

Commonwealth Marine Economies Programme

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CARIBBEAN MARINE CLIMATE CHANGE REPORT CARD: SCIENCE REVIEW 2017
Science Review 2017: pp 1-9.

Impacts of Climate Change on the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS)

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EXECUTIVE SUMMARY

Temperature – sea surface temperature has risen by more than 1 °C over the last 100 years. Future temperature rises will have impacts on hurricanes, rainfall, coral reefs and wider marine ecosystems.

Hurricanes - The IPCC (IPCC AR5 WG1) found strong evidence for an increase in the frequency and intensity of the strongest tropical hurricanes since the 1970s in the North Atlantic.

El Niño- Understanding the influence of the El Niño - Southern Oscillation (ENSO) phenomenon on Caribbean's marine environment and timescales of variability is key to understanding how climate has been changing; projecting these relationships and ENSO itself into the future becomes vital to understand the fingerprint of global warming in the region.

Precipitation – there are a wide range of projections for future precipitation change in the area with some models finding increases in the coming century while most suggest a drier future for the region.

Ocean surface aragonite saturation state (Ω_{arg}) has declined by around 3% in the Caribbean region relative to pre-industrial levels.

Climate variability – the Caribbean region needs a smaller increase in temperature for its conditions to become distinct (climate emergence) from the envelope of climate variability over the last hundred years, compared with the rest of the world.

Introduction

Here we briefly summarise some of the key characteristics of the marine climate in the Caribbean Small Island Developing States (SIDS) **Antigua and Barbuda, Belize, Dominica, Grenada, Guyana, Jamaica, St. Lucia, and St. Vincent and the Grenadines (Figure 1)**. These marine climate characteristics set the prevailing conditions experienced by marine ecosystems and habitats and the properties through which global climate change is being experienced within oceans and seas. As the marine climate changes these characteristics will combine with or alter the external pressures to which marine ecosystems and habitats are exposed.

While the primary and best understood climate component is sea temperature, there are a wide range of other physical characteristics or properties with implications for marine biodiversity, safe, clean seas, sustainable development and exploitation of marine and maritime resource. Dedicated reviews can be found in the full CME Programme research papers

concentrating on the topics of sea temperature (Taylor & Stephenson, 2017), ocean acidification (Melendez & Salisbury, 2017) and Extreme Events (Stephenson & Jones, 2017). In this report, we briefly summarise current understanding of changes to the climate of the marine environment drawing out information from those 3 papers but also adding some information on changes in salinity, coastal erosion, mean sea-level and winds. Changes on land are not discounted as precipitation and the delivery of water through catchments to the marine environment is an important climatic driver of the marine environment. The influence of teleconnections on the regional marine climate is also important and so we also include some information on the El Niño - Southern Oscillation.

Key information sources

Beyond the 3 detailed papers, we have drawn on three other key resources for the material in this review. While we cannot cover the full literature on all topics these 3 sources give a broad.

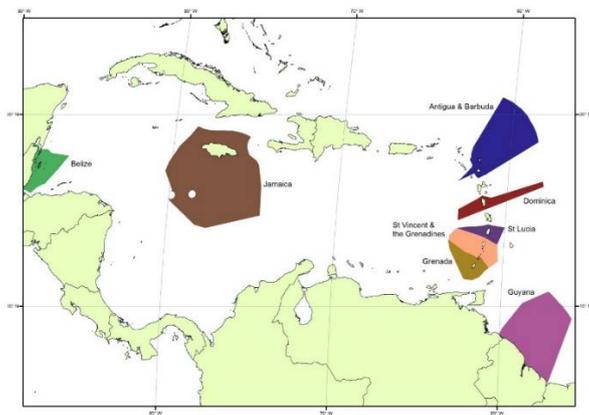


Figure 1: Maritime area of the CME Programme SIDS in the Caribbean region.

overview of the current changes being seen in the marine climate of the region alongside what could happen in the future.

IPCC Fifth Assessment Report: In 2013-14 the Intergovernmental Panel on Climate Change (IPCC, 2013, 2014a,b,c) published its 5th Assessment set of reports, synthesizing the current state of understanding on climate change impacts and adaptation. They state that "warming in the climate system is unequivocal, with many of the observed changes unprecedented over decades to millennia, including warming of the atmosphere and the ocean". This set of reports give the best global overview of the current understanding of climate change, whether that be under Working Group 1 covering the observed changes in climate seen to date as well as the projections made into the future or under Working Group 2 covering the impacts on change alongside a regional perspective. We draw out from the IPCC reports findings with direct relevance to the Caribbean region and the interests of the Small Island Developing States (Figure 1) that form the focus of this project.

NOAA Climate Change Portal - CMIP5: The huge volume of climate and earth system model output that underpinned the IPCC AR5 reports is available to display via The Climate Change Portal, a web interface developed by the NOAA/ESRL Physical Sciences Division. The ensemble of model outputs was generated as part of the Climate Model Intercomparison Project 5 and for shorthand called CMIP5. The portal gives simple climate change metrics as either maps or time-series plumes for different components of the climate system in the form of the model representation (mean and variance) of the 50-year period 1956-2005, and how the subsequent 50 years (2006-2055) are different (difference in the mean and ratio of the variances). For each variable we select all available members (between 13 and 36 depending on variable) of the CMIP5 ensemble in the portal to generate maps for the area spanning 5°N to 28°N, and from 90°W (270°) to 60°W (300°). This encompasses all of the Caribbean (including the Bahamas) as far south as Guyana. The portal contains ensembles for two projections of the future called Representative Concentration Pathways (RCP) that each give a projection of future change in radiative forcing due to greenhouse gasses. All illustrations here use the RCP8.5 projection which gives the strongest change in climate forcing

where emissions of greenhouse gases rise throughout the 21st century (Moss et al 2010).

Caribsave Climate Change Risk Atlas (CCCRA): Thirdly, in 2011 the Caribsave Climate Change Risk Atlas (CCCRA) was published and is the most detailed climate change assessment for the region currently available. It was generated using regional scale models that capture more of the spatial variations around the SIDS than the coarse resolution global models. The CCCRA predates the IPCC-AR5 and this is reflected in its use of projections based on the socioeconomic scenarios used by the IPCC in earlier assessment reports – the 3 scenarios used A2, A1B and B1 which represent high, medium high and low CO₂ emissions futures respectively. The CCCRA also used available observational data sources to identify changes that are already occurring in the climates of the Caribbean nations. The SIDS covered by the CCCRA report did not include Guyana, but had information on Jamaica, Belize, Antigua & Barbuda, St Vincent and the Grenadines, St Lucia, Grenada and Dominica.

The 3 primary information sources used for the report are supported by some further literature where necessary but this is not a full, detailed and comprehensive survey of the entire literature or new analysis of data and model outputs.

Sea temperature

The detailed review by Taylor & Stephenson (2017) identifies that it is important to continue to develop understanding of the impacts of sea surface temperature (SST) on ecosystems specific to the Caribbean since (i) some parts of the Caribbean marine ecosystem are unique and (ii) ecosystem response to SST variability in other climates may not hold true for the Caribbean. They report on studies that find temperatures have risen in the region by more than 1 °C over the last century (Antuna et al. 2015; Peterson et al. 2002; Stephenson et al., 2015; Jones et al. 2016). The IPCC AR5 regional assessment (IPCC-AR5 WG2b) stated that the Caribbean Sea warmed by 0.50°C from 1982 to 2006 (Belkin, 2009) with a confidence rating of 'very likely'. Trends over an intermediate length (from 1950 to 2009) were not statistically significant in the IPCC assessment (IPCC-AR5 WG2b) possibly due to the spatial variability in warming patterns.

The CCCRA used the Hadley Centre gridded SST product (HadISST) to identify trends over the period 1960 to 2006. They found no significant trends for either annual or seasonal temperature in the waters of Belize. All 6 other SIDS experienced significant warming trends over this period and these are strongest on the warmest periods of the year. The weakest trends were in the waters surrounding Jamaica where they found that the Northern Hemisphere summer and autumn seasons (June-August -JJA; Sept-Nov -SON) warmed by 0.07°C per decade. Around Grenada the trends over these seasons were found to be 0.08°C per decade and around St Vincent and the Grenadines 0.09°C per decade. For St Lucia, Dominica and Antigua & Barbuda the same seasonal trends were significant at 0.10, 0.11, and 0.12°C per decade respectively. In these 3 SIDS trends were also significant in the SST average over the full

calendar year, but weaker than the seasonal trends at 0.07, 0.08 and 0.09°C per decade respectively.

Over the course of the 21st century, the global ocean will warm in all scenarios of emissions – called Representative Concentration Pathways in IPCC AR5. They report that the strongest projected warming of the ocean SST will be in the subtropical and tropical regions (IPCC AR5). The CMIP5 RCP8.5 projections (Figure 2) show average SST warming over the area is relatively homogeneous with the coming 50 years projected to be between 0.9 and 1.1°C warmer than the five decades that preceded them (Figure 2). The change is slightly greater in the west of the region (including the waters of Belize and Jamaica) than in the East (from Antigua and Barbuda to Guyana). By the 2080s, half of the model ensembles project that SST in the region will be 2-3°C warmer than the period 1976-2005 (Figure 3). The IPCC AR5 (WG1) reported that the summer (JJA) model projections exhibit greatest warming in the region. They also reiterate that Greenhouse Gas driven long-term increase in SST must be considered in conjunction with shorter-term decadal changes. The CMIP5 models also represent SST in the area with an area of lower variance further north, the variability of SST around the SIDS appears to decrease in general but greater decreases are shown around the northern SIDS (Jamaica and Belize).

Away from the El Niño region of the Pacific, tropical sea surface temperature tends to vary less over seasonal to interannual timescales than in the subtropics and this is evident for the Caribbean region (see Climate portal global maps). These ‘natural’ scales of variability are closer in magnitude to the decadal scale trends, which means that the Caribbean region needs a smaller increase in temperature for it to become distinct (climate emergence) from the envelope of climate variability over the last hundred years (Hawkins & Sutton, 2012; Mora et al 2013).

Ocean acidification

A full and detailed description and review of ocean acidification in the region is given in Melendez & Salisbury (2017) in which they reiterate that the process of ocean acidification is well understood and has “potentially detrimental consequences for marine life and dependant human communities”, and that this is particularly so for the Caribbean SIDS partly due to the knock-on effects of OA impacts on coral reefs.

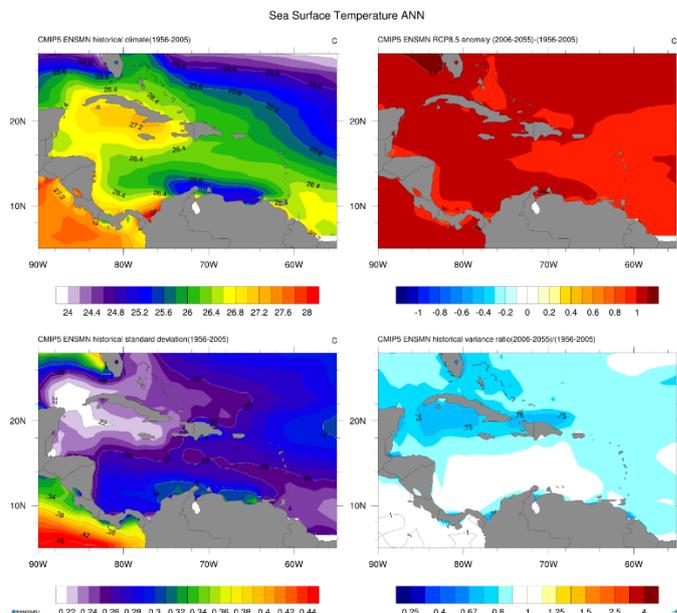


Figure 2: Annual sea surface temperature output averaged across the full CMIP5 ensemble (27 members) of models under a high emissions scenario RCP8.5. Left panels: the CMIP5 representation of historical conditions (1956-2005 – upper panel: mean lower panel: standard deviation[de-trended]). Right panels: the comparison between the historical period and the subsequent 5 decades (2006-2055 – upper panel: different in the mean; lower panel: ratio of the de-trended variance).

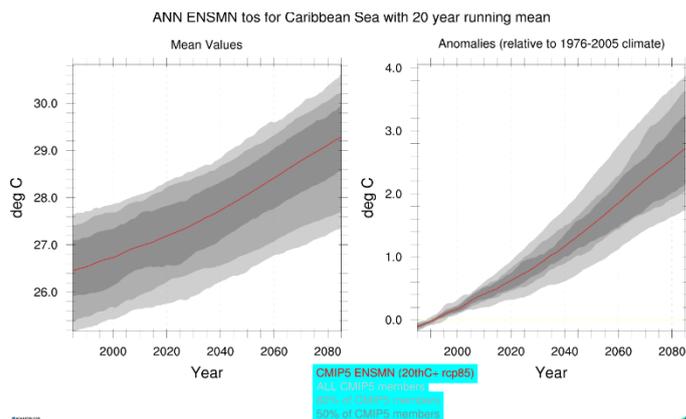


Figure 3: Progression of annual average sea surface temperature of the Caribbean Sea output averaged across the full CMIP5 ensemble (27 members) of models under a high emissions scenario RCP8.5. Left panel: the envelope and mean of absolute temperature modelled by the ensemble. Right panel: the envelope of temperature anomaly with respect to a climatology period 1976-2005.

When CO₂ is absorbed by surface sea water the concentration of the bicarbonate ion (HCO₃⁻) increases, while the amount of carbonate ions (CO₃²⁻) and pH of the surface ocean waters decrease. This has already had a significant impact on ocean chemistry, with estimates of mean surface ocean pH decrease of ~0.1 (equivalent to a ~30% increase in hydrogen ion (H⁺) concentration), from a value of ~8.18 around the time of the industrial revolution (Caldeira & Wickett, 2003). The major immediate effect is at the surface in terms of direct pH change but this spreads to depth with time, and at depth the major impact on ecosystems will be through changing saturation horizons.

Saturation horizons are particularly important for shell forming organisms. They signify the depth at which aragonite and calcite, the two forms of calcium carbonate minerals, stop being formed and start to dissolve. Aragonite is the more soluble form and the aragonite saturation horizon (ASH) is shallower than the calcite saturation horizon (CSH). The depths of these horizons naturally vary within the oceans, the ASH is generally shallower in the North Pacific (< 600 m) than in the North Atlantic (>2000 m - Orr *et al* 2005; Guinotte *et al.*, 2006). Continued uptake of anthropogenic CO₂ by the ocean is making the ASH shallow, although this varies with location and season.

The IPCC report on regional climate change within their AR5 (IPCC-AR5 WG2b) summarised a report from Gledhill and co-authors (Gledhill *et al.*, 2008) giving a high confidence assessment of 'very likely' to the finding that the Caribbean region had experienced a sustained decrease in aragonite saturation state from 1996 to 2006.

Over the course of the 21st century the pH of the surface of the global ocean is expected to decrease due to the increase in concentration of CO₂ in the atmosphere above it. For the models in the CMIP5 ensemble that have surface ocean pH (13 members are in this ensemble available in the NOAA Climate Change Portal), the expected change is reflected in a decrease of pH of the order of 0.1 for the 2006-2055 period versus the previous 5 decades. The variance of the pH in the modelled future appears to decrease by as much as 50% in this period.

Sea-level rise & storm surge

Sea-level rise (SLR) can cause flooding, coastal erosion and the loss of coastal regions. It reduces the return period for extreme water levels (storm surges) and threatens existing coastal ecosystems. Future impacts from SLR will be felt most keenly on low-lying coastlines with high population densities and relatively small tidal ranges (Kundzewicz *et al.*, 2001). Decisions on adaptation measures (e.g. coastal defence or re-alignment) will affect coastal communities and ecosystems. We tend to think of sea level rise as a global change across all the oceans, but this overall total can mask strong regional variations associated with local processes and regional circulation.

The IPCC regional impacts report (IPCC-AR5 WG2b) made two key statements about sea level rise in the region. Firstly, the regional change over the period 1950 to 2000 was 2-3 mm/year (Church *et al.*, 2004; Zervas, 2009) which as a mean rate was diagnosed by Palanisamy *et al.* (2012) to be similar to the global average (1.8 mm/year). Palanisamy *et al.* (2012) also demonstrates the spatial variability in trend component of sea level change experienced across the region (greatest around Antigua and south to Grenada and least in the central Caribbean Sea and north of Jamaica) and also how variability in sea-level correlates with periods of high (La Niña) and low (El Niño) hurricane and storm activity. In 2011 the CCCRA reported for all the SIDS that rates of sea-level rise observed at Caribbean tide gauge stations were in the range 1.5 to 3 mm/year, covering different periods of the 20th Century.

In the IPCC 5th Assessment report, global mean SLR by 2100 under the highest RCP 8.5 scenario was 0.45 (5th percentile) to 0.82 m (95th percentile). These estimates do not include some of the plausible events that are not well understood but could lead to sea-level rises exceeding 1 m such as, for example, the collapse of marine-based sectors of the Antarctic ice sheet. In their detailed information as part of the extremes paper, Stephenson and Jones (2017) point to the suggestion that "gravitational and geophysical factors will lead to the region experiencing a greater rise in sea levels than most global areas. In fact, sea level rise over the Northern Caribbean may exceed the global average by 25 % (IPCC-AR5 WG1)." In their Table 6 (Stephenson and Jones, 2017) they reproduce CMIP5 sea-level projections for the SIDS identifying that the likely range of change under RCP8.5 for the period 2081-2100 relative to 1986-2005 is, for example, 0.73-1.05m in Jamaica and 0.80-1.15m in Belize.

The CCCRA points out, for all the SIDS covered, that storm surge heights will be increased by the underlying increases in sea level but that these will be enhanced by increases in hurricane and tropical storm intensity. The third factor that is important for storm surge increase is the bathymetry and topography around the individual SIDS which determine the sensitivity of the region to storm surge by influencing the height of the storm surge generated by a given storm (CCCRA).

Wind, tropical cyclones & hurricanes

The CCCRA reports identified some evidence for significant trends in monthly mean windspeeds using the ICOADS dataset, over the years 1960-2006, changes which may or may not be due to ongoing global warming. For Belize and Jamaica, they report uncertainty in any trends in monthly windspeeds but do suggest a significant increase around Jamaica. Around Grenada the trends are only significant in summer and autumn (at about 0.25 ms⁻¹/decade). For the other SIDS reported (Antigua and Barbuda, Dominica, St Lucia and St Vincent and the Grenadines) they found increasing trends in all seasons over the periods 1960-2006 ranging from 0.55 ms⁻¹/decade over Antigua and Barbuda to 0.3 ms⁻¹/decade over St Lucia.

The greatest impact of wind is seen during extreme events known as tropical cyclones (when speeds are >39mph) and the strongest type of tropical cyclone (>74mph) called a hurricane in the Atlantic. Hurricane season officially runs from June through November. Although hurricanes are generally unpredictable, the peak season is at a different time in different areas. In the Eastern Caribbean and along the US East Coast, the season tends to be peak between mid-August and mid-September. In the Western Caribbean, it picks up in mid-September and stretches into early November. Early- and late-season hurricanes (June and mid- to late-November respectively) are rare but not unprecedented.

The 1980-2010 long-term average is for 12 tropical cyclones to occur in the North Atlantic in a hurricane season, of these the average that are strong enough to be classified is 6 (<http://www.metoffice.gov.uk/weather/tropicalcyclone/seasonal/northatlantic2016>).

The IPCC (IPCC AR5 WG1) found strong evidence for an increase in the frequency and intensity of the strongest tropical cyclones since the 1970s in the North Atlantic. Diagnosis of longer term change (100 year scale) is not justified given the evidence available. The CCCRA report in a similar way with evidence supporting increased intensity of storms over the last three decades but that this is not clearly part of a longer-term trend. Stephenson and Jones (2017) make the point that tropical cyclone activity is also dependent on large-scale atmospheric and oceanic influences varying over years (ENSO) and decades (Atlantic Multidecadal Oscillation, AMO).

The IPCC reported (IPCC AR5 WG1) that “while projections indicate that it is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and rainfall rates, there is lower confidence in region-specific projections of frequency and intensity”. The improvements in model resolution and downscaling allowed them to give a marginal confidence of “more likely than not” to the statement that the “frequency of the most intense storms will increase substantially in some basins under projected 21st century warming”.

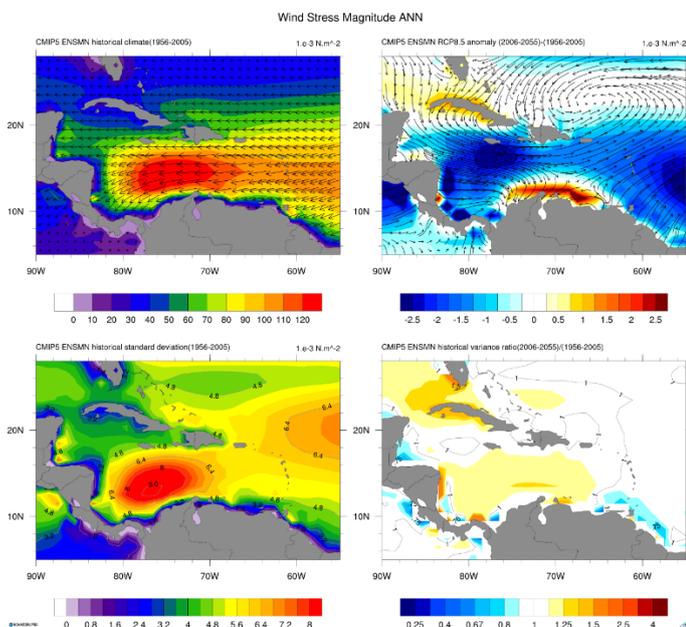


Figure 4: Annual surface Wind Stress Magnitude Annual output averaged across the full CMIP5 ensemble (14 members) of models under a high-emissions scenario RCP8.5. Left panels: the CMIP5 representation of historical conditions (1956-2005 – upper panel: mean lower panel: standard deviation[de-trended]). Right panels: the comparison between the historical period and the subsequent 5 decades (2006-2055 – upper panel: different in the mean; lower panel: ratio of the de-trended variance).

The CCCRA reported that the projections from their downscaled Regional Climate Models indicated potential decreases in the frequency of tropical cyclone and again that projecting El Niño change has a strong control on projections of extreme winds in the Caribbean.

The CMIP5 projections (Figure 4) show average windstress decreasing in the broad easterly trade winds between 10 and 20 degrees N and for the maritime areas of the SIDS under

consideration. The area changes have a lot of spatial structure associated with the prevailing wind and sea level pressure systems in the area. Variance in the modelled annual windstress patterns appears to increase over the Caribbean Sea in general but for the SIDS the change in variance between the future and present model climate are small.

The CCCRA reported changes in windspeeds in the RCMS that varied between model set up depending on the global model used as the driver. Where decreases were evident they were generally smaller (0.1 m/s) than when increases were projected, which could be greater than 1 m/s.

El Niño (or ENSO)

The El Niño - Southern Oscillation phenomenon is a mode of climate variability that acts within the Pacific but has impacts globally through teleconnections. The events are irregular but tend to work on a 2-5 year timescale that imposes its signal within interannual climate variations across the world. Of relevance to the Caribbean region are its effects on the local rainfall and storm climate – during El Niño years rainfall in the region is increased particularly in the north while tropical cyclones (including hurricanes) occur less frequently. The IPCC and CCCRA both note the important role that El Niño (or ENSO) plays in the regional climate, and that this influence can be expected to continue. The representation of El Niño (ENSO) in climate models is improving and the IPCC expect it to remain (with high confidence) the dominant mode of interannual climate variation in the future. This role allied with increased moisture in the atmosphere leads to an inference that the regional precipitation variations associated with El Niño are likely to become stronger. However, the changes in El Niño over the next century itself and the resultant global impacts (including in the Caribbean) are still uncertain (IPCC AR5).

Hydrological regime: Salinity, rainfall, rivers and catchments

Salinity is an important property of seawater. As one of the controls of its density (with temperature) variations in salinity are dynamically important to the oceans circulation. It acts as a tracer of seawater origin and can be seen as the flipside of the freshwater taking part in the global water cycle which in accelerating may be making the tropics more saline (increasing evaporation) at the same time as freshening high latitudes (increased precipitation). The IPCC report with confidence of ‘very likely’ that the regional trends in sea surface salinity since the 1950s have followed the pattern expected of a stronger hydrological cycle. They report that the mean difference between high- and low-salinity regions increased by 0.08 to 0.17, and that the Atlantic has become saltier while the Pacific and Southern Ocean have freshened.

Regionally and locally changes in precipitation over the catchments in to the region’s seas will have a strong effect on salinity. Changed precipitation can have a more direct impact to society as surface water catchments can be the main water supply, which may be difficult to maintain during periods of little rainfall (IPCC AR5 WG2). The IPCC (IPCC AR5 WG1) reported,

with medium confidence, that rain in the tropical land areas has increased over the last decade, following the mid-1970s to mid-1990s drying trends that had previously been reported in AR4. Trends in precipitation in the region are difficult to identify as there are large interdecadal variations, either in the intensity of prevailing winds or through the influence of Pacific or Atlantic variability (IPCC-AR5 WG2b). The CCCRA report found no significant trends in mean precipitation for the period 1960-2006 in the SIDS that they considered, just noting some decreases too small to be significant.

For Jamaica, the CCCRA did find that observed rainfall extremes (1- and 5- day annual maxima) decreased between 1973-2008 along with the proportion of total rainfall occurring during 'heavy' rainfall events.

In summarizing changes in SST around the Caribbean SIDS, Taylor & Stephenson (2017) highlight the link between SST and rainfall in the region. They describe the effect that leads higher regional SST to generate more rainfall, and also bring forward the rainfall season when SST is high early in the year. These SST relationships provide some link to the climate multi annual to multi decadal timescale variations associated with ENSO and AMO (both positively correlated with Caribbean SST).

Consecutive dry days (CDD) are a useful climate index in relation to occurrence of drought conditions and were reported in Stephenson et al. (2012) who found that on a regional basis CDD decreased slowly but steadily from the 1960s to the mid-1990s after which the trend was upwards to 2010. The increase in CDD overall is most evident in the north of the region and less so over the SIDS considered here. At the same time, they found that heavy precipitation events had increased, so by combining these results Stephenson et al (2012) characterise the change as longer dry spells interrupted by heavier downpours.

The IPCC AR5 reported that salinity is projected to increase in the tropical and sub-tropical Atlantic. (IPCCAR5 WG1) This is borne out in the CMIP5 projections (Figure 5) which show average surface salinity increasing over the area which is greatest near Belize and Jamaica and weakest in the generally fresher waters of the Guyana Current. The coming 50 years are projected to be between 0.1 and 0.3 more saline than the 5 decades that preceded them (Figure 5). Future salinity variance

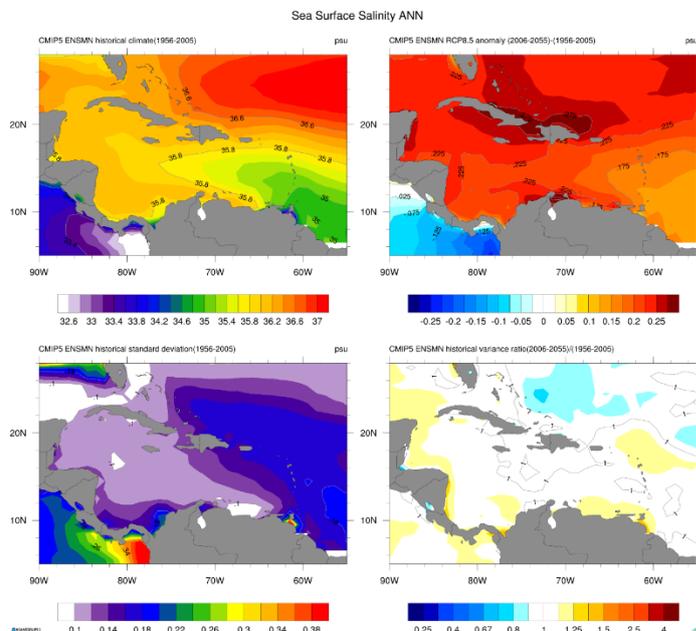


Figure 5: Annual Sea Surface Salinity output averaged across the full CMIP5 ensemble (27 members) of models under a high-emissions scenario RCP8.5. Left panels: the CMIP5 representation of historical conditions (1956-2005 - upper panel: mean lower panel: standard deviation[de-trended]). Right panels: the comparison between the historical period and the subsequent 5 decades (2006-2055 - upper panel: different in the mean; lower panel: ratio of the de-trended variance).

is broadly similar to the present with some suggestion of higher variability in the modelled future around the coast of Belize in particular. The model salinity ensemble average across the area rises from about 36.0 to almost 36.8 on an ensemble mean basis by the 2080s with half of the model ensemble members projecting that salinity in the region will be 0.55-95 more saline than the period 1976-2005 (NOAA Climate Change Portal).

The IPCC AR5 regional report (IPCC AR5 WG1) suggests that "warm-season precipitation will decrease in the Caribbean region, over the coming century". They note that tropical precipitation changes vary regionally and the CMIP5 projections (Figure 6) show average precipitation generally decreasing across the SIDS but with increases possible in the north towards Florida and the Bahamas and in the south west near Panama. The projection ensemble models these decreases to be greatest over Guyana, and then decreasing north of Grenada with the coming 50 years projected to be between 40 and 80 mm/year in these south-western SIDS (Figure 6). Future precipitation variance is broadly similar to the present with some suggestion of higher variability in the modelled future. The model precipitation is very uncertain with the models having very different levels of rain and change in rainfall throughout the period where the ensemble variation is much smaller than the range of the model estimates. Half of the model ensemble members projecting that the region will experience between 4 and 18 mm/year less rainfall than the period 1976-2005 (Figure 7).

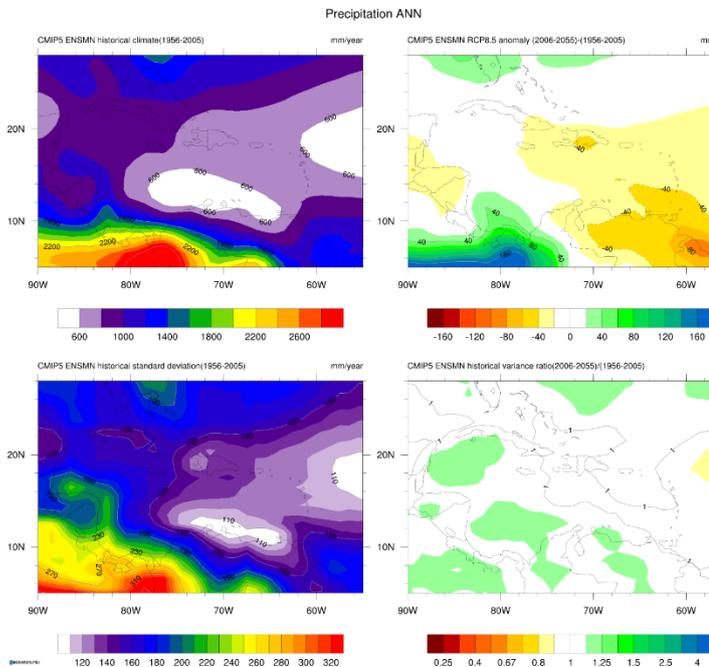


Figure 6: Annual precipitation output averaged across the full CMIP5 ensemble (36 members) of models under a high-emissions scenario RCP8.5. Left panels: the CMIP5 representation of historical conditions (1956-2005 - upper panel: mean lower panel: standard deviation[de-trended]). Right panels: the comparison between the historical period and the subsequent 5 decades (2006-2055 - upper panel: different in the mean; lower panel: ratio of the de-trended variance).

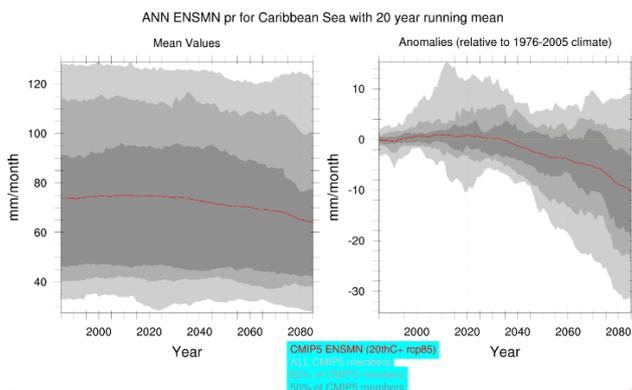


Figure 7: Progression of annual average precipitation over the Caribbean Sea output averaged across the full CMIP5 ensemble (36 members) of models under a high emissions scenario RCP8.5. Left panel: the envelope and mean of absolute temperature modelled by the ensemble. Right panel: the envelope of temperature anomaly with respect to a climatology period 1976-2005.

Coastal erosion

The IPCC regional impacts report (IPCC-AR5 WG2b) cites Scott and co-authors (2012) who identified that approximately 29% of Caribbean resorts are within 1 m of the high tide mark and 60% are at risk of beach erosion from sea-level rise (Scott *et al.*, 2012a).

The Bruun Rule (Bruun, 1962) is a useful tool (Cambers, 2009; Scott *et al.* 2012) to understand the vulnerability of a beach to

SLR. It predicts that as sea level rises, sand is eroded from the upper beach and deposited offshore to maintain an equilibrium profile. This results in beach retreat so that for every 1 cm of sea-level rise, the beach retreats inland by 1 m (Cambers, 2009; Scott *et al* 2012).

A paper by Cambers (2009) provides a lot of information on beach erosion in the Caribbean focussed on 8 islands including the SIDS Antigua and Barbuda, Grenada and Dominica. By monitoring beaches over the period 1985-2000 they found an average beach erosion trend of 0.5 m/year and that this is higher where hurricanes are more frequent. They suggest anthropogenic factors are causing the erosion alongside climate change and variability.

Scott *et al.* (2012) looked at erosion through the issue of vulnerability of resorts to beach erosion identifying 906 major coastal resort properties in 19 Caribbean Community (CARICOM) countries. They assessed their potential risk to a regional 1 m sea level rise. About 60% of the resort properties would be at risk of beach erosion damage associated with this sea-level rise scenario (Scott *et al.* 2012). Of the SIDS Belize was identified as having the highest number of resorts at risk of sea-level rise erosion damage with over 80% of resort properties at risk to erosion of 50 m.

Different vulnerability to this erosion between countries is explained by three factors (Scott *et al* 2012):

- 1) the geophysical characteristics of the islands and their different coastal topographic settings (e.g. extensive low coastal plains, low lying islands largely composed of unconsolidated materials, volcanic islands);
- 2) the proximity of resort properties to the coastline; and
- 3) the level of coastal structural protection in place to prevent erosion impacts.

Further development of understanding to support adaptation

Availability of future projections at timescales to support decision making (e.g. near term, medium term, long term). Answering the question of what could happen in the future has generally been done using climate projections where a climate model run under a particular emissions scenario is used to examine plausible conditions 50 to 100 years in the future. However, impacts and planning activities tend to occur over seasonal to decadal timescales where the changes or one off events can be of greater magnitude than the long term transient change. In recent years, studies have begun to demonstrate the potential for skilful climate predictions or forecasts over seasons to decades that include this shorter-term climate variability alongside the effects of long term climate change. Particularly important for the Caribbean has been the increasing understanding of the seasonal predictability of El Niño and how this can help forecast storms and precipitation in the region. Models now have skill in predicting the number of tropical storms and the Met Office issue

a forecast for North Atlantic Tropical Cyclones and Hurricanes each May. The modelling system they use was successful in identifying the difference between and change from a high activity year 2005 to weak season in 2006 (Camp *et al.* 2015).

ENSO representation in longer term climate models. The IPCC recognised that this El Niño influence means that its representation within climate projection models is an important limiting factor in our ability to interpret and have confidence in Caribbean projections. In its 5th assessment report, the IPCC identify low confidence in the ability of the global climate models to project the climate change effect on El Niño. For precipitation, any El Niño associated variability will probably intensify simply due to increased moisture in a warmer atmosphere. (IPCC AR5 WG1).

The CCCRA identified several limitations in our understanding of impacts in the region which would limit the region's capacity to adapt:

- 1) spatial/temporal coverage of observations alongside short records; and
- 2) resolution of models and the ability to represent small islands even in downscaled Regional Climate Models.

In order to support adaptation more needs to be understood about the socio-economics of these changes which has major implications for decision-making and planning.

Citation

Please cite this document as:

Dye, S.R., Buckley, P.R., Pinnegar, J.K. (2017) Impacts of Climate Change on Settlements and Infrastructure in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS), Caribbean Marine Climate Change Report Card: Science Review 2017, pp 1-9.

The views expressed in this review paper do not represent the Commonwealth Marine Economies Programme, individual partner organisations or the Foreign and Commonwealth Office.

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