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

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EXECUTIVE SUMMARY

Sea surface temperatures (SSTs) in the Caribbean are an important determinant of Caribbean climate and a significant contributor to the health of the regional marine ecological systems.

Over the last century to present, the entire north tropics has warmed. The wider Caribbean (5°–35°N and 100°–55°W) has seen an increase in SSTs of 1.08±0.32°C per century and the Antilles (defined as the region covering the insular countries in the Caribbean) has seen a slightly higher increase at 1.32±0.41°C per century.

Warmer future SSTs will impact the climate of the region, future hurricane intensities, coral reefs and other marine ecology.

Future SST trends in the Antilles may range between 0.39 and 2.21°C per century for scenarios representing low CO_2 emissions through business-as-usual. For the wider Caribbean the range is between 0.43 and 2.15°C per century.

By mid-century, there is projected to be a “blanket” of uniformly warm temperatures across the Caribbean Sea throughout the entire year. For higher emissions scenarios, the projected SSTs may exceed 28 °C across the entire Caribbean Sea year round by mid-century.

What is Already Happening?

Introduction

Sea surface temperatures (SSTs) in the Caribbean are an important modulator of the climate of the Caribbean region, as well as a significant contributor to the health of the regional marine ecological systems. In this brief paper, the mean annual variation of Caribbean SSTs is examined along with what is currently known about its historical and future changes. The paper closes with a brief examination of the significance of changes in Caribbean SSTs for the region and an indication of where gaps in our knowledge or action may lie.

Annual SST variation and the role of the Atlantic Warm Pool (AWP)

SSTs in the Caribbean Sea undergo small variations year round with a mean annual range of approximately 3°C, and a peak in September. Monthly variations are linked to the appearance and annual evolution of the Atlantic Warm Pool (AWP) (see Figure 1). At the start of the year, SSTs across the Caribbean Sea are at their coolest and below 26.5°C (generally considered as the threshold for convection to occur). By March the AWP first appears in the Gulf of Mexico, placing there a pool of warm waters in excess of 26°C. The eastern Caribbean is by comparison 0.5°C cooler.

Thereafter the AWP warms while gradually spreading eastward, so that by the start of the Caribbean's early rainfall season in May, SSTs in excess of the 26.5°C threshold reach the Leeward Islands with even warmer waters in the western Caribbean Sea. By August (the start of the late rainfall season) very warm SSTs cover the entire Caribbean and by October (the peak of the hurricane season) warm waters in excess of 28°C typically extend from the Gulf through to the west coast of Africa. At the peak extent of the AWP in September/October temperatures of approximately 29.5 C cover the waters surrounding Jamaica, Cuba, and Hispaniola, while the waters of the eastern Caribbean are about a degree less. During the last 3 months of the year, the warm pool progressively retracts to the western Caribbean resulting in the ocean surface temperatures across the entire region gradually cooling toward their northern hemisphere winter minimum.

Historical Change

A number of studies have recently emerged examining the historical trend in Caribbean SSTs. Antuna et al. (2015) examine tropical north Atlantic SST trends between 1906 and 2005 using a globally reconstructed observational dataset. They find that the entire north tropical Atlantic including the Caribbean Sea has warmed over the past century concomitant with the warming observed in regional surface temperatures (Peterson et al. 2002; Stephenson et al., 2015; Jones et al. 2016). Their study shows that the wider Caribbean (5°–35°N and 100°–55°W) has seen an increase in SSTs of the order 1.08±0.32°C per century while the Antilles (defined as the region covering the insular countries in the Caribbean) has seen a slightly higher increase at 1.32±0.41°C per century (see Figure 2). These magnitudes are consistent with those reported for the tropics and subtropics by Deser et al. (2010) who similarly found positive SST trends in the range of 0.4–1.6°C per century for the period 1900–2008.

If only the sub period 1972–2005 is considered, the corresponding trends are slightly higher at 1.18±0.49°C per century and 1.41±0.68°C per century for the wider Caribbean and the Antilles respectively (Antuna et al. 2015). Glenn et al. (2015) also examine SST trends for the wider Caribbean over the more recent period 1982–2012. Using a blended global product that combines satellite and in situ data they find a statistically significant regional increase in SSTs of 0.015°C per year or 1.5°C per century, similar to that reported by Antuna et al (2015) for the Antilles. Glenn et al. (2015) also note consistency between the magnitude of their warming trends with those identified by other studies based on reanalysis, point-based observations, and future projections (e.g. studies by Jury, 2011 and McLean et al.,2015). They however also note that the wider Caribbean trend is larger than the global SST trend of 0.011°C per year or 1.1°C per century for the same period i.e. the global trend is present in the Caribbean region but is more intense.

Spatially the observed warming trend increases to the southeast. Antuna et al. (2015) estimate that for the 1906–2005 period the SST trends are approximately 0.75°C per century around Cuba but

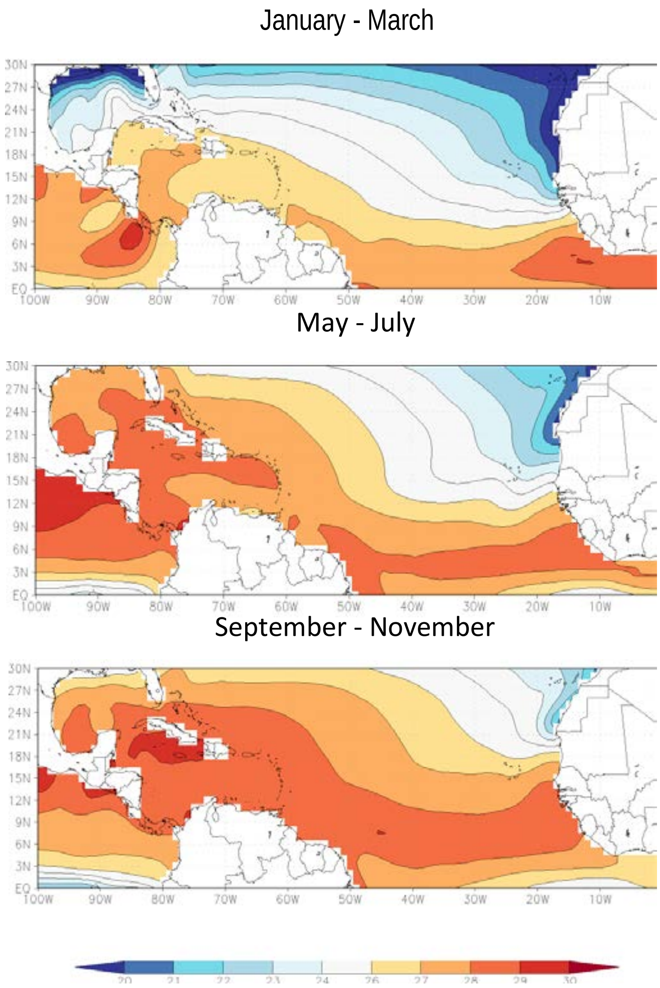


Figure 1: Average SST (°C) during January to March (top), May to July (middle), September to November (bottom panel). Warm waters associated with the Atlantic Warm Pool (AWP) appear first in the western basin early in the year and then gradually spread eastward eventually covering the entire region. The data above are averaged over the period 1982 to 2016. Data source: Reynold's Optimum Interpolated SST dataset.

increase to 1.25°C per century in the southernmost area of the Lesser Antilles or to 1.75°C per century if only the later period 1972–2005 is considered. Main intensification of the trend occurs in the southernmost area of the Lesser Antilles and off the Caribbean coast of Colombia and Venezuela. In contrast, Antuna et al. (2015) noted insignificant or even negative trends in the Gulf of Mexico. The same spatial pattern of warming and cooling in the high latitudes of the Caribbean is also found for trends derived from satellite measurements and observations for the more recent period of 1985–2009 (Figure 3). The observed cooling in the higher latitudes has been attributed to the increasing intensity and frequency of North American cold fronts that particularly impact this region (Melo-González et al., 2000).

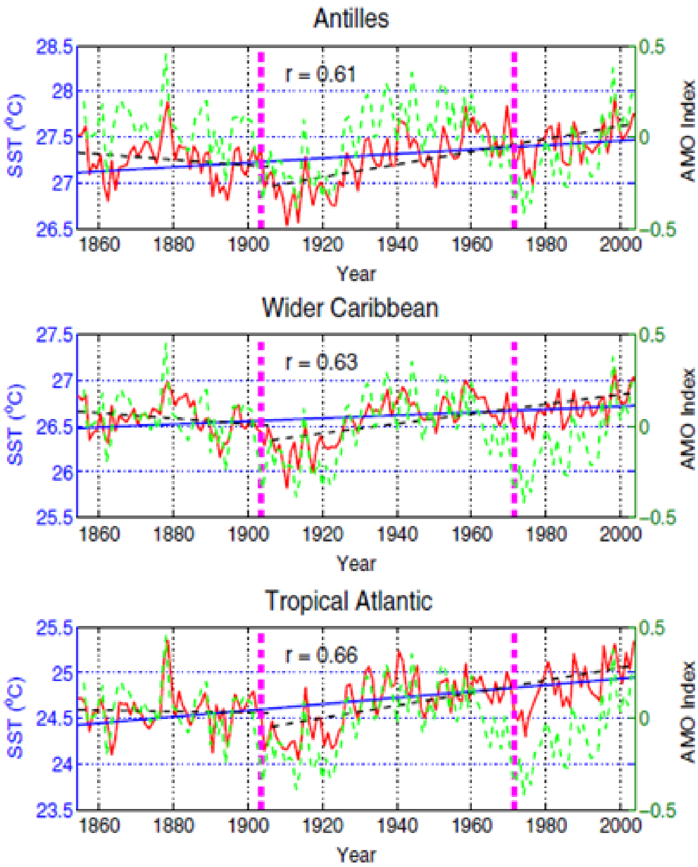


Figure 2: Annual area average of SST from observations (red solid lines) for three tropical north Atlantic regions for the period 1854-2005. The least squares linear regression trend lines are shown for the entire period 1854–2005 (blue solid lines) and for the sub-periods 1854–1905 and 1906–2005 (black dashed lines). The Atlantic Multidecadal Oscillation (AMO) Index is also plotted (green dashed lines) for the entire period. Correlation coefficients between the two time series are noted. Diagram source: Antuna et al. (2015).

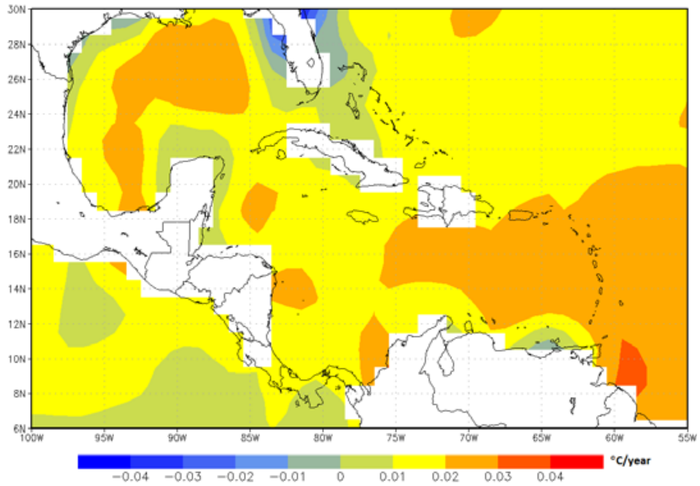


Figure 3. Detected SST trends (°C/yr) for the Intra-Americas Region over the period 1982–2016. Data is from NOAA Optimum Interpolation SST Dataset.

Seasonally, maximum warming trends occur during the summer for both the Antilles and the wider Caribbean (1.68 and 1.62°C per century respectively for the period 1972–2005) while minimum trends are found during northern hemisphere winter and spring (Antuna et al., 2015). When the comparison is made between the early and late Caribbean rainfall season for the period 1982-2012, statistically significant trends of 0.0161°C per year and 0.0209°C per year respectively are found (Glenn et al., 2015), reinforcing the idea of greater warming later in the year. In comparison, the Caribbean dry season which corresponds to northern hemisphere winter, shows an increase of 0.0077°C per year, which is not statistically significant.

Other Time Scales of Variability

The linear trend is not the only time scale of variability present in time series of Caribbean SSTs. Another long mode of variability present in the data is linked to the Atlantic Multidecadal Oscillation (AMO). The AMO is a natural cycle of variation in basin-wide North Atlantic Ocean SSTs with a period of 60-80 years (Enfield et al., 2001; Sutton and Hodson, 2005). In the historical record it is represented by alternative periods of SST warming and cooling lasting approximately 30-40 years. The AMO swung into a warm phase in the late 1990s which may account for some of the warming trend seen in Caribbean SSTs in recent times. Both Antuna et al. (2015) and Glenn et al. (2015) report significant correlation coefficients between tropical north Atlantic SSTs and the AMO (see again Figure 2), with high values over the Caribbean Sea versus lower and statistically insignificant correlations over the waters just south of the USA.

A second mode of variability present in Caribbean SSTs is linked to the El Niño Southern Oscillation (ENSO). ENSO manifests as a warming of SSTs in the central and eastern equatorial Pacific which generally peaks in December after onset and occurs on an irregular time scale of every 3-7 years. There is a tendency for the north tropical Atlantic to warm four to six months after the mature ENSO phase so that during northern hemisphere spring or at the start of the early Caribbean rainfall season for the year after an El Niño the Caribbean Sea is anomalously warm (Enfield and Mayer, 1997; Taylor et al., 2002). A number of studies have established a statistically significant relationship between Caribbean SSTs and strong ENSO occurrences (Taylor et al. 2002; Glenn et al., 2015) with the latter accounting for some of the periodic peaks seen in the time series of Figure 2.

What Could Happen?

There are only a few studies which examine how north tropical Atlantic SSTs are likely to change in the future due to climate change. Antuna et al. (2015) determine future Caribbean SSTs for the period 2000-2099 for both a business-as-usual and a low CO_2 emission scenario using a coupled ocean-atmosphere model. Their results are summarized in Table 1 and suggest a continuation of the warming trend of the recent historical past. Under the business-as-usual scenario the SST trends in the Antilles range between 1.39 and 2.21°C per century and for the wider Caribbean between 1.37 and 2.15°C per century. Under the low CO_2 scenario the trends in the Antilles and wider Caribbean are between 0.39 and 1.15°C per century and 0.43 and 1.29°C per century respectively.

Table 1: Projected north tropical Atlantic SST trends (°C per century) for two future scenarios. Bracketed numbers indicate standard errors. Adapted from Antuna et al. (2015)

	SST Increase (°C per century)	
	Business-as-usual scenario	Low CO_2 scenario
Antilles	1.80 (0.41)	0.77 (0.38)
Wider Caribbean	1.76 (0.39)	0.86 (0.43)
Tropical Atlantic	1.72 (0.42)	0.70 (0.42)

Nurse and Charlery (2014) also produced projections of Caribbean SSTs for two future scenarios using skin temperature from a regional climate model as a proxy. They do so for three future time slices: 2000–2009, 2050–2059, and 2090–2099. Their results similarly show that SSTs will increase across the region throughout the twenty-first century irrespective of scenario examined. They note, however, that the mean decadal rate of warming increases from 0.13°C for the period 2000–2029, to 0.31°C for 2030– 2059, and eventually reaches 0.41°C for 2070–2099 i.e. that the warming intensifies.

The work of Nurse and Charlery (2014) also suggests other features about the future warming of Caribbean SSTs. These include the following:

- Through 2050s for the northern hemisphere winter months (January-March), the warming is lower in the northern and northwestern Caribbean (approximately 0.5-1.0 °C above observed mean temperatures for 2000-2009) when compared to the remainder of the region (approximately 1.0-1.5°C above mean temperatures for 2000-2009).
- By mid-century, the expanding and contracting of the AWP previously noted as an important feature of regional SSTs is replaced by a “blanket” of uniformly warm temperatures across the Caribbean Sea throughout the entire year. The projected SSTs therefore exceed 28 °C across the entire Caribbean Sea year round.
- The mean annual SST range of approximately 3.3°C currently observed in the Caribbean Sea is projected to contract to 2.9 °C in the 2030s and to 2.3 °C in the 2090s.
- By the end of the century, years of coolest projected SSTs fall within the range of the warmest years in the present.

The Significance of Warmer SSTs

SSTs and Rainfall

Regional rainfall is strongly correlated with tropical north Atlantic and Caribbean SSTs on annual through multidecadal time scales (Giannini et al., 2000; Peterson et al., 2002; Taylor et al., 2002; Gamble and Curtis, 2008). On the one hand, anomalously warm Caribbean SSTs during the first half of the year result in an early start to the early rainfall season and greater rainfall amounts during this same period. In contrast, cold SST anomalies delay the start of the early rainfall season and rainfall totals are less (Taylor et al. 2002). Warm SST anomalies during the early Caribbean rainfall can result from a larger than usual and faster eastward spreading AWP or may also be associated with the previously noted lag relationship with El Niño occurrence and peak during the year prior.

The increase in rainfall due to the warmer SSTs is a direct result of the threshold for convection (usually taken as 26.5 °C) being exceeded earlier in the year. Waliser et al. (1993) and Zhang (1993) showed that tropical rainfall quantity is a function of SST magnitude, with small or no variability to SSTs below 26.5 °C but a rapidly increasing association for changes between 26.5 to 29.5 °C, before decreasing again with larger temperature values. The warm north tropical Atlantic SSTs result in lower surface pressures, an abundance of moisture in the lower levels of the atmosphere, and a weakening of atmospheric vertical wind shear, all of which in tandem create a favourable environment for convective development and rain (Wang 2007).

The projection of uniformly warm SSTs in excess of the convection threshold year round and across the entire Caribbean basin through mid century (Nurse and Charlery, 2014) is therefore significant. The impact will be on early season rainfall onset and amount. That is, through mid-century, the Caribbean will see increased variability in early season rainfall amounts as regional SSTs warm and fluctuate within the band associated with convection. There is need for the region to account for rainfall extremes (both floods and droughts) moving toward the mid-century, with adaptation efforts targeting water availability and security. The significance of the SST-rainfall link will, however, thereafter decline through to the end of the century, because of the much higher SST values (> 29°C) which will be attained due to continued warming.

It also bears noting that currently as the year progresses and by the late Caribbean rainfall season, SSTs in the tropical Atlantic no longer become the primary determinant of rainfall but rather it is the SST gradient between the tropical Atlantic and equatorial Pacific (i.e. how much warmer one basin is relative to the other), that takes on greater importance. By the late rainfall season the Caribbean basin SSTs routinely exceed the threshold for supporting convection and so other factors which modulate the vertical shear environment (e.g. an El Niño event) become important. This may help explain the projections of future drier conditions for the Caribbean by the end of the century, notwithstanding the warmer SSTs projected (Campbell et al., 2012; Taylor et al. 2012).

SSTs and Hurricanes

Warm SSTs in the tropical north Atlantic and Caribbean Sea are important to the development and intensification of tropical storms and hurricanes. It is therefore not surprising that statistically premised operational forecast models of North Atlantic hurricane frequency and intensity incorporate indices representative of these SSTs. Warm SSTs ensure that the threshold requirement of 26.5 °C to facilitate the amount of water vapour necessary to sustain the tropical cyclone's warm core structure is met.

It has been observed that during warm phases of the AMO, a greater numbers of tropical storms (at least twice as many) mature into severe hurricanes than when the AMO is in its cool phase (Figure 4) (Klotzbach, 2011). This however is not to suggest that projections of warmer SSTs in the future may result in more hurricanes, though they may facilitate stronger hurricanes. The frequency of hurricane appears to be associated more with relative SSTs (e.g. between the tropical Atlantic and tropical Pacific basins) than with SSTs in any one basin alone. Nonetheless, the prospect of more intense hurricanes associated with continuously warming SSTs has significant implications for coastal settlements, resources (natural and otherwise) and infrastructure.

SSTs and Coral Bleaching

Coral reefs in the Caribbean serve important functions including serving as habitat and nursery for fisheries, attenuating waves before they reach the coast, as sources of beach sediment, and as vital natural resources for the tourism industry. They therefore contribute significantly to regional biodiversity as well as economic and social development and livelihoods. The region's coral reefs possess a strong sensitivity to SSTs and during very warm episodes when average monthly temperatures attain anomalies of 0.2 °C and above mass bleaching has been known to occur (McWilliams et al. 2005; Baker et al. 2008).

The Caribbean has experienced several coral bleaching events since the 1980s (e.g., 1997, 1998, 2005, 2010), with the most intense events occurring mainly during the summer months from August through October when SSTs are hottest for sustained periods. Corals provide important services for the Caribbean's fishing, tourism and pharmaceutical industries and are a main form of coastal protection. Nurse and Charlery (2014) suggest that this

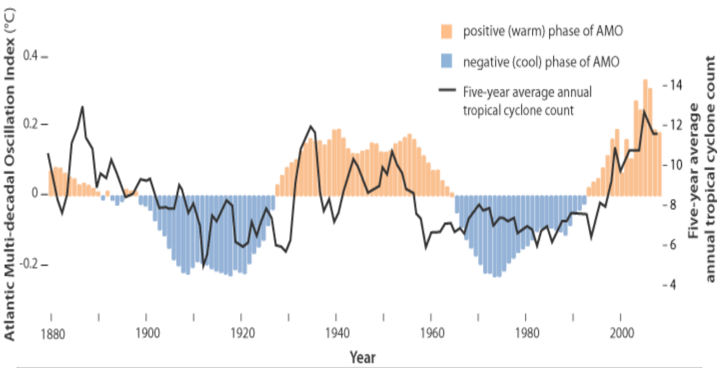


Figure 4: The Atlantic Multidecadal Oscillation Index and five-year average counts of tropical cyclones. Before averaging, counts of tropical storms were adjusted to omit short-duration storms and to account for storms that were likely missed before satellite technology was available. Diagram accessed from NOAA climate.gov at https://www.climate.gov/news-features/features/will-hurricanes-change-world-warms

may change in the future as (i) the mean monthly range in SSTs over the Caribbean Sea becomes gradually smaller, (ii) there is an expansion of the areal extent of very warm SSTs, and (iii) SSTs become or stay warm (comparable to present day summer levels) much earlier in the year. These conditions, they argue, would create favourable conditions for coral bleaching to persist well beyond the normal summer months, as observed in the 2005 and 2010 coral bleaching events in the Caribbean.

Bleaching events in the Caribbean have also been linked to warmer regional SSTs associated with El Niño events. It is projected that the occurrence of extreme El Niño events will double over the next 100 years under global warming (Cai et al. 2014) suggesting that the frequency of bleaching events will also increase. A number of studies have concluded that the majority of the Caribbean will experience conditions that currently lead to coral bleaching annually or bi-annually over the next 20 to 50 years (e.g. Donner et al. 2005, 2007). This would potentially lead to increased levels of morbidity and mortality in the Caribbean region.

SST and Marine Ecology

Regional SST changes likely impact other aspects of the Caribbean marine ecology (in both positive and negative ways) but there are very few studies being conducted to determine this. It is important to examine the SST-ecological impacts 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.

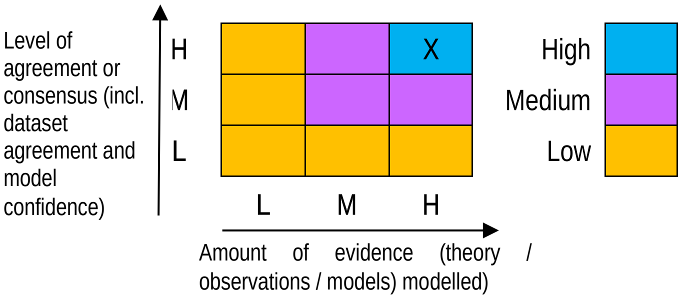
As an example of the latter, Precheur et al. (2016) examined the relationships between climate change and the survival of adults, nesting success, and population dynamics of the tropical seabird, Audubon's shearwater *Puffinus lherminieri*, which breeds in Martinique (the south Caribbean). Seabirds are top marine predators and are often considered indicators of marine ecosystem changes. Notwithstanding, studies of the impact of climate change on top predators have been limited to polar or temperate regions. In the Caribbean, the Audubon's shearwater population is considered as near threatened. In their study, Precheur et al. (2016) show that the annual adult survival rate of the Audobon shearwater has increased over the last 20 years and they link this to the increase in regional SSTs during the nonbreeding season as well as with Amazon River discharge. They suggest that there is a positive relationship between SST and chlorophyll a during years of high discharge from the Amazon and Orinoco and that this bodes well for future survival of seabird if regional SSTs continue to increase (barring other non-climatic factors). Their population models predict a stable or increasing population over the next 50 years which contrasts with the negative effect of increasing SST on seabird populations found in temperate and polar regions.

Another study by Taylor et al. (2012) makes it clear that there are ecological changes occurring in the Caribbean Sea which can be linked to global climate change indices including SSTs. Taylor et al. (2012) examine monthly observations from the CARIACO Ocean Time-Series in the marginal south Caribbean Sea between 1996 and 2010. They document significant decadal scale trends in SSTs (an increase of approximately 1.0 ± 0.14 °C) as well as concomitant intensified stratification, reduced delivery of upwelled nutrients to surface waters, and diminished phytoplankton bloom intensities evident as overall declines in chlorophyll a concentrations and net primary production. Additionally they note that there were shifts in phytoplankton taxon dominance, increases in mesozooplankton biomass, and the collapse of commercial landings of planktivorous sardines. They suggest that collectively their results reveal an ecological state change in this planktonic system. The SST warming, particularly during the upwelling season, caused mean water density in the upper 100 m to decline resulting in less intense upwelling, which in turn amplified density differences with underlying waters and enhanced stratification. They conclude that the hydrographic conditions at the CARIACO site changed to a state which was less favorable for upward nutrient transport and consequently one less supportive of primary producers.

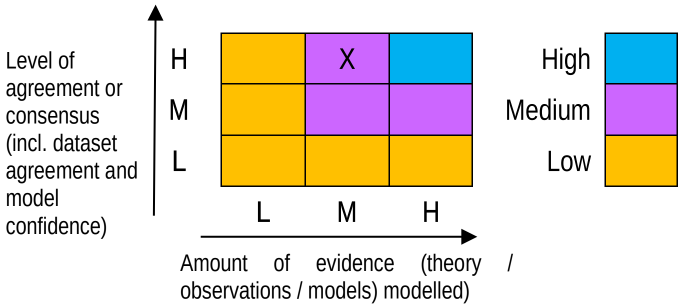
As a final example of the SST-marine ecology link, it is noted that the Caribbean marine ecosystem is heavily dependent on coastal mangroves for the stability of the coastline, management of sedimentation and as nurseries for juveniles of many marine species. Although coastal mangroves are largely situated in estuarine environments and accustomed to harsh conditions, they are also sensitive to fluctuations in those conditions. Water temperatures affect survival, growth rate and zonation. Alongi (2007) notes that despite the potential for increased range and production in some species, higher SSTs in the future will likely lead to decreased survival in drier areas, changes in species distribution, increased microbe activity and changes in reproduction. Seagrass beds have a similarly strong relationship with SSTs as observed by Lopez-Caulderon et al. (2013) in studies of *Thalassia testudinum* off the coast of Panama. In their study, data obtained from long-term monitoring in Bocas del Toro, Panama, by the Caribbean Coastal Marine Productivity Program (CARICOMP) was used to assess changes in biomass and environmental variables since 1999. SSTs were found to have the strongest link to increases in seagrass biomass and likely accounted for an increase in growth under recent warming. However, at the time of the study, they note that SSTs were approaching the optimum temperature for *T. testudinum*, which is 29°C. The likely outcome of further warming, then, will be a decrease in productivity and increase in respiratory requirements, favouring anoxic conditions within the sediment and the proliferation of algae, which may block sunlight penetration.

Confidence Assessment

What is already happening



What could happen in the future



There is high confidence in what is already happening because:

- Both observations and satellite data support the increasing trend.
- The satellite data suggest the warming may be at an even faster pace than the observations.
- The warming is consistent with an increase in observed near surface atmospheric temperatures.
- Increased frequency of coral reef bleaching events support the warming trend.

There is medium confidence in what is going to happen because:

- Most models are consistent with the sign and direction of the future trend.
- Most models also project an increase in observed near surface atmospheric temperatures.
- The number of models available for study could be increased.

The magnitude of the increase varies dependent on model and scenario.

Knowledge Gaps

The ocean occupies 95% of the Caribbean and SSTs are a significant modulator of regional climate and a determinant of the health or state of the region's marine biodiversity. There is nonetheless an absence of a suitably dense network of monitoring stations for SSTs across the Caribbean region. There are also insufficient resources (human, technical and financial) to support research investigating the link between SST variability and other areas of the regional marine ecosystem besides coral reefs. This includes insufficient data gathering and inadequate or no data monitoring or data rescue efforts for other components of the marine ecosystem, particularly those which show sensitivity to SST variations. Consequently the potential for using changes in SST as an early warning indicator or predictor for climate or biodiversity impact is under-explored in the Caribbean region.

Socio-economic Impacts

The region is heavily dependent on rainfall for water security. Projected changes in SSTs will result in variable amounts of water harvested from rainfall through mid- century and contribute to a drier region by end of century. Insecure water supply impacts quality of life and hinders the quest toward the achievement of developed status. Two recent region-wide droughts since 2010 have highlighted the vulnerability of the region to rainfall variability.

Warmer SSTs may translate into more intense hurricanes passing through the region even if not more hurricanes. The socio-economic impact of strong hurricanes on the island economies and on individual and communities can be seen through historical impacts which include lives lost and the devastation of entire economies.

The potential degradation of the natural resources will challenge their use to attract visitors to islands dependent on tourism.

The UWI through various departments, other regional Universities (e.g. AdeKUS (Suriname)), and institutions such as Meteorological Service of Cuba (INSMET) are conducting research on SSTs in the Caribbean.

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References

Alongi, D.M, 2008. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. Estuarine, Coastal and Shelf Science 76: 1–13.

Antuña-Marrero, J. C., O. H. Otterå, A. Robock, and M. d. S. Mesquita, 2015: Modelled and observed sea surface temperature trends for the Caribbean and Antilles. *Int. J. Climatol.* DOI: 10.1002/joc.4466.

Baker A. C., P. W. Glynn, B. Riegl, 2008: Estuar Coast Shelf Sci 80:435–471

Cai, W., S. Borlace, M. Lengaigne, P. van Rensch, M. Collins, G. Vecchi, A. Timmermann, A. Santoso, M.J. McPhaden, L. Wu, M.H. England, G. Wang, E. Guilyardi, and F.-F. Jin (2014): Increasing frequency of extreme El Niño events due to greenhouse warming. Nature Climate Change, 4, doi: 10.1038/nclimate2100, 111-116.

Campbell, J. D., M. A. Taylor, T. S. Stephenson, R. A. Watson, F. S. Whyte, 2011: Future climate of the Caribbean from a regional climate Model. Int. J. Climatol. 31: 1866–1878.

Deser C, A. S. Phillips, M. A. Alexander, 2010: Twentieth century tropical sea surface temperature trends revisited. Geophys. Res. Lett. 37: L10701, doi: 10.1029/2010GL043321.

Donner S. D., W. J. Skirving, C. M. Little, M. Oppenheimer, O. Hoegh-Guldberg, 2005: Global assessment of coral bleaching and required rates of adaptation under climate change. Glob Chang Biol 11(12):2251–2265

Donner S. D., T. R. Knutson, M. Oppenheimer, 2007: Model-based assessment of the role of human-induced climate change in the 2005 Caribbean coral bleaching event. Proc Natl Acad Sci 104(13): 5483–5488

Enfield, D. B., and D. A. Mayer, 1997: Tropical Atlantic sea surface temperature variability and its relation to El Nin˜o-Southern Oscillation, J. Geophys. Res., 102, 929–945.

Enfield D. B., A. M. Mestaz-Nuñes, P. J. Trimble, 2001: The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S. Geophys. Res. Lett. 28: 2077–2080.

Gamble, D. W., and S. Curtis, 2008:, Caribbean precipitation: Review, model and prospect, Prog. Phys. Geogr., 32(3), 265–276.

Giannini, A., Y. Kushnir, and M. A. Cane, 200: Interannual variability of Caribbean rainfall, ENSO and the Atlantic Ocean, J. Clim., 13, 297–311.

Glenn, E., D. Comarazamy, J. E. González, and T. Smith, 2015: Detection of recent regional sea surface temperature warming in the Caribbean and surrounding region, Geophys. Res. Lett., 42, doi:10.1002/2015GL065002.

Jones, P. D., C. Harpham, I. Harris, C. M. Goodess, A. Burton, A. Centella-Artola, M. A. Taylor, A. Bezanilla-Morlot, D. Martinez-Castro, J. D. Campbell, T. S. Stephenson, O. Joslyn, K. Nicholls and T. Baur, 2015: Long-term trends in precipitation and temperature across the Caribbean. *Int. J. Climatol.*, 10.1002/joc.4557

Jury, M. R., 2011: Long-term variability and trends in the Caribbean Sea, Int. J. Ocean., 2011, 465810, 9.

Klotzbach, P. J., 2011: The Influence of El Niño–Southern Oscillation and the Atlantic Multidecadal Oscillation on Caribbean Tropical Cyclone Activity. *J. Clim.*, DOI: 10.1175/2010JCLI3705.1.

López-Calderón, J. M., H. M. Guzmán, G. E. Jácome, and P. A. G Barnes, 2013. Decadal increase in seagrass biomass and temperature at the CARICOMP site in Bocas del Toro, Panama. Revista de Biología Tropical 61(4): 1815-1826.

McLean, N. M., T. S. Stephenson, M. A. Taylor, and J. D. Campbell, 2015:, Characterization of future Caribbean rainfall and temperature extremes across rainfall zones, Adv. Meteorol., 2015, 18, doi:10.1155/2015/425987

McWilliams, J. P, I. M. Côté, J. A. Gill, W. J. Sutherland, A. R. Watkinson, 2005: Accelerating impacts of temperature-induced coral bleaching in the Caribbean. Ecology 86(8):2055–2060

Melo-Gonzalez N, F. E. Müller-Karger, S. Cerdeira, R. Pérez, I. Victoria del Río, P. Cárdenas, I. Mitrani, 2000: Near-surface phytoplankton distribution in the western Intra-Americas Sea: the influence of El Niño and weather events. J. Geophys. Res. Oceans 105: 14029–14043.

Nurse. L., and J. L. Charlery, 2014: Projected SST trends across the Caribbean Sea based on PRECIS downscaling of ECHAM4, under the SRES A2 and B2 scenarios. Theor Appl Climatol DOI 10.1007/s00704-014-1346-1.

Peterson, T. C., M. A. Taylor, R. Demeritte, D. L. Duncombe, S. Burton, F. Thompson, A. Porter, M. Mercedes, E. Villegas, R. Semexant Fils, A. Klein Tank, A, Martis, R. Warner, A. Joyette, W. Mills, L. Alexander, B. Gleason, 2002: Recent Changes in Climate Extremes in the Caribbean Region. *J. Geophys. Res. Atmospheres* 107(D21) 4601, doi:10.1029/2002JD002251.

Precheur, C., C. Barbraud, F. Martail, M. Mian, J-C. Nicolas, R. Brithmer, D. Belfan, B. Conde, V. Bretagnolle, 2016: Some like it hot: effect of environment on population dynamics of a small tropical seabird in the Caribbean region. Ecosphere. DOI: 10.1002/ecs2.1461

Stephenson, T. S., L. A. Vincent, T. Allen, C. J. Van Meerbeeck, N. McLean, T. C. Peterson, M. A. Taylor, A. P. Aaron-Morrison, T. Auguste, D. Bernard, J. R. I. Boekhoudt, R. C. Blenman, G. C. Braithwaite, G. Brown, M. Butler, C. J. M. Cumberbatch, S. Etienne-Leblanc, D. E. Lake, D. E. Martin, J. L. McDonald, M. O. Zaruela, A. O. Porter, M. S. Ramirez, G. A. Tamar, B. A. Roberts, S. Sallons Mitro, A. Shaw, J. M. Spence, A. Winter and A. R. Trotman, 2014: Changes in extreme temperature and precipitation in the Caribbean region, 1961–2010. *Int. J. Climatol.* DOI: 10.1002/joc.3889.

Sutton R. T., D. L. R. Hodson, 2005: Atlantic Ocean forcing of North American and European summer climate. Science 309: 115–118.

Taylor, G. T., *et al.* 2012. Ecosystem responses in the southern Caribbean Sea to global climate change. *Proceedings of the National Academy of Sciences USA* 109:19315–19320.

Taylor, M. A., D. B. Enfield and A. A. Chen, 2002: Influence of the tropical Atlantic versus the tropical Pacific on Caribbean rainfall, J. Geophys. Res., 107(C9), 3127, doi:10.1029/2001JC001097.

Taylor, M. A., F. S. Whyte, T. S. Stephenson, and J. D. Campbell, 2012: Why Dry? Investigating the future evolution of the Caribbean Low Level Jet to explain projected Caribbean drying. *Int. J. Climatol.* doi: 10.1002/joc.3461.

Waliser, D. E., and N. E. Graham, 1993: Convective cloud systems and warmpool sea-surface temperatures—Coupled interactions and selfregulation. J. Geophy. Res., 98, 12 881–12 893.

Wang, C. and S.-K. Lee, 2007: Atlantic Warm Pool, Caribbean Low-Level Jet, and Their Potential Impact on Atlantic Hurricanes. *Geophysical Research Letter*, Vol. 34, No. L02703, doi:10.1029/2006GL028579.

Zhang, C., 1993: Large-scale variability of atmospheric deep convection in relation to sea surface temperature in the tropics. J. Climate, 6, 1898–1913.