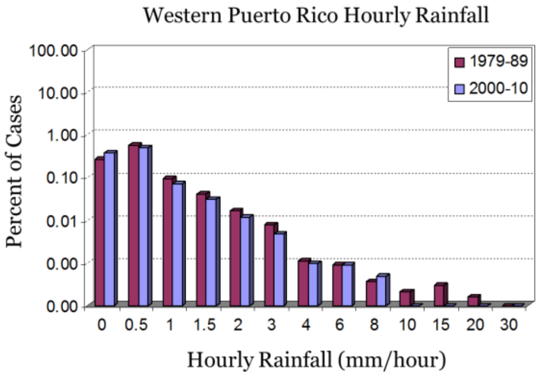


Figure 37: Hourly rainfall averaged over the western half of Puerto Rico from CFS-reanalysis, using data for two 10 yr periods, indicating a decline of flood events in the satellite era and a corresponding increase in light rain events.

5.3.3 Projections for Extreme Precipitation Events

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

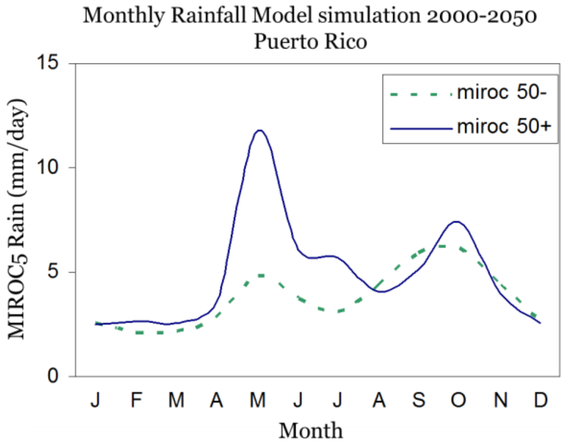


Figure 38: : CMIP5 MIROC5 model 1900-1950 simulation (50-) and 2000-2050 projection (50+) of top 2.5% of monthly rainfall cases over the annual cycle, indicating a significant increase of floods in May in the next 50 years. There is no appreciable change in flood events in the hurricane season.

5.3.4 Knowledge Gaps and Future Research Needs

The continued development and maintenance of high quality climate observing systems will improve our ability to monitor and detect future changes in climate extremes. Also, efforts to digitize, homogenize, and analyze long-term observations in the instrumental record with multiple independent experts and analyses would improve our confidence in detecting past changes in climate extremes. Weather observing systems adhering to standards of observation consistent with the needs of both the climate and the weather research communities would improve our ability to detect observed changes in climate extremes. Furthermore, the creation of annually-resolved, regional-scale reconstructions of the climate for the past 2,000 years would help improve our understanding of very long-term regional climate variability.

5.3.5 Summary of Historic Trends and Projections for Extreme Events

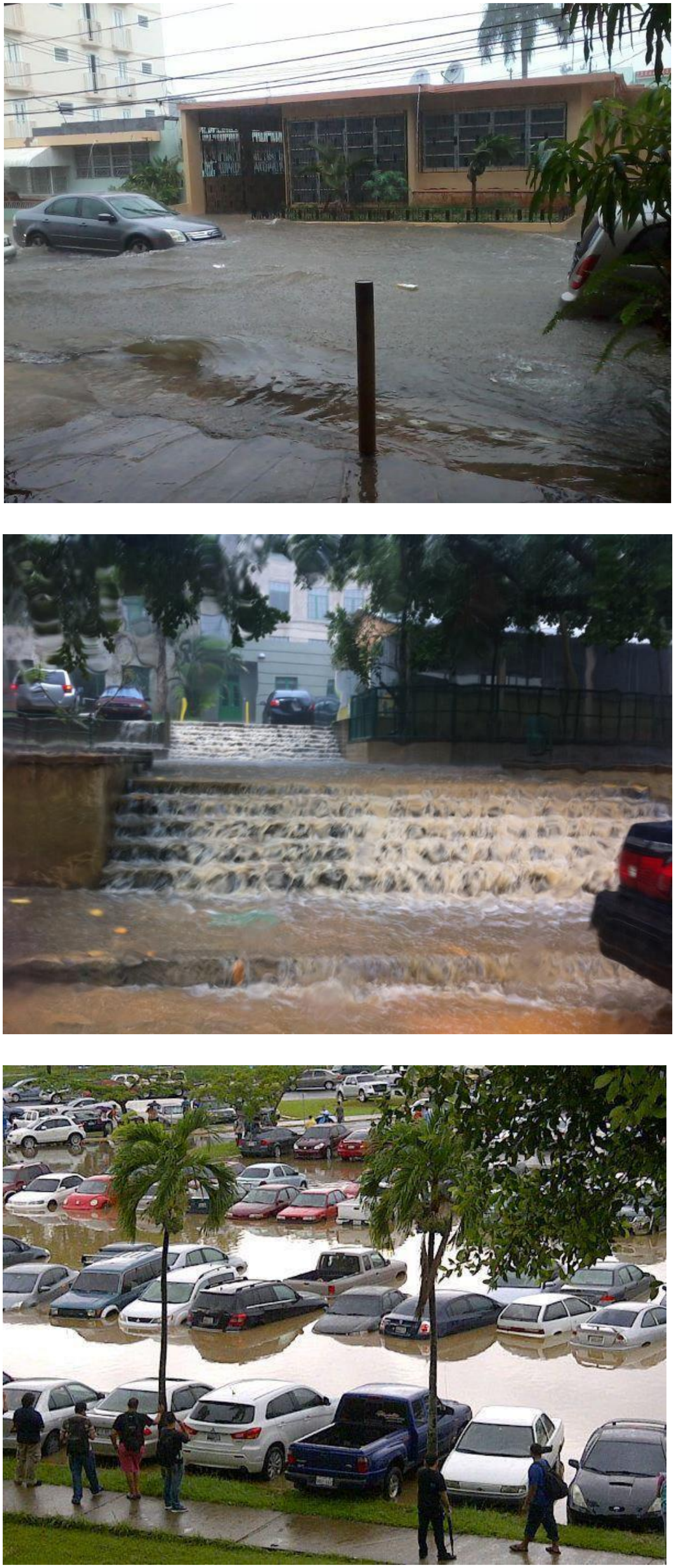
Globally there is evidence from observations gathered since 1950 of change in some extreme events. Extreme events are rare, which means there are few data available to make assessments regarding changes in their frequency and intensity. The more rare the event the more difficult it is to identify long-term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

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

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

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

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



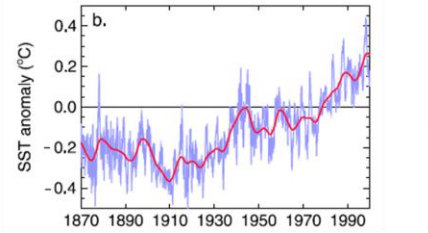
2011 downpour event in Mayagüez, PR: Flooding after only 30 minutes of rain. It is *likely* that the frequency of heavy precipitation events like this one will increase in the 21st century. *Photo Credits: Professor Aurelio Mercado, UPR.*

5.4 Sea Surface Temperatures (SST)

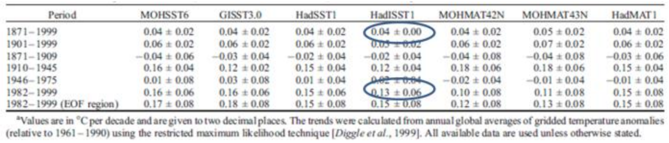
5.4.1 Observed Sea Surface Temperature Trends in the Northeastern Caribbean

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

a



b



Period	MOHSST6	GISST3.0	HadSST1	HadISST1	MOHMAT42N	MOHMAT43N	HadMAT1
1871–1999	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.00	0.04 ± 0.02	0.05 ± 0.02	0.04 ± 0.02
1901–1999	0.06 ± 0.02	0.06 ± 0.02	0.06 ± 0.02	0.05 ± 0.02	0.06 ± 0.02	0.07 ± 0.02	0.06 ± 0.02
1871–1909	−0.04 ± 0.06	−0.03 ± 0.04	−0.02 ± 0.04	−0.02 ± 0.04	−0.04 ± 0.08	−0.04 ± 0.08	−0.03 ± 0.06
1910–1945	0.16 ± 0.04	0.12 ± 0.02	0.15 ± 0.04	0.12 ± 0.04	0.18 ± 0.06	0.18 ± 0.06	0.15 ± 0.04
1946–1975	0.01 ± 0.08	0.03 ± 0.08	0.01 ± 0.04	0.02 ± 0.04	−0.02 ± 0.04	−0.01 ± 0.04	−0.01 ± 0.04
1982–1999	0.16 ± 0.06	0.16 ± 0.06	0.15 ± 0.06	0.13 ± 0.06	0.10 ± 0.08	0.11 ± 0.08	0.15 ± 0.08
1982–1999 (EOF region)	0.17 ± 0.08	0.18 ± 0.08	0.15 ± 0.08	0.15 ± 0.08	0.12 ± 0.08	0.13 ± 0.08	0.15 ± 0.08

[a]Values are in °C per decade and are given to two decimal places. The trends were calculated from annual global averages of gridded temperature anomalies (relative to 1961–1990) using the restricted maximum likelihood technique [*Diggle et al.*, 1999]. All available data are used unless otherwise stated.

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

Dr. Julio Morell of the University of Puerto Rico's Caribbean Coastal and Ocean Observing System (CariCOOS) compared this result with local observations through an analysis of sea surface temperatures around Puerto Rico for the PRCCC based on data collected from the Prediction and Research Moored Array in the Atlantic (PIRATA) buoy in the tropical Atlantic (15°N, 38°W) (http://www.pmel.noaa.gov/pirata/). Besides "in situ" he also explored estimates at these sites from a global weekly sea surface temperature data product, NOAA OI.v2 SST, operationally issued by NOAA. The two sources used for this study include annual SST from the Hadley center SSTv2 and the NCDC NOAA erSSTv3 because they have at least 30 years of data. A spatial map of linear trend regression is made and temporal plot of linear trend for a Puerto Rican area-average is analyzed. Sea surface and subsurface temperature measurements were collected with PMEL electronics coupled to a YSI (Yellow Springs Instruments) thermistor 46006 with a resolution of 0.001°C (±0.02°C). SST data (1981 to 2010) analysis of the West Tropical Atlantic PIRATA station data yields a slope of 0.026 (+/-0.002) °C per year (figure 40a).

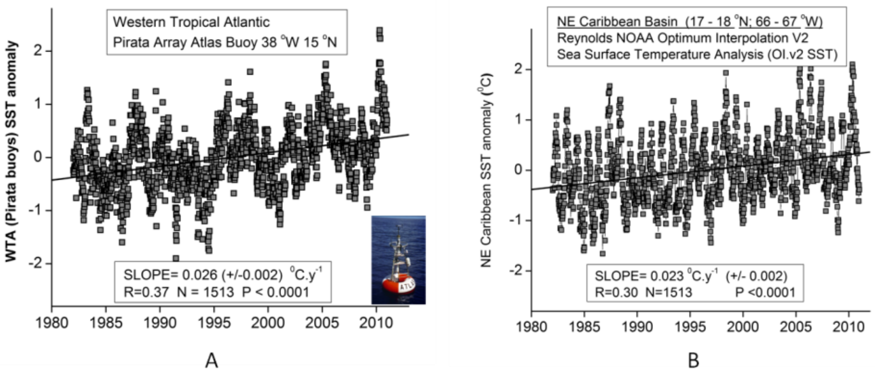


Figure 40: (a) PIRATA data analysis for sea surface temperature trends. The data yields a slope of 0.026 (+/-0.002)°C per year; (b) Reynolds NOAA Optimum Interpolation V2 Sea Surface Temperature Analysis anomaly data from OI.v2 SST product for the CaTS region (Northeastern Caribbean) from 1982 to 2011.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

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

SST analysis was also conducted for the PRCCC by Dr. Mark Jury. Observed SST trends near Puerto Rico were assessed to be 0.008°C/yr over the 20th century (from 1982 – 2011). This trend is projected to remain similar in the 21st century according to the CMIP5 ensemble average (figure 41). Part of the reason for the low rate of change is that **the ocean is warming much slower than the atmosphere**. Also in the Puerto Rico record, the 1970s are rather cool. If only data for recent decades are considered, then the SST trend is higher (0.026°C/yr), a rate consistent with Winter et al (1998) for inshore waters on the southwest coast (1966-1995) and the analysis by Morell described above.

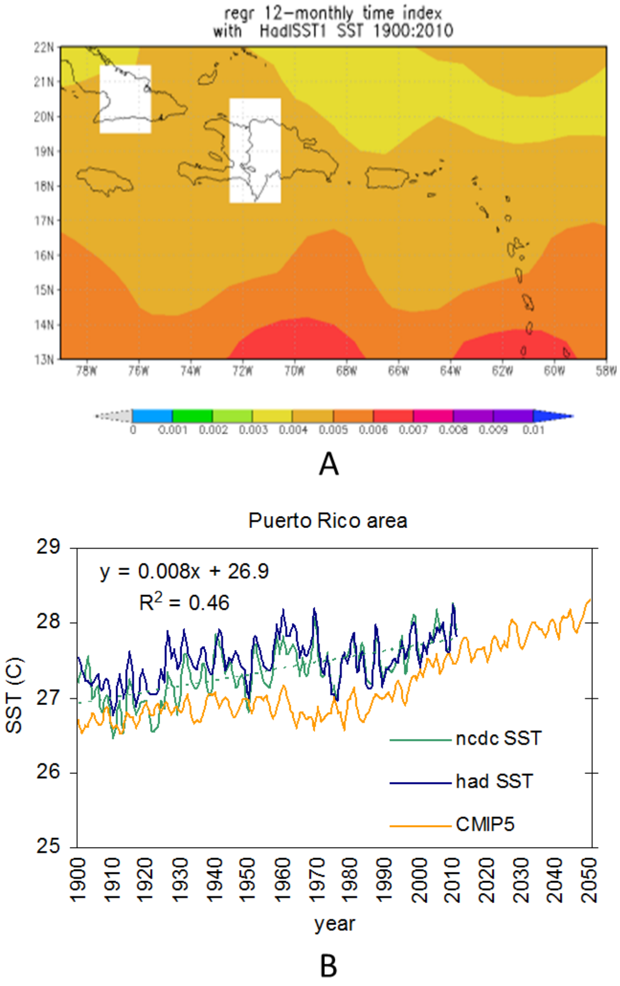


Figure 41: (A) Past trends in SST mapped over the Caribbean and for the Puerto Rico area; (B) including CMIP5 ensemble average projected data.

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

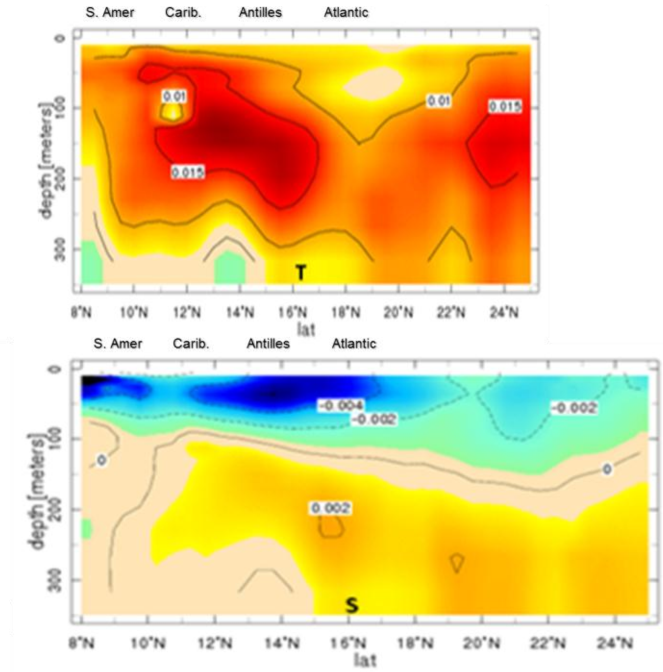


Figure 42: (top) Past trends in subsurface sea temperatures (°C/yr) and (bottom) salinity (ppt/yr) in N-S depth section from SODA reanalysis 1958-2007. Courtesy of Jury (2011).

5.4.2 Future Sea Surface Temperature Projections for Puerto Rico

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

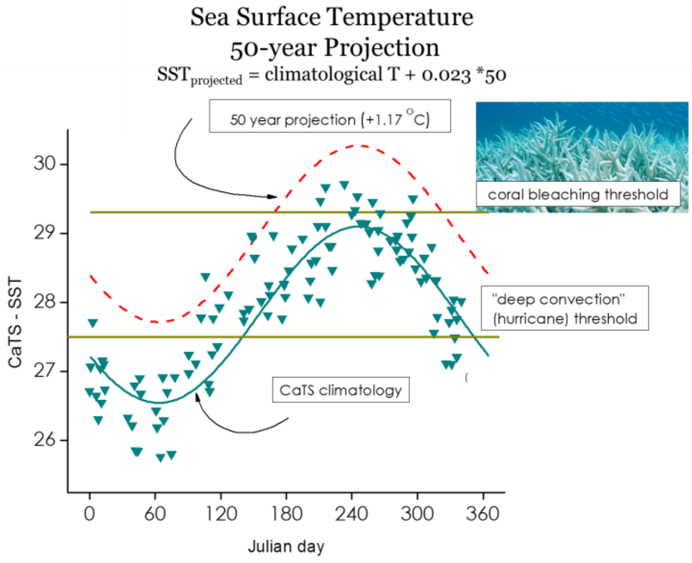


Figure 43: OI v2 SST trend (0.023°C/yr) and climatology obtained at the Caribbean Time Series Station (17o 36’ N 67o W: 1994 – 2007 monthly data). An increase of 1.17°C (2.1°F) over a 50 year period can be expected.

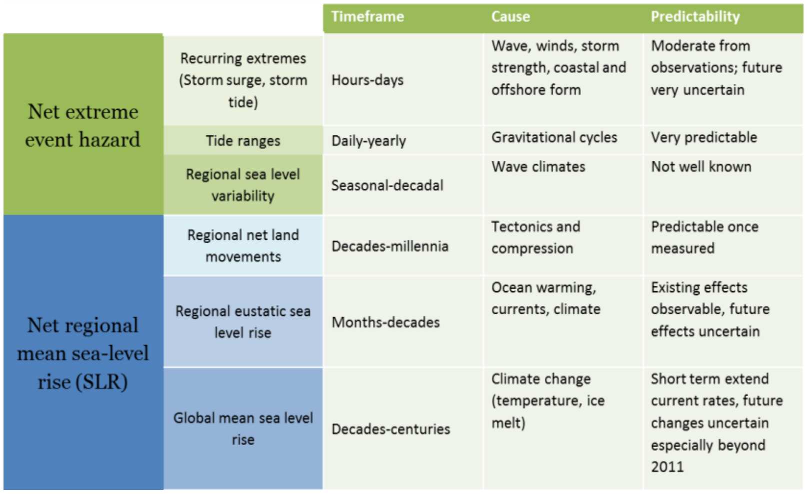
5.4.4 Summary of Historic Trends and Projections for Sea Surface Temperatures

Caribbean sea surface temperatures have warmed by 1.5^{o}C over the last century (IPCC 2007). Three SST analyses were conducted for the PRCCC. The first used the West Tropical Atlantic Prediction and Research Moored Array (PIRATA) station data and found an increase of 0.026 (+/- 0.002) °C per year from 1981 to 2010. The second analysis used the optimum interpolation SST analysis product (OI.v2 SST), which is operationally issued weekly for 1 degree grid for the global ocean, and found an increase of 0.023 degrees (+/- 0.002) °C per year from 1982 to 2011. The third analysis found observed SST trends near Puerto Rico to be 0.008°C/yr over the 20th century (from __ - __). Different SST trends are found depending on the length of time analyzed. If only data for recent decades are considered, then the SST trend is higher. However, all three trends show a clear warming. SST warming trends south of Puerto Rico are faster than to the north and sub-surface temperatures are warming faster than the surface, particularly south of Puerto Rico. The higher rate of warming south of Puerto Rico is related to a significant weakening of trade winds (as they travel over the higher elevations of the central mountain range), evaporation and westward currents (Jury 2011). The Caribbean has warmed faster than the Atlantic. This observed warming trend is projected to remain similar in the 21st century according to two studies conducted for the PRCCC. One showing that an increase of 1.17^{o} C (2.1^{o}F) over a 50 year period can be expected. Additionally, SST above the threshold for coral bleaching will be exceeded over a third of the year.

5.5 Sea Level Rise

5.5.1 Observed Sea Level Rise Trends in Puerto Rico

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



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

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

Globally speaking, global sea levels have been rising via thermal expansion resulting from warming of the oceans, as well as freshwater input from the melting of a majority of Earth's glaciers and ice sheets. Global sea level on average has risen by 120 meters over the last 18,000 years. The average rate during the last 3,000 years has only been about 1-2 centimeters (cm) per century, but the past century saw an average of 17 ± 5 cm of sea level rise around the globe (Bindoff et al. 2007). The long-term rise has been driven by polar ice melt and thermal expansion of the oceans (Cayan et al. 2006). The United States Geological Survey has been researching the sea level history of Puerto Rico using interglacial sea level deposits. Their research has shown that sea levels around Puerto Rico over the past 120,000 years have decreased by more than 6 meters. Because sea level rise or fall is influenced by the rising or sinking of land masses, USGS also looks for tectonic "uplift" (land masses increasing elevation, slowing the rate of sea level rise) and "subsidence" (land masses sinking increasing the rate of sea level rise). The deposits USGS has analyzed are at (or no more than slightly above) the sea level at which they formed (+6 m, relative to present sea level, 120,000 years ago), indicating that on the northern and northwestern coasts of Puerto Rico uplift has been very minimal, if these coasts have been uplifted at all (Muhs 2004). USGS has also dated corals of the last-interglacial age on Mona Island and measured the elevation of the last interglacial reef and since they are 4 to 6 meters above present, there are indications of little or no uplift. On the other hand, there is evidence of coseismic uplift during the Holocene (the past ~10,000 years) on the south and west coasts of Puerto Rico (Prentice and Mann 2005). In some areas in these two regions Prentice and Mann found evidence of young marine deposits, well above high-tide level. It is unknown, however, if these deposits represent coseismic events or tsunamis. In order to answer that question, last-interglacial marine deposits would need to be found in these areas of Puerto Rico in order to get a long-term uplift rate for the south and east coasts.

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

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

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

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

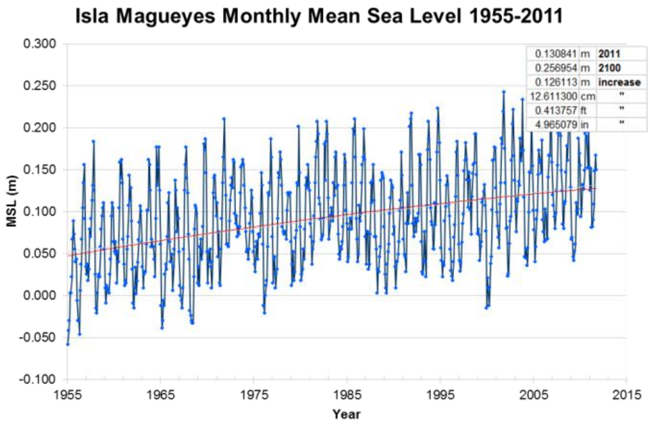


Figure 46: Tide gauge data from Isla Magueyes show that from 1955 to 2011 the south coast of Puerto Rico experienced a 1.35 mm/yr rise in sea levels. From 2001 to 2011 the South Coast experienced a 1.10 mm/yr rise. Source: Dr. Jorge Capella 2011, UPR/CariCOOS

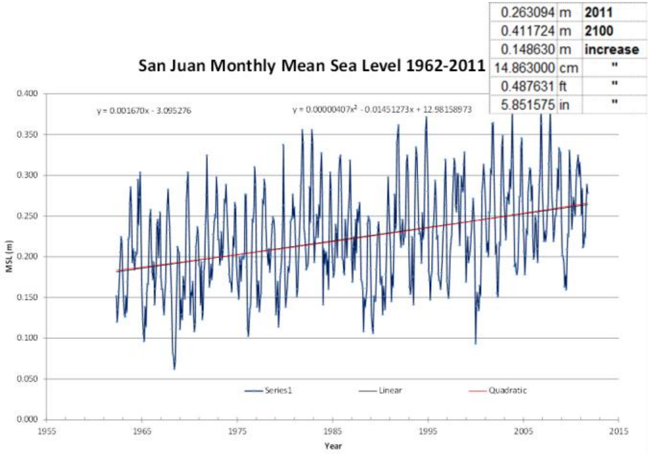


Figure 47: Tide gauge data from San Juan show that from 1962 to 2011 the North Coast of Puerto Rico experienced a 1.65 mm/yr rise in sea level. From 2001 to 011 the rise was 0.50 mm/yr. Source: Dr. Jorge Capella 2011, UPR/CariCOOS.

A second sea level rise study was conducted for the PRCCC by UPR Professor Aurelio Mercado using two methods. First, a Low Pass Butterworth Filter with a sharp cut-off frequency at 1/10 cycles per year was used to analyse the NOAA tide gauge data. This means that oscillations with periods less than 10 years were filtered out. The results show that since about 2007 the low-passed curves flattened out and the low-frequency oscillations of periods of about 13 years seen in the past disappeared during the last decade. Using the last common peak observed around 1995, the low-passed curves should have started to go down by around 2007. But instead both low-passed curvies continued to go up slightly and flattened out, as mentioned, for at least five years now. The second method used was a least-squares fit starting in 1990. The results show that for the San Juan tide gauge the trend increases from 1.63 mm/year to 2.21 mm/year (figure 48). The Magueyes tide gauge also showed an acceleration up from 1.5 mm/year to 2.67 mm/year, showing an acceleration in sea level rise as also detected by Dr. Capella. These accelerations are in accord with satellite data (since 1993) and with Sallenger et al. (2012) though not to the same magnitude of up to 6mm/year sea level rise as seen from 1970-2009 in the northeast hotspot for sea level rise in the Northeast of the continental United States (Sallenger et al. 2012).

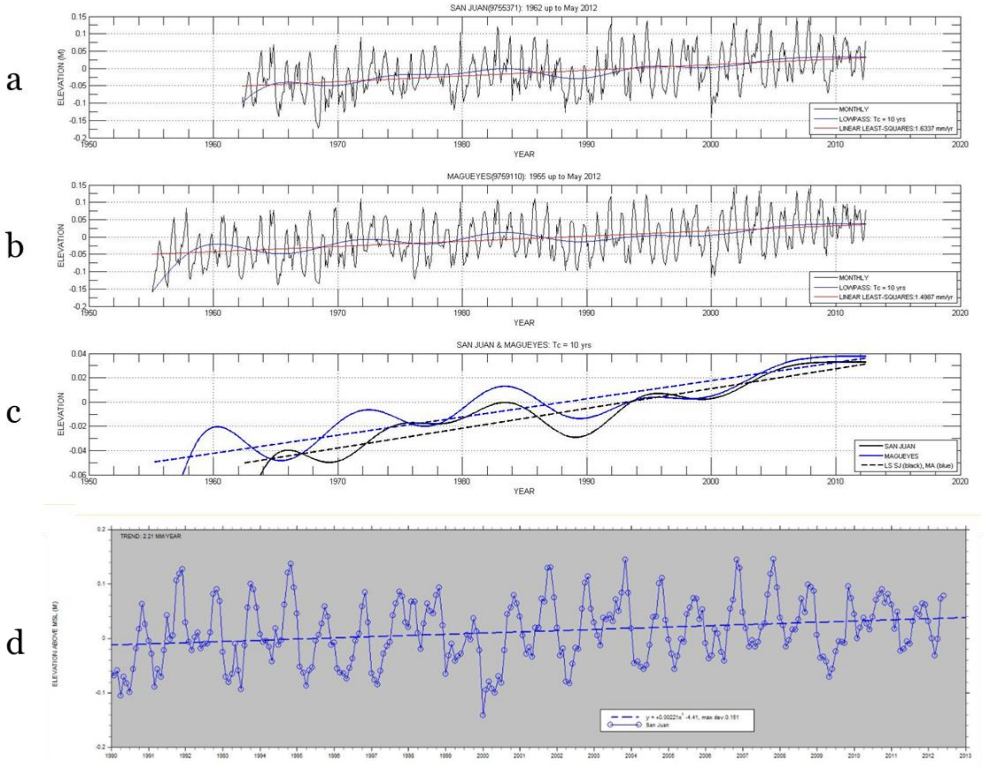


Figure 48: (A) San Juan 1962 to May 2012. Black is monthly data. Blue is Lowpass Tc=10years, Red is Linear least-squares regression; (B) Magueyes (1955 to May 2012). Black is monthly data. Blue is Lowpass Tc=10years, Red is Linear least-squares regression; (C) San Juan and Magueyes Tc=10 years. Black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

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

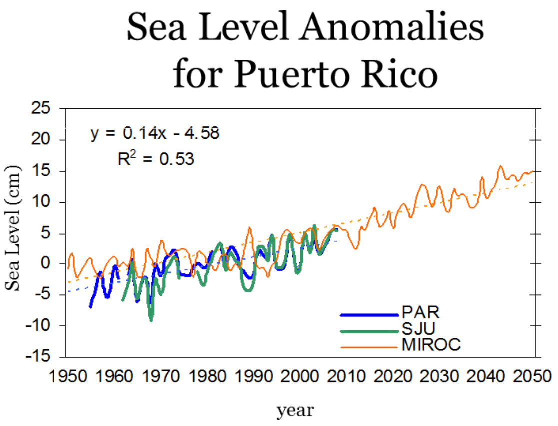


Figure 49: Observed and projected sea level anomalies for Puerto Rico. Blue line is sea level rise data for the south coast, green line is sea level rise data for the north coast, and the orange line is the MIROC ocean model forecast with A1B scenario (mid-high IPCC emission scenario).

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

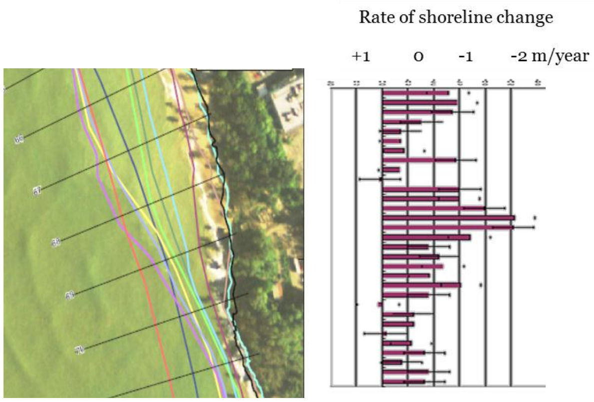


Figure 50: Coast lines approximately every 10 year near Rincon, PR, with matching coastal recession graph.

5.5.2 Future Sea Level Rise Projections for Puerto Rico

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

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

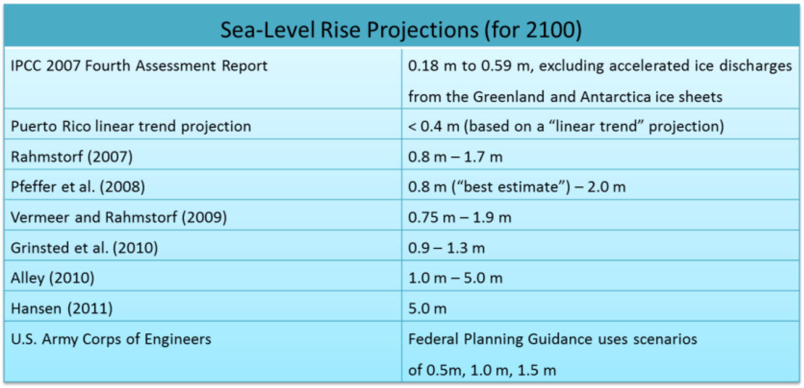
- **Carbon dioxide uptake**. Evidence suggests that warming tends to reduce land and ocean uptake of atmospheric carbon dioxide, increasing the portion of carbon dioxide emissions that remain in the atmosphere. This would result in further warming and cause additional sea-level rise.
- **Ice sheet instability**.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

> initiate irreversible melting of the Greenland ice sheet, contributing up to 6 m of sea-level rise. The risk for crossing this threshold could occur within our generation, while the consequences would be felt by future generations.

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

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

Recent projections of global sea level rise (Pfeffer et al. 2008, Vermeer and Rahmstorf 2009, Grinsted et al. 2010, Jevrejeva et al. 2010) have generally been significantly higher than estimates from the 2007 IPCC Report. Combining climate modeling and paleoclimatic data, total sea-level rise of about 2.0 m by 2100 has been estimated as the maximum that could occur, with a best estimate of about 0.8 m (Pfeffer et al. 2008). Even newer estimates suggest that global sea level could rise approximately 3.26 meters from the melting of the West Antarctic Ice Sheet. If perturbations in Earth's rotation and shoreline migration are taken into account, the Pacific and Atlantic coasts of the United States, could be impacted by sea levels 25 percent higher than the global mean at the end of the century (Mitrovica et al. 2009). All these Figures are substantially higher than the model-based estimates in the IPCC Fourth Assessment Report. See figure 51 for a summary of sea level rise projections for globally and in the Caribbean.



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

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

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

The Figures show a 50 year and 100 year planning horizon for adaptation with sea level rise estimates ranging from 0.07 to 0.57 meters (0.20 to 1.87 feet) above current mean sea level by the year 2060 and between 0.14 and 1.70 meters (0.40 to 5.59 feet) above current mean sea level by the year 2110. Due to the variability and uncertainty in the system it is important to project sea level rise across a range and plan for all possible future scenarios when possible, rather than just the lower bound conservative estimate. Table 1 shows a comparison of sea level rise analyses for Puerto Rico as well as future projections.

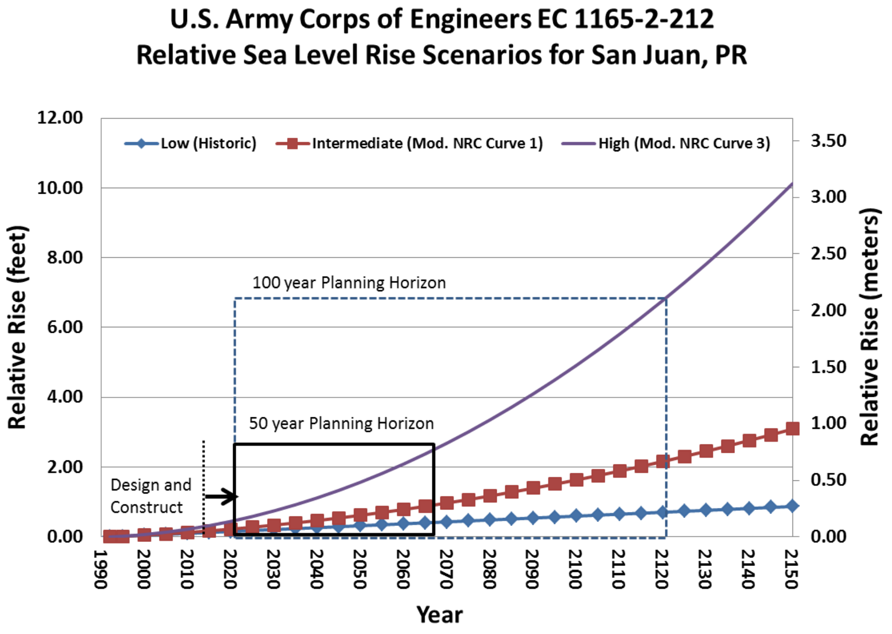

U.S. Army Corps of Engineers EC 1165-2-212
Relative Sea Level Rise Scenarios for San Juan, PR

Figure 52

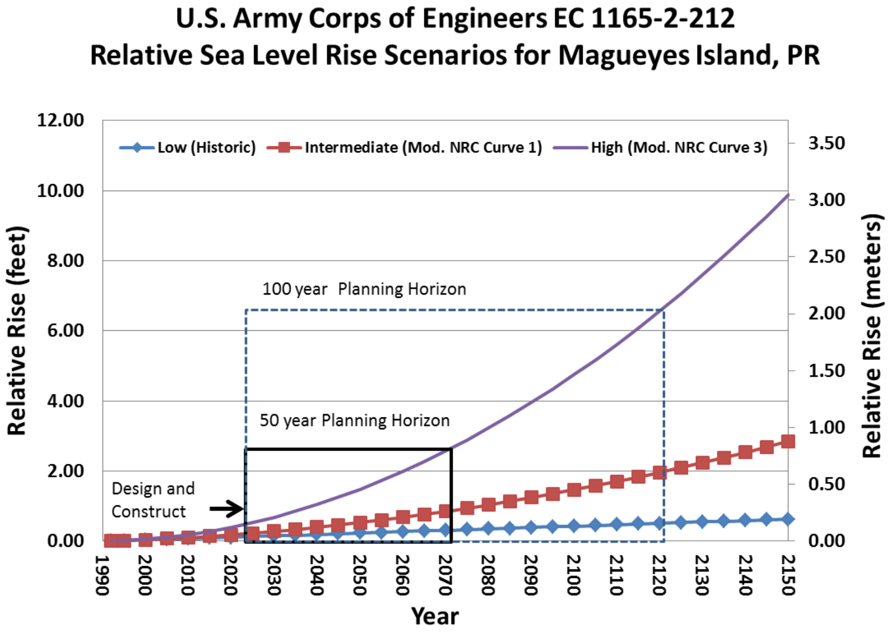

U.S. Army Corps of Engineers EC 1165-2-212
Relative Sea Level Rise Scenarios for Magueyes Island, PR

Figure 53

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

5.5.3 Knowledge Gaps and Future Research Needs

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

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

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

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

5.5.4 Summary of Observed and Projected Trends for Sea Level Rise

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

5.6 Tropical Storms and Hurricanes

5.6.1 Observed Trends in Tropical Storms and Hurricanes in Puerto Rico

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

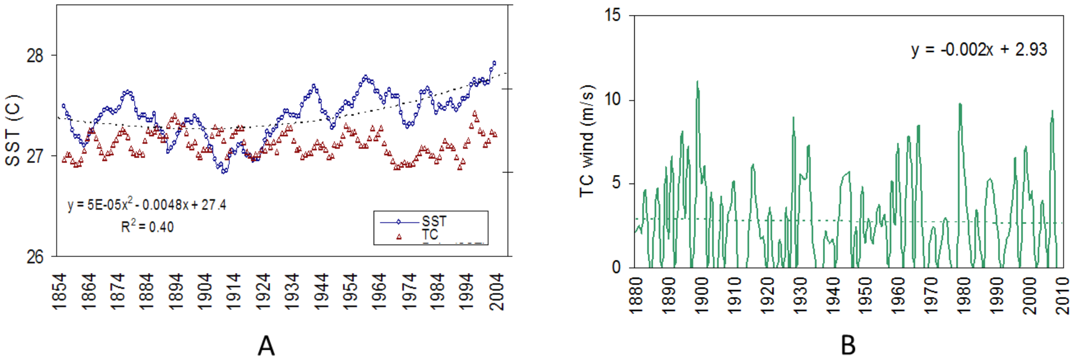


Figure 54: (A) NOAA hurdat number of tropical cyclones and SST within 500 km of Puerto Rico shown in red and blue respectively; (B) MIT observed mean wind anomaly for tropical cyclones passing within 100 km of Puerto Rico, showing weak downtrend since 1880.

Uncovering a clear long-term trend specific to Puerto Rico is challenging, however, due to data uncertainty being larger in the early part of the record compared to the satellite era beginning in 1965. The U.S. Global Change Research Program states that "even taking these factors into account, it is likely that the annual number of tropical storms, hurricanes and major hurricanes in the North Atlantic have increased over the past 100 years, a time in which Atlantic sea surface temperatures also increased. The evidence is not compelling for significant trends beginning in the late 1800s. Uncertainty in the data increases as one proceeds back in time" (CCSP 2008). Jury (2011) asserts that we have not seen a long-term increase in tropical cyclones in the Caribbean mainly because the ocean is warming much slower than the atmosphere. Tropical cyclones within 500 km of Puerto Rico are plotted with sea surface temperatures in figure 54 (printed with permissions from Jury 2011). The

acceleration of the Hadley circulation and related increase in upper westerly wind shear tend to suppress hurricane development and intensification.

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

A gradual downward trend is evident from an average of ~4.1 (1755 – 1785) to ~1.5 major hurricanes during the late 1960s to early 1990s, which experienced strong and few major hurricanes compared to other periods since 1730. Furthermore, the active phase of 1995-2005 is unexceptional compared to other high-activity periods and appears to represent a recovery to "normal hurricane activity" despite the increase in SST…indicating that increases in SST during the past 270 years have been offset by increased vertical wind shear which suppresses major hurricanes…A more rapid warming of the atmosphere relative to the ocean could have caused the anomalous calm period between the 1970s and 1990s" (Nyberg et al. 2007).

Another study uses an inverse hurricane modeling technique to reconstruct flooding conditions for 29 overwash events (29 sediment

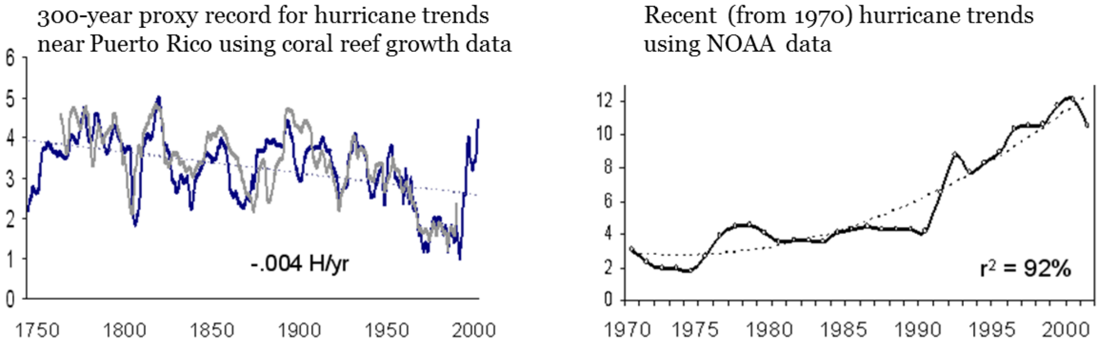


Figure 55: Intercomparison of hurricane trends near Puerto Rico, based on (left) coral reef growth in a 300-year proxy record (data from Nyberg et al. 2007), and NOAA hurdat data (right) over 30 yr. Notice that the coral reef growth data depicts a decrease in the number of hurricanes reaching Puerto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

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

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

5.6.2 Future of Hurricanes in Puerto Rico

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

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

Intense hurricanes and associated extreme wind events will more likely than not become more frequent due to expected warming of the upper ocean in the tropical cyclone genesis regions (IPCC 2007). That is, once formed, the fraction of hurricanes that become intense is expected to increase, along with the overall destructive power. However, because future changes in other critical factors for tropical cyclones, including wind shear, the vertical temperature gradient in the atmosphere, and trends in ENSO and the Atlantic Multidecadal Oscillation are uncertain, it is unclear whether the total number of tropical storms will increase. However it is likely that the most probable tracks or trajectories of hurricanes will shift northward, as ocean water temperatures increase.and intense hurricanes may change in the future.

The uncertainty about the effects of global warming on hurricane frequency (Landsea et al. 1996, Emanuel 1997, Henderson-Sellers et al. 1998, Emanuel 1999, Meehl et al. 2000) arises from the fact that the ocean is warming slower than the atmosphere. Therefore the uptake of heat energy necessary for hurricane development has to work against a downward gradient. Studying the effect of global warming at a time of doubled CO_2, (Bengtsson et al. 1997) concluded that there were significantly fewer hurricanes (especially in the Southern Hemisphere), but little change in the spatial distribution of storms. Nested high-resolution models (18 km) indicate a 5-11% increase in surface winds and a 28% increase in near-storm precipitation (Knutson et al. 1998, Knutson and Tuleya 1999) recent overall assessment regarding changes in hurricane strength suggests a 5-10% increase in tropical storm wind speed by the end of the 21st century (Henderson-Sellers et al. 1998).

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

Atlantic. These easterly waves are responsible for hurricane activity in the Caribbean. Therefore, changes in THC help regulate hurricane occurrence in the Caribbean as reflected in the correlation map (figure 56) with late summer rainfall.

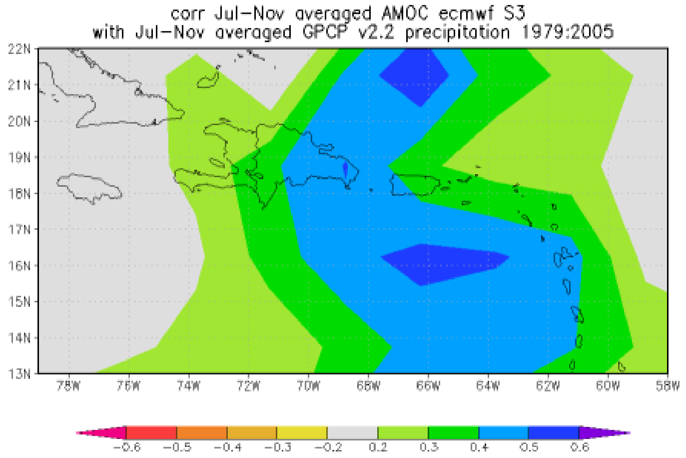


Figure 56: Cross-correlation between Global Precipitation Climatology Project (GPCP) precipitation data and the Atlantic Ocean subsurface meridional overturning thermohaline circulation (THC) in July-November season.

Current global climate models are rather poor in simulating tropical cyclones, due in part to the coarse spatial resolution of these models. Short-term studies suggest that the frequency of strong tropical cyclones has increased globally in recent decades in association with increases in sea-surface temperature (Saunders and Lea 2008), and that anthropogenic GHG emissions are the main driver of observed changes in SST in tropical cyclogenesis regions (Santer et al. 2006).

A comprehensive reanalysis of satellite records has found significant upward trends in the strongest cyclones in all world regions during the last 30 years, with the largest increase occurring over the North Atlantic (Elsner et al. 2008). Another study has shown that the trend of increasing numbers of category 4 and 5 hurricanes for the period 1970-2004 is directly linked to the SST trend (Hoyos et al. 2006; Fussel 2009). It is important to note that the Atlantic Multi-decadal Oscillation underwent an upturn since the 1970s that contributes much of the observed short-term trend in Caribbean-Atlantic basin hurricanes. The longer IPCC fourth assessment report climate simulations suggests that global warming will decrease tropical cyclone frequency, but that an increase in the frequency of the most intense events is to be expected (Emanuel et al. 2008). Similar results have been obtained by simulations with a high-resolution version of the ECHAM5 global climate model (Bengtsson et al. 2007). In summary, substantial uncertainties about past and future changes in cyclone activity remain, and the scientific debate on this subject is expected to remain very active.

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

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

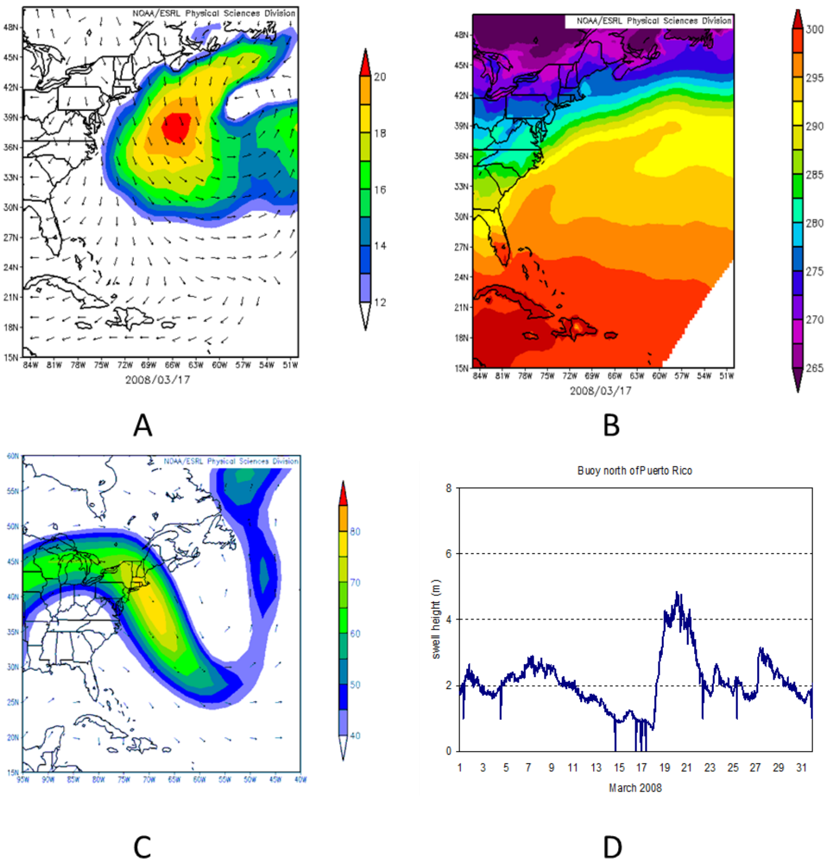


Figure 57: (A) surface winds from NARR for 17 March 2008, (B) surface temperatures (K), (C) upper level winds showing looping jet stream, and (D) hourly swell data from a buoy north of Puerto Rico for March 2008.

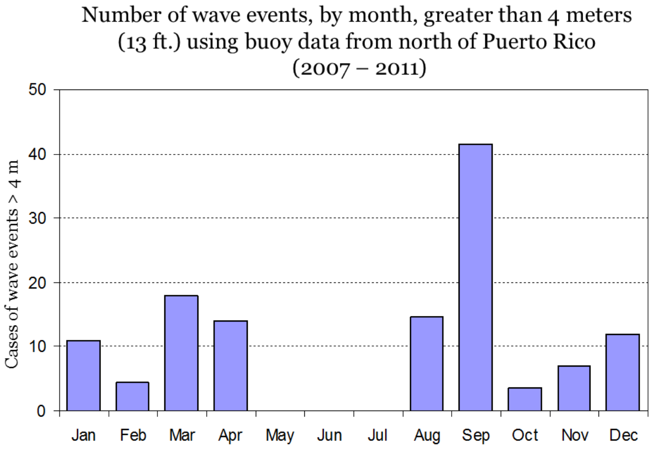

Number of wave events, by month, greater than 4 meters (13 ft.) using buoy data from north of Puerto Rico (2007 – 2011)

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

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

5.6.3 Knowledge Gaps and Future Research Needs

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

5.6.4 Summary of Observed and Projected Trends for Tropical Storms and Hurricanes

Proxy reconstruction of the past 5,000 years of intense hurricane activity in the western North Atlantic suggests that hurricane variability has been strongly modulated by El Niño during this time, and that the past 250 years has been relatively active in the context of the past 5,000 years. Nyberg *et al.* (2007) suggest that major hurricane activity in the Atlantic was anomalously low in the 1970s and 1980s relative to the past 270 years. According to the U.S. Global Change Research Program, Atlantic tropical storm and hurricane destructive potential as measured by the Power Dissipation Index (which combines storm intensity, duration, and frequency) has increased. This increase is substantial since about 1970, and is likely substantial since the 1950s and 60s, in association with warming Atlantic sea surface temperatures. There have been fluctuations in the number of tropical storms and hurricanes from decade to decade and data uncertainty is larger in the early part of the record compared to the satellite era beginning in 1965. Even taking these factors into account, it is likely that the annual number of tropical storms, hurricanes and major hurricanes in the North Atlantic have increased over the past 100 years, a time in which Atlantic sea surface temperatures also increased. The evidence is not compelling for significant trends beginning in the late 1800s as uncertainty in the data increases as one proceeds back in time. There is also evidence for an increase in extreme wave height characteristics over the past couple of decades in the North Atlantic, associated with more frequent intense hurricanes and in the future there may be an increase in the intensity of winter swells reaching Puerto Rico’s coasts. Current global climate models are rather poor in simulating tropical cyclones, due in part to the coarse spatial resolution of these models, however the IPCC fourth assessment report’s climate simulations suggests that the North Atlantic and Caribbean will experience a decrease in tropical cyclone frequency, but an increase in the frequency of the most intense events. Other models concur. Due to the substantial uncertainties about past and future changes in cyclone activity the scientific debate on this subject is expected to remain very active.

5.7 Ocean Acidification

5.7.1 Trends in Ocean Acidification

As a result of the fossil carbon released to the atmosphere from human activities, seawater pH and carbonate saturation state (Ω) have decreased and will continue to decrease as the ocean continues to absorb carbon dioxide (CO_2). The oceans are currently taking up about one ton of anthropogenic CO_2 per year for each person on the planet (IPCC 2001). During the Industrial Revolution (1800) the concentration of atmospheric CO_2 was an about of 280 parts per million (ppm), and the global ocean pH averaged 8.16 (Ruttimann and Witze, 2006). Currently, atmospheric CO_2 concentration has reached 395 ppm (Tans and Keeling 2012), and the average pH of the oceans has dropped to 8.05 (IPCC 2007). This is equivalent to an increase of CO_2 concentration of about 35% and a decrease in pH of 0.1 units (IPCC 2007). If we continue as business as usual path of fossil carbon release to the atmosphere, by the next century the average pH of oceanic waters will decrease by 0.3 – 0.4 units below the level of pre-industrial times (Kleypas et al. 2006b). The oceans play an important role in the uptake of anthropogenic CO_2 as it eventually absorbs an about 50% of the antropogenic CO_2 released to the atmosphere. As shown by the Hawaii Ocean Time Series program long term increses in atmospheric CO_2 are clearly linked to an increase in CO_2 dissolved in surface water and corresponding decreases in pH (figure 59).

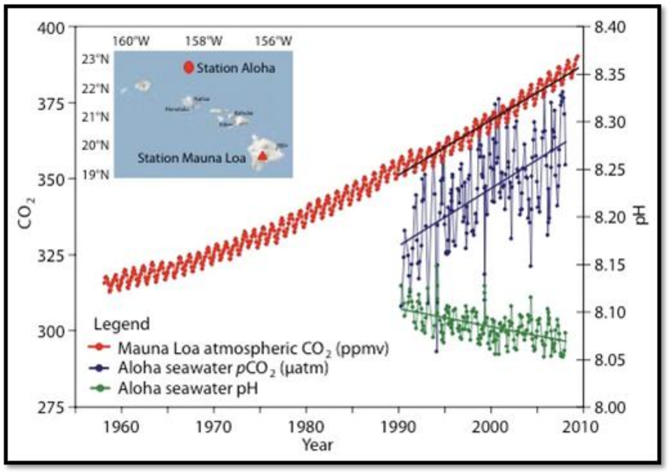


Figure 59: Time-series from 1960 to 2010 shows in red atmospheric CO2 (ppmv) at Mauna Loa and in dark blue partial pressure of CO2at Ocean Station ALOHA. The Mauna Loa time series constitutes the longest record of direct measurements of CO2 in the atmosphere. Mauna Loa data courtesy of Dr. Pieter Tans, NOAA/Earth System Research Laboratory and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/)(http://www.esrl.noaa.gov/gmd/ccgg/trends); Hawaii Ocean Time-Series (HOT)/ALOHA data courtesy of Dr. David Karl, University of Hawaii (http://hahana. soest.hawaii.edu).

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

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

$$(1) \qquad \Omega=[Ca^{+2}][CO_3^{2-}]/K^*_{SP}$$

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

Potentially adverse consequences arising from the decrease of surface seawater calcium carbonate saturation state could imply serious problems for marine calcifying organisms that use carbonate minerals as principal components to produce their skeletons and shells (figure 60). In addition, some of the most fundamental biological and geochemical processes such as marine calcifying rates, physical strength of calcareous skeletons of corals reef, shells growth, recruitment success, reproduction, survivorship, and food web dynamics in general, may be adversely affected by a decrease in the availability of carbonate ions. As a result, species that undergo calcification may become displaced by species that do not. By some estimates, calcification rates will decrease as much as 60% by the end of this century. Laboratory experiments have conclusively shown that lowering carbonate ion concentration reduces calcification rates in tropical reef builders by 7–40%. These rapid changes do not allow for natural adaptation to occur in ecosystems that have experienced only moderate changes in ocean chemistry over most of geological time. Marine organisms at risk from ocean acidification are coralline algae, green algae, benthic foraminifera, reef-building coral, deep-water coral, bryozoans, mollusks like oysters, echinoderms like the brittle star, and crustaceans such as lobsters (figure 60).

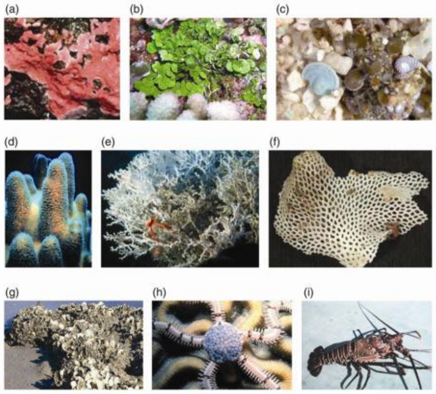


Figure 60: Representatives of major benthic calcifiers: (a) coralline algae (photo by Nancy Sefton; courtesy NOAA/CORIS); (b) Halimeda (photo by James Watt; courtesy NOAA/NMFS); (c) benthic foraminifera (courtesy P. Hallock); (d) reef-building coral (Dendrogyra cylindrus; Cmdr William Harrigan, NOAA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

5.7.2 Status of Ocean Acidification in the Caribbean

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

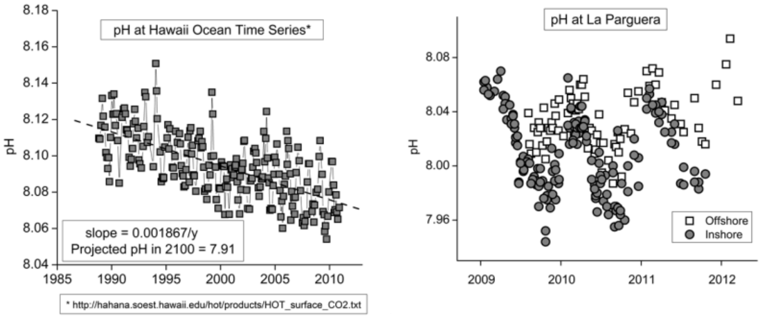


Figure 61: pH data from the Hawaii Ocean Time Series since 1985 (left) and the available pH data for the south coast of Puerto Rico since 2009 (right)

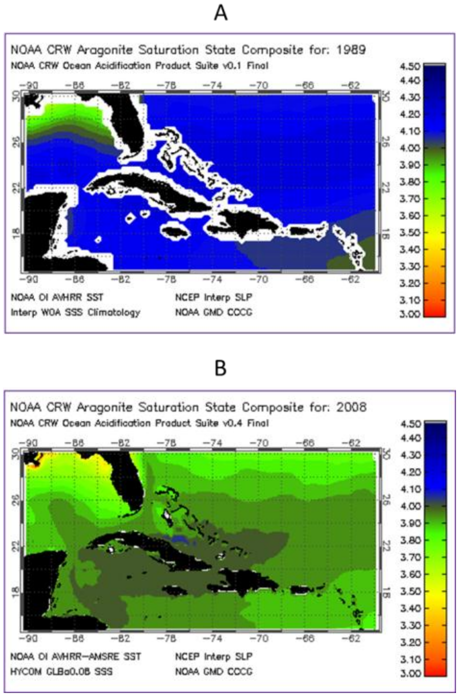


Figure 62: Caribbean Aragonite Saturation States for 1989 and 2008, showing clear decline. Aragonite saturation state refers to whether calcium carbonate is saturated (1), subsaturated (<1), or super saturated (>1). Ocean acidification causes decreased aragonite saturation states which in turn decreases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

5.7.3 Future Saturation State Scenarios for the Caribbean

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

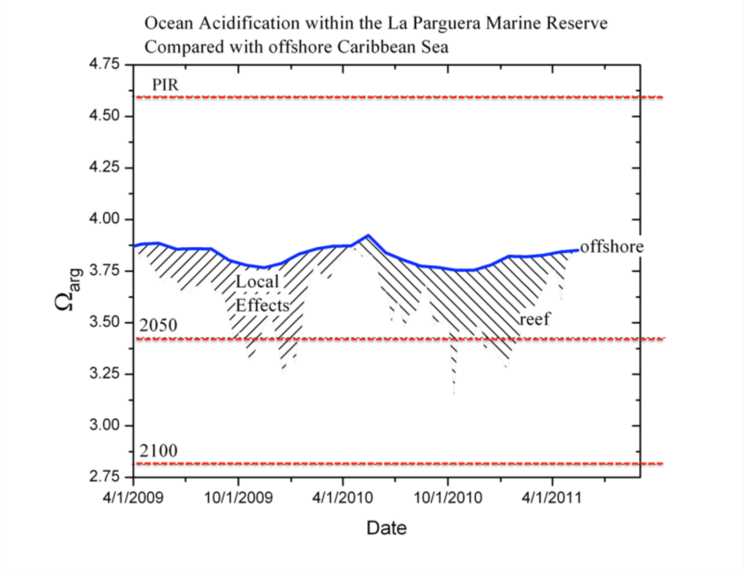


Figure 63: The figure shows measurements of annual seawater aragonite saturation state (Ωarg) at Enrique reef compared to offshore model-based estimations (blue line) (Courtesy of Dwight Gledhill, modified by Melissa Meléndez).

5.7.4 Knowledge Gaps and Future Research Needs

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

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

5.7.5 Summary of Observed and Projected Trends for Ocean Acidification

Currently, atmospheric carbon dioxide concentration has reached 395 ppm globally and because half of the carbon dioxide released both naturally and by humans is taken up by the oceans, average pH of the oceans has dropped from 8.16 to 8.05 since the year 1800. This change in seawater chemistry is equivalent to an increase of carbon dioxide concentration of about 35% and a decrease in pH of 0.1 units. As a result, there has been a global decrease in surface seawater carbonate saturation states and thus, the rate of calcification in marine calcifying organisms and the precipitation of carbonate minerals like calcite and aragonite are decreasing as well. The Caribbean and Puerto Rico saturation states of carbonate minerals reflects this global trend. For example, the values of aragonite saturate states are declining within the Puerto Rico-Caribbean region at a rate of about 3% per decade. Currently it is unknown if future saturate state scenarios will continue to follow the same rate of decline in the Caribbean as it will be largely dependent on the amount of carbon dioxide emitted to the atmosphere and oceans today and in the near future.

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