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

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EXECUTIVE SUMMARY

Since the early 1960s much of the coastal area of the Caribbean has undergone a change in land use, from being primarily agricultural, to become increasingly residential, commercial, and tourism orientated. Areas that were previously undesirable for settlement were increasingly developed. This has led to a concentration of infrastructure and wealth in low lying coastal areas, prone to multiple natural hazards, the impacts of which are being exacerbated by climate change. Climate change projections for the Caribbean suggest that sea levels will rise by as much as 1.4 m by the end of the century increasing coastal flooding brought about by variations in storm surge extreme events superimposed on these rising sea levels. This is likely to lead to an acceleration of severe damage to coastal settlements, with the accompanying impacts on national economies. Predictions of the impact of climate change on hurricane activity suggest an increase in frequency of higher category events. Changes in temperature and rainfall indicate a general warming and drying trend, varying across the Region. The drying has two components; a reduction in total rainfall, and longer dry period accompanied by more intense rainfall. These changes imply increasing frequency and severity of pluvial flooding. The economic impacts will pose a severe challenge to the Region.

What is Already Happening?

Background

Increased anthropogenic greenhouse gas (GHGs) emissions into the atmosphere have been the major contributor towards global warming, with 69% of these emissions coming from ten (10) countries over the past two decades (Ge, Friedrich, and Damassa 2014). The total contributive ratio of GHGs produced by Caribbean SIDs is negligible in comparison. This fact becomes even more pertinent when we consider that few other places in the world exhibit greater vulnerability to changes in the climate system than the low-lying SIDS of the Caribbean (Lewsey, Cid, and Kruse 2004). The Region is not only on the receiving end of the impacts associated with anthropogenic climate change and climate variability, but will experience them sooner and more severely than other parts of the world.

The Caribbean Region is doubly vulnerable due to its geographic location and to its socio-economic circumstances. In the first instance it is vulnerable to earthquakes, volcanic eruptions, mass movements (landslides), and tsunamis. In addition, its location in the Tropical zone means it is subject to storm and hurricane activity as well as climatic anomalies such as El Niño and La Niña events.

In the second instance, the Region's socio-economic vulnerability is a product of population size and distribution, small open economies, social and intellectual capital, the robustness of infrastructure and built environment, the nature and relative strength of the economy, governance, and institutional strengths.

The Caribbean is a heterogeneous region and is taken to be made up of the island states, the South American coastal states of

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Guyana and Suriname and, Belize in Central America. The island states are separated by geographical location into two (2) regions: the Greater Antilles comprising of larger islands situated towards the north and the Lesser Antilles comprising of the remaining smaller islands to the east and south-east of the Caribbean Sea.

The pattern of settlement throughout the Caribbean has been superimposed on the colonial era economic development, heavily determined by the colonial experience and economic means of production. Generally, with the exceptions of the continental territories, a plantation style economy was developed, supported in part by a parallel small-holder economy (Mintz 2016). This implied a dispersed settlement pattern across the landscape, concentrated in those areas not too steep to be farmed. These were economies exporting raw materials with small internal markets and limited local industry. This required harbours to export and import materials. The associated urban areas were often the site of local government agencies as well as commercial activity. It is notable that with the exception of Belize, all of the capital cities of the insular Caribbean are located on the coast and are port cities.

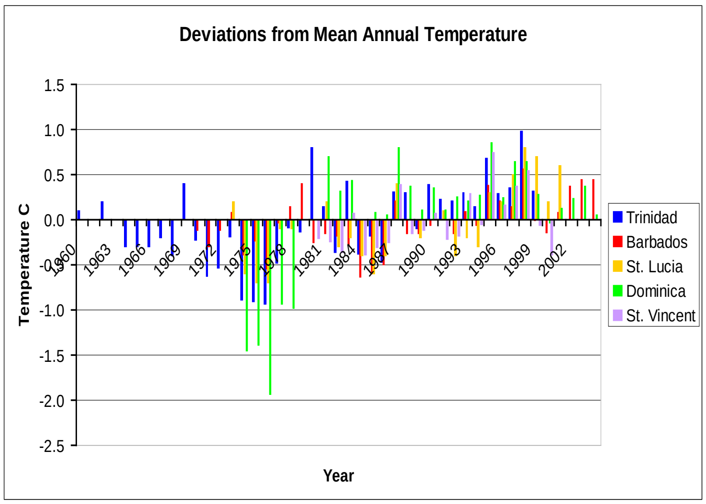

Figure 1: Temperature trends in the Eastern Caribbean (Cashman, Nurse and Charlery 2010)

This pattern of settlement started to change with the rise of the importance of tourism as the dominant economic activity with the building of beachfront hotels and the development of supporting services and infrastructure (Mintz 2016). As a result, coastal areas became increasingly densely settled, often crowded into a narrow coastal strip of land with infrastructure such as schools, hospitals, roads, and utilities running parallel to the coastline (Lewsey, Cid and Kruse 2004). Continued growth of developments and shifts in population have contributed to encroachments onto hazard prone as well as environmentally sensitive and important areas (e.g. flood prone areas or steep slopes) (Lewsey, Cid and Kruse 2004).

Figure 2: Increase in settlement density, Holetown Barbados 1951 & 2015

Even islands where changes in elevation are significant have a substantial share of their population and capital investment in vulnerable near-shore areas (Lewsey, Cid and Kruse 2004). In Jamaica, for example, over 50% of economic assets and tourism infrastructure are concentrated in coastal areas (Richards 2008). Many of the power stations throughout the region are located at the coast due to the need to import and off-load fossil fuels to run them. In Trinidad the country's most important heavy industry site, which contributes a significant portion of GDP, is located on the coast at Point Lisas.

As a result of this settlement pattern, upwards of 70% of the population live within 5 km of the coast. The exceptions are the larger islands that form the Greater Antilles in the northern Caribbean where the figures drop to around 20%. Urban populations have increased significantly since the 1950s (Lewsey, Cid and Kruse 2004) such that in several of the smaller islands 100% of the people live in urban areas; the least urbanized is Trinidad and Tobago at 14%. Figures taken from the Socioeconomic Data and Applications Center (SEDAC) of Columbia University indicate that the rate of urbanization is decreasing suggesting a redistribution of settlement away from the traditional urban areas. Urban growth does continue to take place but into areas such as up the slopes of the areas surrounding the original core coastal areas, very evident in cities such as Kingston, St George, and Port of Spain.

The concentration of populations and economic assets in potentially vulnerable coastal zones is a cause for concern. The threats posed to Caribbean SIDs are significantly increased because as indicated the majority of human populations and infrastructure are located along low-lying coastal zones (LLCZ) with limited on-island relocation opportunities (Woodroffe 2008).

Climate-related Hazards and Risks

This section considers climate related hazards. Though there may be little that can be done to avert hazards associated with climate-related events, their consequences are much more within societal control as they are related to vulnerabilities arising from human actions and interventions. The level of exposure to climate hazards varies from territory to territory based on factors such as population distribution, island type, and topography, all of which provide a framework when considering vulnerability (Forbes et al. 2013). It is the combination of hazard, exposure, consequences, and return periods that taken together characterise risk.

Here we identify the range of climate-related hazards that can have an impact on coastal and marine settlements and infrastructure, compromising their functioning and result in damage and loss. These can take place on a relatively short timescale and in this category storm surges, high winds, and abnormal rainfall events would be placed. These can be either individual events or collective events where two or more of the effects occur near simultaneously. On the other hand, there are longer term events, the onset of which are often problematic to detect and whose impacts are more diffuse and operate through secondary causes. Heat stress effects and drought would be typical.

Heat Stress

Temperatures in urban environments are often elevated and have given rise to the term heat island effects. The very nature of the built urban environment, the materials used, the presence or absence of green space, and the spatial planning are contributing factors. Above average temperatures are associated with drought periods and hence compound other drought related effects, though these are not peculiar to just coastal environments. Elevated temperatures are known to have an impact on vulnerable sections of the population, such as the elderly, although there are no recorded instances of related mortalities in the Caribbean. On the other hand there are recorded instances of effects on livestock and poultry, for example, during the 2009/10 drought in the region. Significant die-offs had an impact on local food supplies compounding the drought effects.

At the same time the demographic structure of the region has undergone significant change. The younger proportion of the population has declined whilst the older proportion has increased. In other words, there is an increasingly aging population, which will be supported by a smaller economically active working population. Since the 1990s a trend in increasing temperatures has been observed. Generally, both average day and night time temperatures have been increasing and the difference between them has been narrowing (Figure 1) (Cashman, Nurse and Charlery 2010).

Drought

There is no detectable trend that suggests that the frequency and/or duration of droughts is changing. There are indications that there are decadal variations in rainfall patterns possibly associated with long-term climatic oscillations. Since 2000 there have been five drought periods affecting various parts of the Caribbean; 2000/01 – Cuba & Jamaica, 2003/04 - Haiti, 2004/05 – Cuba, Dominican Republic, 2009/10 – Barbados, Cuba, Grenada, Jamaica, St Lucia, St Vincent and the Grenadines, and Trinidad and Tobago (CRED n.d.). The effect of the droughts was felt in urban areas through water shortages. The following Box illustrates the impact of the 2009/10 drought on the Kingston St Andrews coastal urban area.

Box 1: 2009/10 Drought Impacts on Kingston St Andrews

Streamflows were reduced by between 50-70% affecting 600,000 people. Revenue from water sales dropped by 36% but operating costs increased due to inter alia tanker services and overtime. There was a loss of productivity as workers arrived late for work after waiting for water. There was an increase of 20% of children under 5 needing treatment for oral rehydration or diarrhoea. Increases in cases of domestic violence, stress, anxiety and depression were recorded as were incidents of reduced nutrition (Barnett 2011).

Photo 1: Tanker supplies Jamaica

Droughts also affect coastal groundwater aquifers which supply urban areas. In these instances, reduced recharge from rainfall and runoff, coupled with reliance and continued abstraction from these aquifers in order to meet water demand of urban areas has resulted in saline intrusion due to over-pumping. This has also occurred in the case of Barbados during drought periods. Furthermore, modelling work carried out in the early 2000s indicated that “under the sea level rise scenarios projected, the wells in the west coast catchment could not be used for drinking water purposes.” (Barbados' First National Communication 2001).

Storms and Hurricanes – Wind Damage

Like storm surges, high winds are associated with tropical storm and hurricane activity and bring with them varying amounts of rain. Typically, the type of damage caused by winds will be to buildings particularly roofs and overhead utilities. Further destruction is caused by windblown debris including trees. The concentration of buildings and overhead services in built up areas means that there is a high potential for extensive damage and disruption to be caused. Among the knock-on effects of damage to power generation and distribution is that the water distribution system is disrupted as pump stations cannot function. The same holds for other services reliant on power but without back-up generation facilities.

The case of the impact of Hurricane Ivan on Grenada illustrates the level of damage that can arise. Ivan was predominantly a ‘dry’ hurricane with rainfall intensities not exceeding those experienced during an average wet season (OECS 2004, 6). Damage to the Housing sector accounted for over half the total value of the estimated damages. This was followed by the Tourism sector which constituted 17% of the total estimated damages.

Photo 2: Devastation to housing in Grenada after Hurricane Ivan

Since 2000 there have been 22 Category 4 and 9 Category 5 hurricanes as compared to 18 and 4 in the same period prior to 2000. There does seem to be an increase in hurricane activity and higher intensity hurricanes and with it comes increased damage potential. Although risks and losses differ across islands, factors determining the extent appear to be related to island size and spatial concentration of economic wealth (Bertinelli, Mohan and Strobl 2014); smaller islands where social and economic infrastructure are densely concentrated tend to be more impacted.

Coastal Erosion and Coastal Flooding

Storm surges are frequently associated with tropical storm and hurricane activity and as such occur during the hurricane season. They also occur from northerly swells which are long period waves driven from cold fronts far up north. Storm surges give rise to physical damage to settlements and infrastructure through direct and indirect impacts and concomitant flooding of coastal areas. The severity of coastal flooding depends on a combination of factors. These include the geomorphology of the coastal area: what the bathymetry is; how any fringing reefs can dissipate the wave energy; the topography of the impact area (low-lying and flat, broad or narrow, or how steeply the land rises). There is also the extent to which human activities have altered coastal ecosystems: how degraded the reef ecosystems are; how intact the dune fields are; if the mangrove and swamp areas been filled in and built over. All of these provide varying forms of coastal protection and natural mitigation. The impact of the 2004 Christmas Tsunami on coastal areas around the Indian Ocean highlighted the role that coastal ecosystems play (McIvor, et al. 2012) in mitigating the effects of surges and swells. Degraded reef ecosystems diminish the role of, for example, parrot fish in the production of sand (Morgan and Kench 2016). However, as indicated above coastal development in the Caribbean has altered many of these areas and degraded the fringing reefs, increasing the vulnerability of coastal settlements and infrastructure. Between 1980 and 1990 The Bahamas lost 54% of their mangrove areas and Antigua and Barbuda has lost over 80% (Lewsey, Cid and Kruse 2004).

Beaches are the first line of coastal defence and are dynamic in nature. Under normal conditions, beaches are shaped by a myriad of coastal processes such as wind, waves, currents, tides, sediment transport, and high energy events. Increasingly the interactions of coastal processes are being skewed by anthropogenic influences leading to a reduction in beach width. Studies have shown just how quickly many of the region's coastlines are being affected by development, deforestation, sea level rise, tidal and wave action, storms, and beach mining (Daniel and Abkowitz 2003). On the small Grenadian island of Carriacou for example, beach recession was estimated at 1 metre per year (Fitzpatrick, Kappers and Kaye 2006). More generally it has been estimated that 70% of Caribbean SIDS' beaches are eroding at rates of 0.25 and 9 metres per year (Agard et al. 2007). Much of this has been ascribed to inappropriate coastal developments rather than climate change, up to now.

Sea Level Rise

The severity of storm surges also depends on sea conditions, particularly sea levels. Monitoring records over the last 50 years from tide gauges and more recently from remote sensing have added to the understanding of sea level rises through the Region. Sea levels have been rising in the Caribbean though the picture is far from uniform across the Region. Over the period 1950-2009, the mean sea level trend amounts to 1.8mm/year, very similar to the global mean sea level rate for the past 60 years (Figure 3) (Palanisamy, et al. 2012) but with a maximum of 3 mm/year in the central part of the Caribbean sea. The same analysis by Palanisamy et al. (2012) indicated that the interannual sea level variability observed in the data is influenced by and responds to ENSO events (Palanisamy, et al. 2012). They observed that "interannual sea level variability was higher in the Northern Caribbean than in the Southern Caribbean while the Eastern Caribbean shows a greater interannual variability during recent decades." (ibid). Hurricane activity was also considered and Palanisamy et al. (2012) concluded that "the increase in the number of hurricanes during recent decades have caused so far more damages to coastal areas than the sea level rise itself. However, decadal sea level rise projections in response to global warming will represent an additional threat to this region."

Interpretation of tidal gauge data seems to suggest a slight acceleration of sea level rise during the period 1950-2008. However, there are no significant differences in extreme values for areas affected by hurricanes (Losada, et al. 2013). There does appear to be a long-term shift in extreme values which suggests that extreme values in sea levels are becoming more frequent i.e. there is a shift in return periods with major events becoming more frequent. The results suggest that coastal flooding risk in low-lying areas is increasing due to a combination of rising mean sea levels and variations in storm surges (ibid). So, rising water levels associated with storm activities are decreasing the return periods of extreme events. The extreme surge events are influenced not only by ENSO but also by other decadal influences (ibid).

Storm Surges

Jamaica's recent experiences of hurricane induced storm surges illustrates the point being made above. Storm surges have been recoded for Jamaica from 1712. Hurricane Ivan (2004) was accompanied by storm surges of up to 3 metres in height in some places damaging roads and residential infrastructure along the south coast of St Thomas, St Andrew, and Kingston. The road to the main airport was blocked by sand debris 1 metre high and in some places travelled nearly 2 km inland (Richards 2008). Hurricane Dean (2007), a Category 4, generated storm surges in excess of 3 m in height along eastern and southern shores of Jamaica (ibid) causing extensive damage to buildings and road infrastructure predominantly in coastal areas but also along river valleys.

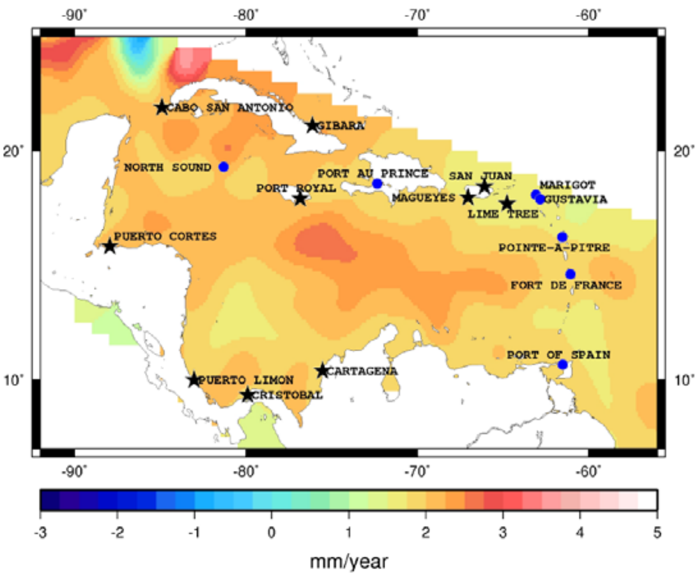

Figure 3: Map of sea level trends from mean reconstruction over 1950-2009 (Palanisamy, et al. 2012)

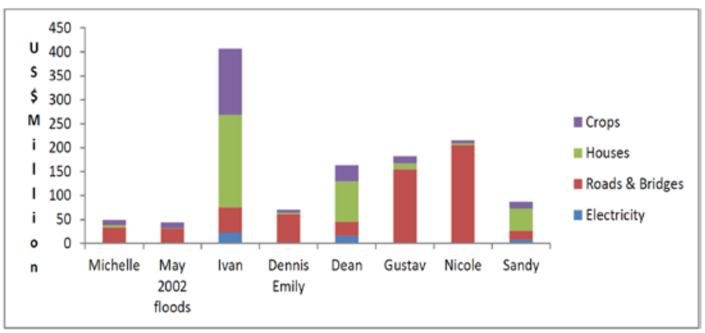

Figure 4: Damages due to meteorological events in Jamaica by sector (source (Smith and Mandal 2014))

Projections for storm surge events with a 25, 50 and 100 year return period were estimated for the Caribbean showing heights that range from 0.6 metres for Barbados and the Eastern Caribbean, to 1.4 m for Belize City, and 2.4 m for Kingston (Project n.d.). Higher values were obtained where coastal morphology was a contributing factor. Climate change is expected to increase the frequency of these return periods with NOAA projections showing an increase in the number of expected high energy category 4 and category 5 hurricanes.

Although the effects of storm surges are not separated out from the overall damage caused by hurricane activity the economic impacts are significant. In the case of Hurricane Ivan (2004), on Grenada it caused US$900 million in damage and losses, equivalent to twice the country's GDP. In Jamaica's case, Hurricane Dean caused US$330 million of damage and loss and knocked a whole percentage point off growth in GDP. The apparent increase in the last decade or so of increased hurricane strength and associated storm surge events and the knock-on effects in terms of damage and loss across the Caribbean are worrying trends.

Pluvial Flooding of Coastal Areas

Recent studies suggest that over the past 25 years the intensity of daily and more importantly heavy rainfall events have been rising significantly, interrupted by longer dry spells (Stephenson, et al. 2014)

Flooding of coastal areas is not only caused by storm surge events. It is often caused by intense rainfall and as water flows down to the sea, it is the coastal areas that are most severely affected. Whilst hurricanes do bring large amounts of rain it is often the case that the associated rainfall intensities are no greater than during normal rainfall events. Indeed, some of the most severe flooding that has occurred in recent years has not been associated with hurricane activity. Examples include the Christmas 2013 event when a low-level weather trough system passed over Dominica, St Vincent, and St Lucia. Up to 400 mm of rain fell in a 24 hour period and the resultant flooding left 15 people dead across the three islands, wrecking homes and infrastructure. Health impacts associated with the disruption of water supplies and contaminated water are a concern but are not discussed further as they are beyond the scope of this paper.

The steep topography of the majority of Caribbean territories and their relative small size means that rainfall accumulation and travel time is quick resulting in flash flooding, and there is often little advanced warning. The situation is often aggravated by developments that have taken place in the catchments upstream from coastal areas. Combinations of land clearance and poor agricultural practices as well as the development of housing and infrastructure contribute to increased run-off and faster rainfall accumulation. Coastal settlement patterns have restricted natural drainage paths and flood retention areas, such as flood plains and lagoons, and they cannot cope with the increased flows within the restricted channels. Flood waters therefore follow the path of least resistance, banks are overtopped, roads become drainage paths, and water flows through properties. In addition, roads, culverts, and bridges have been under-designed to cope with higher return period flows. Recent work being carried out in Barbados has indicated that the design of road culverts is inadequate to handle even the present level of flows. In addition, solid waste generated in urban areas and debris brought down by flood waters has a tendency to cause blockages within the drainage infrastructure, clogging culverts and adding to flooding.

In 2015 Tropical Storm Erika hit Dominica which up to that point, like the rest of the Caribbean, had been experiencing severe drought conditions. It deposited over 430mm of rain in 16 hours, 360 mm of which fell in just 5 hours. As a result of the intense rainfall in combination with steep topography and relative short distance from mountain ridge to the coastal areas (approx. 8 km), flash flooding rapidly ensued with little warning to the population. Flash flooding was worsened due to the accumulation of debris in river courses, effectively creating temporary stream dams which released suddenly when overwhelmed by flow accumulations. The combination of intense rainfall, unusual dry season, and cracking of clay soils contributed to slope failures and debris generation which resulted in major damages and fatalities throughout Dominica, especially the coastal areas. Due to its topography, much of the settlement and infrastructure is confined to the narrow coastal areas.

Photo 3: Debris blocking a road culvert, Barbados.

It was noted during Tropical Storm Erika, that the design of bridges with central piers trapped debris brought down by the rivers. This resulted in overtopping of the bridges and increased scour around abutments leading to the loss of infrastructure. Furthermore, due to the limited space within settled coastal areas there is often little provision of drainage to handle storm water flows.

In May 2008, Tropical Storm Arthur made landfall in Belize dropping up to 380mm of rain. This led to flooding of, amongst others, the Kendal River and swept away the bridge, which at the time was some 8 metres above normal water level indicating the severity of the flooding. This severed the coast road link between central and southern Belize.

Barbados is seldom hit by tropical storms and still less by hurricanes but it is subject to periodic flooding particularly in the coastal areas. Since 1998 there have been at least 15 events that have resulted in flooding. The 2010 Tropical Storm Tomas affected 2,500 people and resulted in US$37 million in damages.

Photo 4: Damage to coastal infrastructure following tropical Storm Erika, Dominica

The total damage and loss of US$483 million is equivalent to 90% of Dominica's GDP. The majority of damages were sustained in the transport sector (60%) and the housing sector (11%). The storm put the airport out of action, which is also located in the coastal area, alongside a river.

Georgetown (the capital of Guyana, and located at the mouth of the Demerara River) is prone to riverine flooding. It lies on the coast and is approximately 0.5 metres below sea level. During high spring tides some areas are prone to flooding. Up to 80% of the population live in the low-lying coastal areas and these same areas account for 75% of economic activity, including all of the agricultural production. About 25 percent of the coast is protected by seawalls. The seawalls have sluice gates that allow floodwaters from heavy rains and waves to drain. However, the gravity–controlled gates cannot open if the tide is not low enough. Given the nature of the area on which it is built, Georgetown is undergoing subsidence and so is at increasing risk of flooding.

Agricultural production relies on flood irrigation, and management of water is critical to maintaining productivity and preventing flooding. Flood waters are managed through a complex system of drainage channels and pumps which also distribute water for agriculture. In 2005 following 3 days of heavy rain, flooding affected more than 200,000 people and resulted not only in damage, but also outbreaks of water related diseases. The estimate of the damage and losses was equivalent to 59% of GDP. However, there are suggestions that this flood was the result of poor maintenance of the flood protection system and inadequate flood management procedures during the event.

Landslides and mass movement frequently occur as a result of rainfall events, including tropical storms and hurricanes. Whilst these are associated with steep slopes and mountainous areas, they never-the-less have an indirect impact on coastal areas and settlements. They contribute to sediment and debris brought down by swollen rivers, which in turn can magnify the destruction of infrastructure and contribute to flooding, and then blanket reefs with sediment. In addition, they disrupt transport links and the provision of water supplies on which coastal urban areas rely.

What Could Happen?

Temperatures

Across the Region work carried out by Hall et al. (2012), McLean et al. (2015), and Stephenson et al. (2014) show a significant warming of the surface air temperature along with the night time temperature increasing more than the daytime temperature. The frequency of warm days, warm nights, and extreme high temperatures has increased while fewer cool days, cools nights, and extreme low temperatures were observed. Projections are for a yearlong warming over the Caribbean by at least 2–3 °C under the A1B scenario, including a 2.5–3 °C warming over the northern Caribbean and southern Guyana, and a 2–2.5 °C increase over the eastern Caribbean, northern Guyana, and Trinidad. This warming is projected to occur in tandem with an increase in the number of tropical nights (tropical days) by approximately 200 (100), 250 (80), and 20 (10) nights (days) for the northern, eastern, and southern domains, respectively. The projected increase in the number of tropical nights appears to at least double the projected increase in the number of tropical days. This is consistent with current trends of minimum temperatures warming faster than maximum temperatures, which have been observed for the Caribbean. The decadal variability in temperature is related to the AMO signal of the North Atlantic SSTs. The warming is also consistent with the warming projected towards the end of century by the ECHAM4 driven PRECIS and the HadAM3P driven PRECIS simulations, as well as GCM studies and extreme analyses conducted under multiple scenarios.

Rainfall

Changes in precipitation indices were less consistent. Small increasing trends were found in annual total precipitation, daily intensity, maximum number of Continuous Dry Days, and heavy rainfall events particularly during the period 1986–2010. A decrease in annual rainfall of 10–30 % is projected across the regional domain except for Guyana and over the far north. This rainfall gradient response is similar to that observed by Campbell, et al. (2011) who suggested a mean annual decrease of approximately of 25–50 %, with an increase north of 22°N under the A2 scenario for 2071–2100. The gradient pattern is generally evident throughout the year, though the drying expands northward, and is more severe in July. The intensification of the projected drying of the north and (to a lesser extent) the eastern Caribbean in MJJ and ASO occurs in tandem with an intensification of the 925-mb winds over the Caribbean particularly south of Jamaica.

The prevailing pattern of future projections from the ECHAM driven PRECIS RCM for 2071–2099 under A2 and B2 relative to the model baseline is a tendency towards more intense rainfall events over the northern and eastern Caribbean, with less consensus with respect to changes in the length of wet and dry spells. On the other hand, drier conditions are projected for Trinidad and Guyana via an increase in consecutive dry days and less intense rainfall events. There is weak consensus with respect to mean changes in consecutive dry days, consecutive wet days, and days with precipitation equal or greater than 10mm (R10) across the A2 and B2 scenarios for the northern and eastern Caribbean. For the same areas, there appears to be a stronger indication across the scenarios of increases in extreme rainfall and increases in maximum 5-day rainfall.

Analysis of two extended rainfall records for Jamaica indicate by 2100, as compared to 2010, there will be a reduction in the intensity events with a return period of less than 10 years. However, for higher return period events rainfall intensities increases, by up to 15% for a 1:25 year event to between 27-59% for 1:100 year events (Burgess, et al. 2015). This suggests, at least for Jamaica, that the less frequent storms will be more intense and that the present climate extremes will become more frequent. This could have a major impact on flooding as well as landslides and mass earth movements.

Wind Patterns

The overall picture for the Caribbean is consistent with the drying projected for the general Meso-America region due to a southward displacement of the eastern Pacific ITCZ, stronger low-level easterlies, and a more intense Caribbean low-level jet. Taylor et al. (2011) suggests that these changes perpetuate the drying beyond the climatological mid-summer drought period of July. Interestingly, the NDJ and FMA wind projections indicate a differential change in the winds over the Caribbean and may be capturing an early westward expansion of the North Atlantic high. The NDJ rainfall projections in the region of this intensification, however, do not suggest a drying.

Sea Level Rise

The consensus for the Caribbean is that sea level rise is occurring and seems likely to be accelerating over time (Meehl et al. 2007, Cazenave and Llovel 2010, Church and White 2011). However, the processes driving coastal flooding are more related to sea surges driven by tropical storms and hurricane activity, and tidal ranges, superimposed on sea level rises (ibid). Nurse (2015) has indicated that by 2050 sea levels could rise by 0.15-0.2 m by 2050 under RCP 2.6 and by 0.35-0.4 m under RCP 8.5. For 2100 the respective figures are 0.3 under RCP 2.6 and 1.1-1.2 m under RCP8.5 (L. Nurse 2015).

Storms and Hurricanes

NOAA general circulation models have projected an increase in the frequency of high intensity category 4 and 5 storms over the next century (ECLAC 2011) further escalating the threat to the already vulnerable coastlines of Caribbean SIDs (Figure 5, (Poly = polynomial curve fitting). These projections are directly related to increased anthropogenic GHG emissions into the atmosphere leading to a warming of sea surface temperatures which is the engine that drives and sustains storms and hurricanes. History has shown us that high intensity storms and hurricanes have overwhelmed Caribbean SIDS which undoubtedly required significant allocation of time, effort and resources to recover from the social, economic, environmental and physical devastation caused. The projected increased frequency of high intensity storms will negatively impact post hurricane recovery efforts by allowing less time for islands to pick up the pieces before being threatened once again. Recovery efforts will therefore necessitate further additional resources over shorter time periods, which will require greater allocation of funding to the already cash-strapped SIDS of the Caribbean.

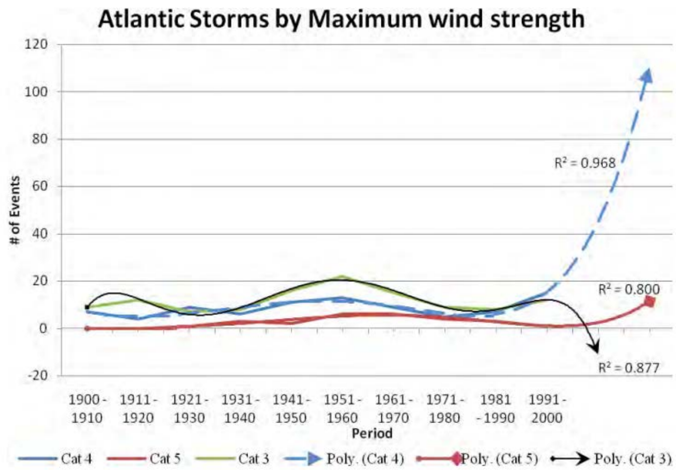

Figure 5 Projections in frequency of high intensity storms over the next 100 years (Poly = polynomial trend)(ECLAC 2011).

> Box 2: Grenada, Hurricane Ivan 2004
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> The passage of Hurricane Ivan in 2004 over Grenada caused more than US$900 million in destruction which was twice the islands GDP. 80% of the country's building structures were damaged or destroyed and in June 2005, the country's public debt stood at US$560 million or 130% of GDP. The hurricane affected 27,000 homes (89% of the housing stock), 73 of the 75 public schools, and 69% of the infrastructure in the health sector. It took more than 5 years for the island to physically recover (World Bank 2005).

Possible Future Impacts on Coastal Infrastructure and Settlements

Sea Level Rise and Storm Surges

The potential effects are best illustrated through reference to case studies that have been carried out to investigate specific aspects of potential impacts. Using national scale data modelling for Jamaica suggested that over 400 km^2 of land would be lost for a one metre rise in sea level. This would affect some of Jamaica's fastest growing urban centres and the location of many economic activities (Richards 2008). In the Kingston Metropolitan Area critical infrastructure would be impacted including the airport, port facilities, and manufacturing and service industries.

Estimates of the coastal population that would be at risk suggest that across the Caribbean Region about 14 million persons already live below 3 metres elevation and 22 million below 6 metres. These persons and their associated properties and livelihoods would be at risk from a combination of sea level rise, storm surges, and high tides of the magnitudes mentioned (Lam, et al. 2009).

It is likely that sea level rise will have a negative impact on beaches. A survey of tourists in the Caribbean (Scott, Simpson and Sim 2012) indicated that 77% would be unwilling to return, for the same price, if the beaches 'disappeared'. They also estimate that a 1 metre sea level rise would partially or fully flood 29% of the regions coastal resort properties – a significant number with the associated economic losses. This is not uniform across the region and in some territories 50% of coastal properties would be lost and in a few cases up to 80% could be at risk (ibid).

The potential impacts of storm surges on selected port and harbours have been assessed taking into account a combination of astronomical tides, sea level rise, sea level anomaly, and wave set up. The results indicate that the Port of Kingston & Causeway would be flooded, as would the Port of Montego Bay. For the Bridgetown port, storm surge inundation would extend up to 300 metres inland (Nurse pers comm). In fact, almost all port and harbour facilities in the Caribbean can expect to suffer inundation in the future, yet few are prepared for this eventuality.

> Box 3: Richard Haynes Boardwalk, Barbados
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> A 1.8Km stretch of the Barbados south coast had suffered from narrow beaches and shorelines following hurricane damage, which prompted the Government to embark on a Coastal Infrastructural Program. Two of the shoreline improvement initiatives addressed were shore protection and beach stabilization during high energy meteorological events along one of the most densely populated sections of coastline (Frank, Logan, and Arthur 2016). The boardwalk which was completed in 2011 intended to mitigate coastal risk against extreme wave conditions such as storm surges as well
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> as climate change related sea level rise. This was achieved by taking into consideration climate change and sea level rise projections during the design phase of the project. The outputs from these model projections were the determining factors used to design the height and strength that the structure could withstand.

Sea level rise will inevitably have an impact on coastal aquifers through saline intrusion, even in the absence of human activity such as pumping. The freshwater-saline water interface will migrate inland meaning that abstraction boreholes which once tapped freshwater may in the future be tapping brackish to saline waters. Such abstraction boreholes would either have to decrease their pumping rates or go out of production. Either way, less water would be available for water supply to consumers, the majority of whom would be resident in coastal areas. This situation would be further exacerbated by the reduced level of aquifer recharge consequential on the changes in rainfall patterns; less overall rainfall, increase in the number of consecutive rain days, and greater rainfall intensity leading to greater run-off rather than recharge due to infiltration.

Pluvial Flooding

Settlements and infrastructure in and along coastal areas of the Caribbean are not just at risk of flooding from storm surges and swells i.e. events that originate in the marine environment. They are also at risk from flooding events originating from the terrestrial environment. The combination of more frequent and more extreme events and anthropogenic alterations of the natural environment, whether through settlement or transformation of catchments for economic activities e.g. farming have together increased the potential magnitude and extent of flooding in coastal areas.

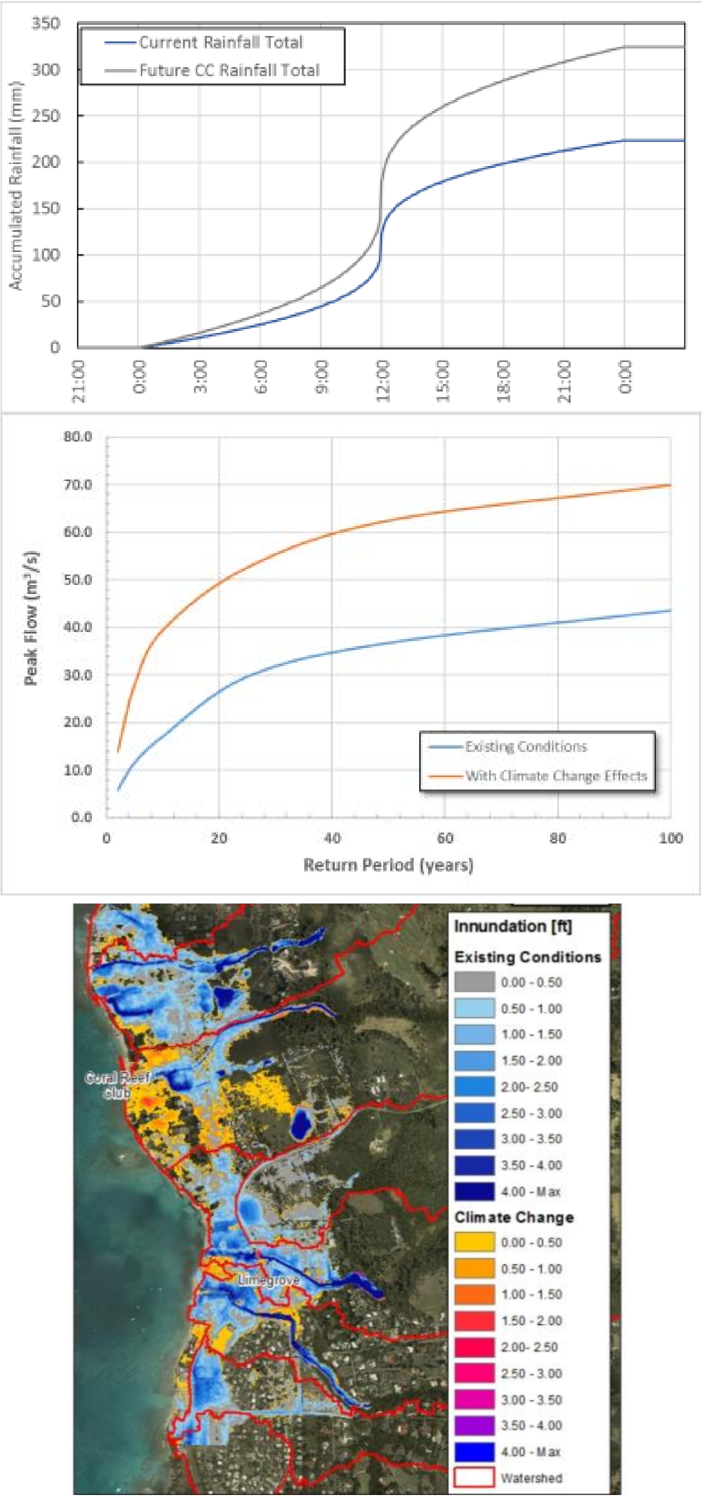


Figure 6: a) Accumulation of rainfall b) Decrease in return period for the same flood flow c) Impact of Climate Change on extent of pluvial coastal flooding (Baird 2016)

Much of the infrastructure in coastal areas runs parallel to the coast, whereas natural drainage runs perpendicular. It therefore serves to create a barrier to the flow of water originating from upstream areas and contributes to flooding. Climate projections suggest an increase in consecutive dry days and an increase in rainfall intensity. These trends have important implications for pluvial flooding. Increased rainfall intensity will lead to greater run-off; for an event of a similar frequency run-off will be greater meaning that more water will be channelled to low-lying coastal areas.

If greater volumes of run-off are being channelled down toward low-lying coastal areas, it means that more of these areas will be subject to flooding. This point is illustrated in Figure 6, a case study of the Holetown area in Barbados, which indicates that under climate change the extent of flooding will increase significantly. What is also shown by the figures is that concentration times are reduced, implying that sediment carrying and erosive capacity will increase. Some of this sediment would end up in the marine environment and have an adverse effect on corals and other ecosystems, especially if mangrove areas and the like have been removed or degraded.

As already suggested developments in the coastal areas compromise the ability to absorb and attenuate flows. In fact, a concentration of infrastructure will increase the barrier effect leading to increased flood risk. Already design standards for road culverts are inadequate to handle current flood flows so that unless revised, future road infrastructure will perform even more poorly and exacerbate flooding. The very presence of roads of themselves alter drainage patterns and the flow of flood waters through coastal settlements. This alteration of flow patterns can potentially place properties at risk which would not otherwise be at risk. In other words, the risk has been compounded by anthropogenic interventions, many of which will be hard to reverse. Thus, even without considering changes in catchments, i.e. changes in land use and management, projected climate change will result in more extensive and frequent flooding associated with changing and intensifying precipitation patterns. This suggests that there is a need for a fundamental rethink of the way coastal areas are developed and re-developed in the future if the risks from flooding are to be minimised.

Impacts on Historical and Cultural Infrastructure

Before the arrival of Europeans the Caribbean region was home to a variety of indigenous peoples; Amerindians, Maya, Taino, Carib, Arawak, Guanahatabey, Sibony and others. Although reduced by Europeans, either by war or disease, there are physical reminders of these earlier Caribbean peoples. Several of their occupation sites that have been subject to archaeological investigation are located in low-lying coastal areas. Their excavation has added to our understanding and appreciation of these cultures. The remaining sites that are in low–lying coastal areas are now at increasing risk from sea level rise, storm surges, and accompanying coastal erosion. The site at Grand Bay, Carricou is illustrative of the future risks such sites face (Fitzpatrick, Kappers and Kaye 2006). The loss of these sites, many of which remain to be fully investigated, would be a loss of part of the Region's patrimony.

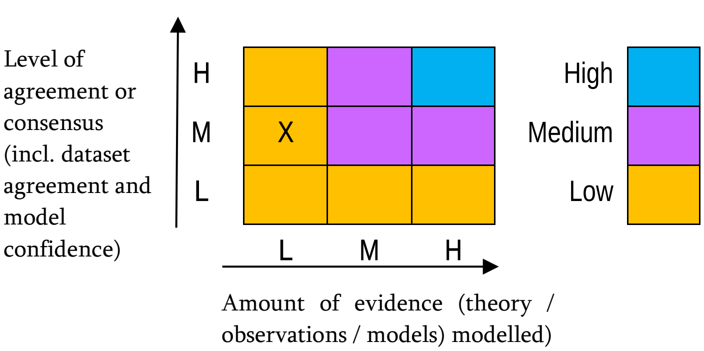
As indicated the Region is host to several UNESCO World Heritage Sites that are located in coastal areas. In addition, it is also home to 30 RAMSAR sites that are located in coastal or low-lying areas. All of these will be at risk, to a greater or lesser extent, from sea level rise, and from conjunctive marine and pluvial induced flooding, storm surges, or more intense hurricane activity.

Coastal erosion is also placing at risk cultural sites which are not recognised and afforded some degree of protection. The situation of Monkey River Village in southern coastal Belize is illustrative of this. First founded in 1891 to service the local banana plantations, it has gone from a peak population of several thousand to approximately 150 inhabitants. Coastal erosion has removed much of the area on which the town stood including the loss of the town cemetery, with graves and bodies washed away. Many villages and coastal communities have existed along the coastline for hundreds of years. The burial and cultural sites associated with these settlements are at increasing risk. They hold significant cultural, emotional, and traditional value to the region, and are under threat from coastal erosion, coastal flooding and being washed away by wave action, tidal influences and storm surges (Fitzpatrick 2012).

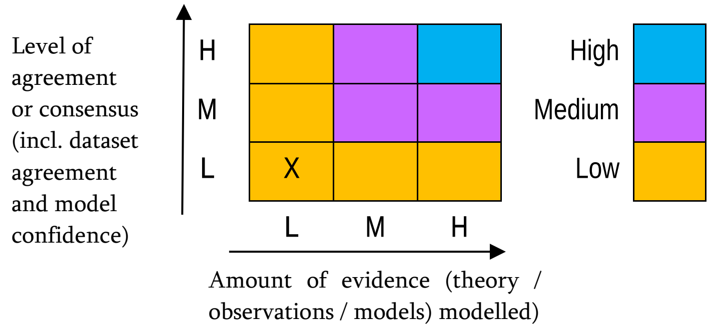
Photo 5: Cemetery at Tibeau on the eastern coast of Carriacou (Fitzpatrick, Rick, and Erlandson 2015).

Confidence Assessment

What is already happening



What could happen in the future



Although there is a growing acceptance of the importance of data collection, its actual realisation continues to be a challenge. The extent of the geographical area, the number of different governments each with their own set of priorities and economic challenges complicates efforts to improve the coverage and data collection. Associated with this are issues around the accessibility and sharing of data which often compound problems. This holds true across the whole range of physical and socio-economic data required to understand the potential impacts of climate change on biotic and abiotic environments. Numerical modelling is important but the Region's resources and ability to carry out this function remain a challenge. There are few centres of excellence with the capability to carry out modelling and these often struggle to maintain adequate funding. To an extent this difficulty is addressed through partnerships within and beyond the region. A further challenge exists in using the outputs from climate models and incorporating them into sector specific models. Here the situation is if anything more problematic. The application of modelling and numerical techniques tends to be sporadic. This is a result of similar problems to those noted above, lack of knowledge and expertise being particularly notable, but also compounded by a degree of inertia in adopting new approaches. This is further compounded by a tendency to adopt a project-based approach with short time horizons rather than be guided by a comprehensive medium to long-term planning approach. This is particularly true in respect of the provision of infrastructure which tends to be reactive to current situations rather than proactive in meeting future needs. This is despite the many diagnostic reports that regularly come out after the passing of each disaster event. Implementation of recommendations after events tends to be neglected.

The development of coastal areas for settlement, the provision of services and economic activity e.g. tourism, ports, and harbours, has removed much of the natural environment and the ecosystem services they would have provided. Furthermore, settlements and the accompanying socio-economic conditions have *locked-in* a pattern of development which in many instances contributes to the continuation of vulnerabilities and risks. The fragile state of many economies means that governments have few opportunities for addressing some of the root causes of current and future risks, even if there were to be a magnitude change in the understanding of climate processes, hurricane activity, and sea level rise, and the modelling of their impacts. There remains the uncertainty around the future changes in climate around the Caribbean Region.

For the 'What is already happening' assessment, we are of the opinion that although there is a better understanding of the science and better confidence in science and amount of available evidence there exist a great many gaps and uncertainties. Improved extremes analysis and ongoing climate research have increased the knowledge and theory available. Further integration of coastal process knowledge with drainage and surface water processes remains a challenge particularly when it comes to the incorporation into codes and standards. There is a need to improve the ability to gather data on coastal flooding, particularly in urbanised areas. There are many tools available now that could be used but this is hampered by a lack of reliable and consistent input data. On-going monitoring and evaluation of coastal and marine ecosystems, the value of the services they provide, and the consequences of their deterioration remain an imperative, though one which is unlikely to be realised.

The frequency of occurrence and size of extreme waves are generally expected to increase, though how this will be distributed across the Caribbean is a matter for further research. Wave heights depend on winds and storms as well as bathymetry, coastal morphology, and the level of protection and energy dissipation provided by coral reefs. There are numerous locations where embayment serves to magnify wave heights with implications for coastal damage. Continuing degradation of protective reefs, mangroves, dunes, and beaches will exert a negative feedback on top of the effects of rising sea levels, tides, wind driven waves, and surges. Whether it will be possible to offset these in the long term through hard engineering and soft interventions is a big question. Continued exposure to increasingly severe events may have serious economic consequences for some coastal settlements and urban areas. How this might vary across the Caribbean needs further consideration. Also of concern is how to respond to the combination of the subsidence of some coastal areas e.g. Georgetown, and Belize City, and rising sea levels. It is a moot question as to whether an increase in severe flooding and the accompanying economic consequences will lead to their relocation. Belize has already done this to a certain extent in response to vulnerability to hurricanes but this will become even more imperative in the future, perhaps not just for settlements in deltaic coastal areas.

Knowledge Gaps

There are a number of gaps and challenges, some of which are given below:

- Gaps in understanding the changes in precipitation patterns across the region and the ability to provide credible island scale information; this has implications for the development of design standards for infrastructure particularly for transport networks (e.g. roads, bridges and drainage);
- How climate change might affect ocean currents and storm surges and by extension coastal erosional processes;
- Can coastal ecosystems be restored to the extent that they could provide coastal protection;
- Understanding the risks and impacts of conjunctive coastal flooding (from storm surges and pluvial flooding);
- Understanding how changes in land use, brought about by climate and anthropogenic changes might impact coastal flooding;
- Gaps in understanding of the influences of interannual and decadal climate oscillations on storm and hurricane activity, and sea level rise. The superimposition of the two oscillations on each other and the way they could magnify their individual effects may have major implications for coastal settlements in terms, for example, of the potential social and economic disruption, damage, and losses;
- Uncertainty and discrepancy between models and model outputs and a lack of understanding of the sources of the differences causes uncertainty and a reluctance to act on the part of decision-makers who tend to view uncertainty in a negative light; the 'science-to-policy' dialogue is important when decisions have to be made regarding the allocation of scarce resources.

Socio-economic Impacts

Throughout this paper socio-economic impacts, actual or potential, have been incorporated into the discussions. These include:

- Adverse impacts on economic activities such as tourism leading to loss of employment and stranded investments;
- Loss of productivity;
- Increased demand on welfare and health services;
- Disruption of education;
- Increases in domestic tension and psychological conditions;
- Loss of cultural heritage and personal/family histories and artefacts;
- Adverse macro-economic impacts related to diversion of expenditures to recovery activities such as repair and replacement of infrastructure, services and utilities rather than growth and development;
- Internal displacement and relocation of sections of the population and, increased outward migration.

There can be no doubt at all that sea level rise and other climatically driven processes are already exerting a significant impact on coastal settlements and infrastructure, and as these are by definition human constructs and sites of activity the two go hand-in-hand. One of the features of the Caribbean is that it will be subject to extreme events such as tropical storms and hurricanes. There is an acceptance of the idea that sea level rise is occurring and that other extreme events, such as flooding and severe hurricanes, are occurring more frequently. However, the connection between these and the negative feedback human activities in the coastal zone are having is not as widely recognised. The short-term pursuit of economic advantage coupled with weak regulatory mechanisms continues to contribute to the adverse impacts of coastal settlements. In almost all instances authorities with responsibility for the management of coastal zones, settlements and infrastructure struggle to meet the challenges due to weak economic circumstances. When damages suffered are measured as very high proportions of GDP then recovery and 'building back better' will be a challenge. That said it is still possible even with limited economic resources to provide a decent level of protection if there are good institutional capabilities. The contrast between Haiti and Cuba in coping with extreme events is instructive in this regard.

There are options available but they come at a high cost. Coastal protection, through combinations of hard and soft engineering requires detailed investigation and proper planning before implementation if it is to be successful. Costs could be of the order of tens of millions of dollars per kilometre of protection provided. Even then it cannot provide protection against increasingly extreme events. A further challenge is the existing urban fabric and configuration suggesting a need for climate resilient urban renewal and climate proofed infrastructure, including ports, harbours and airports. All of which implies the need for re-tooling Caribbean states.

Citation

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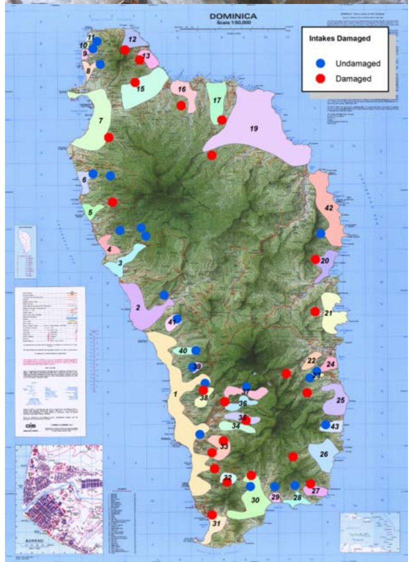
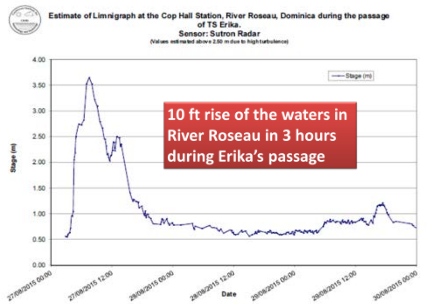
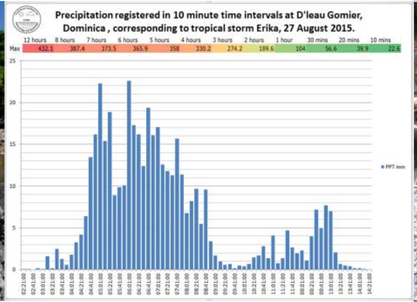
What is already Happening: Impacts of TS Erika on Dominica's Infrastructure

- During 2015 the Caribbean was experiencing extreme drought conditions. On the evening of the 27th August Tropical Storm Erika arrived in Dominica producing heavy rains for 9 hours.
- As a result of the steep topography and short distances from ridge to coast produced catastrophic flash flooding across the whole island. The situation was exacerbated by the unusual dryness of the season and cracking of clay soils which triggered slope failures and the generation of debris, transported by swollen streams and rivers.
- The impact of these flows caused extensive damage to coastal settlements and the infrastructure serving them.
    - Over 40% of the transport network was damaged and 50% of the bridges
    - The country's main airport, situated on the coastal plain the Douglas-Charles Airport was completely flooded and electrical equipment compromised
    - The country's water supply and sewerage network was extensive. Flash floods washed away parts of transmission pipelines, particularly at river crossings where they are attached to bridges.. Damage to sanitation facilities increased exposure to contaminated water and the spread of associated diseases and vectors.
    - Of the country's 75 schools, 38 were damaged to varying degrees.
    - Over 1,000 houses were damaged
    - The on-going cost of the damage is likely to double Dominica's public debt

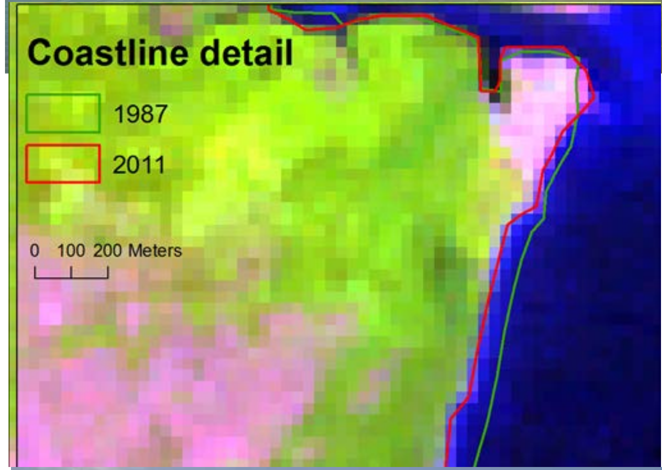






What is already Happening: Loss of Cultural Heritage

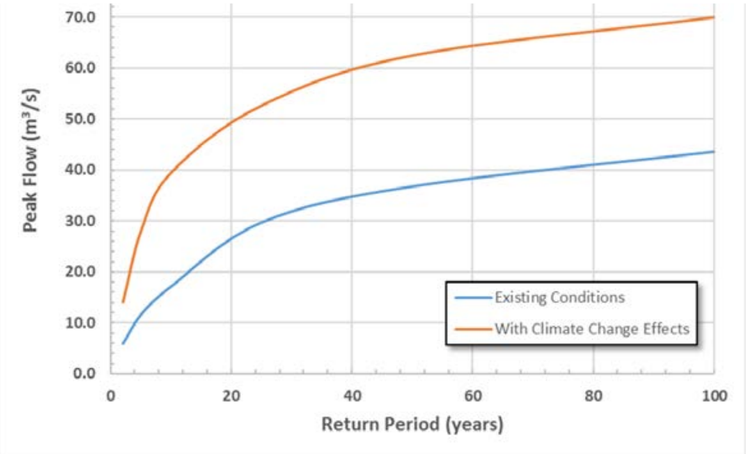
- Monkey River Village in southern Belize was inaugurated as a Town in 1891 with some 2,500 residents. The local economy was based on agricultural production, mainly bananas, until its collapse in the 1930s due to Banana Blight. By the 1960 the population had fallen to 400 and today it is less than 200. Many former residents and their families have relocated to other towns in the area.
- Based on interviews with residents over the last 30 years 40 land plots have been lost including the community playing field between the cemetery and the beach due to coastal erosion. The rate of erosion has been accelerating over the last 10 years. And up to 100 metres of coastal retreat has been measured.
- Beach erosion increased in 1998 and 2002 due to Hurricane Mitch and Iris respectively. While Hurricane Mitch did not make landfall in Belize, the swells and wave action generated did impact the Monkey River coastline.
- Hurricane Iris had a devastating effect on Monkey River Village and surrounding forests. The effects were so severe that several homes and the land on which they sat were lost to the sea. The forest was also severely damaged and the Howler Monkey population was threatened because their food source had been destroyed.
- *The littoral forests/coastal beach scrubs* are important because this forest types acts as a buffer stabilizing beach erosion. Individual efforts to control beach erosion have exacerbated the rate of erosion which is now threatening the littoral forests as well as the cemetery.
- Only 3 metres separates the cemetery from the sea and during storms the sea is breaching increasingly closer. The cemetery provides a connection to the village's past and if submerged the spirits of the deceased will be disrupted and the bodies washed into the sea.

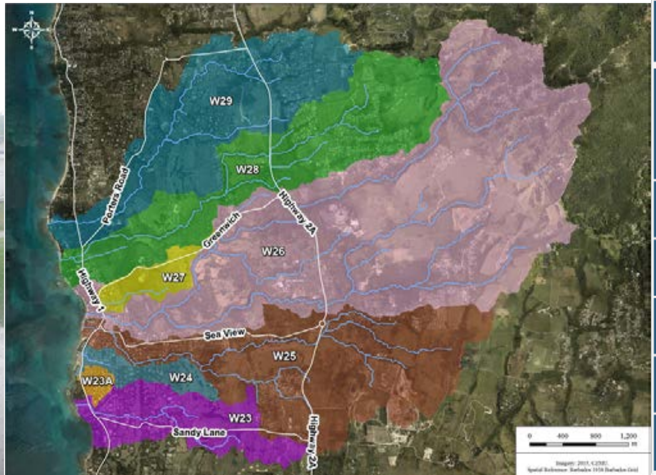


What could Happen: Future Flooding in Holetown, Barbados

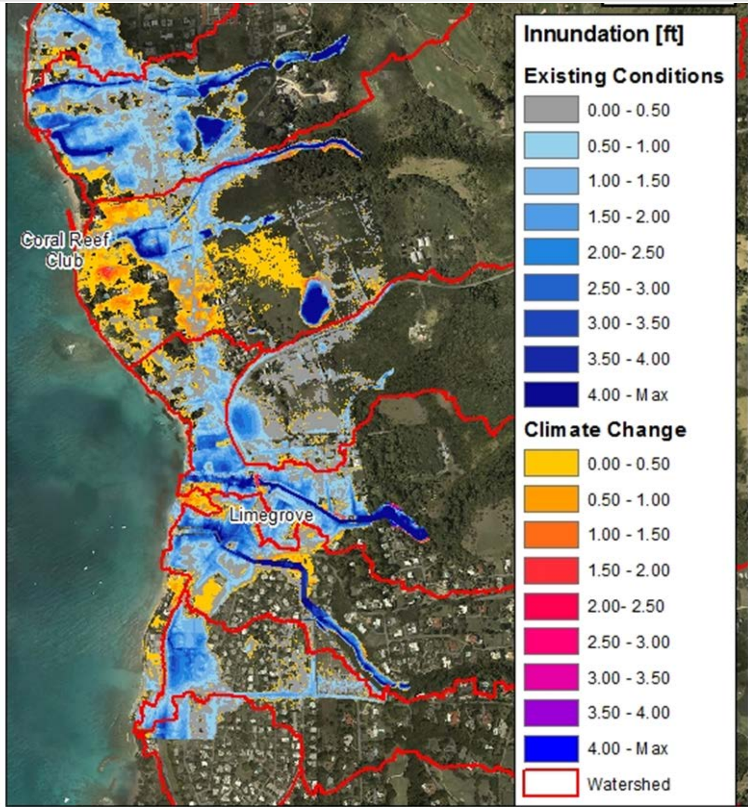
- Holetown on Barbados' West Coast is an up-market tourist hub. It is regularly subject to flooding as developments along the beachfront have impeded natural drainage to the sea, which have channelized. The main coastal road now forms a barrier and its drainage culverts act as choke points, aggravating local flooding.
- Future rainfall projections are for a
  - Decrease in annual rainfall of up to 30%
  - Increase in number of consecutive dry days
  - Increases in extreme rainfall
  - Increases in maximum 5-day rainfall

- Based on reanalysis of rainfall projections under climate change the flood risk for Holetown was investigated
- Rainfall intensity increased by up to 45%
- Run-off in the larger catchments almost doubled
- Existing infrastructure cannot cope with flooding under present rainfall conditions
- Under the climate change scenarios significantly more properties will be at risk of flooding (yellow areas)



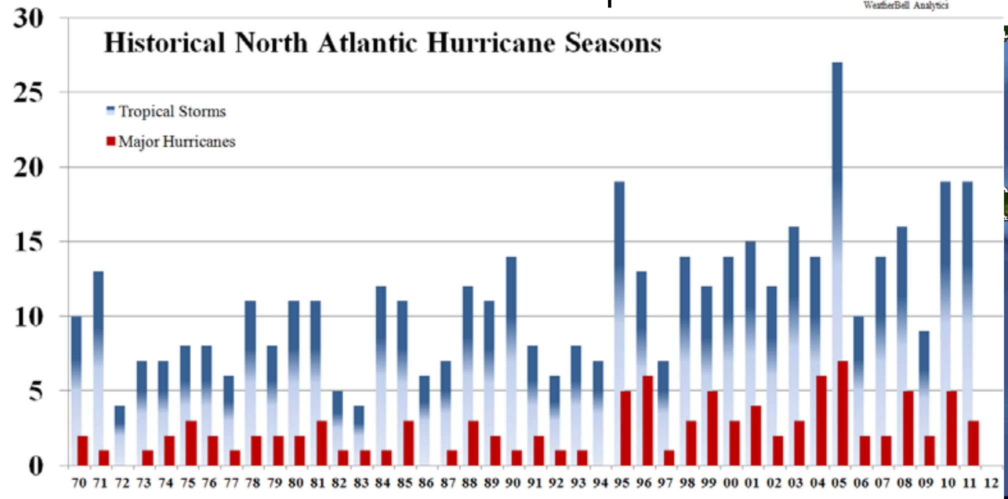


	Peak 25-Year Runoff		
	Original (m^3/s)	Climate Change (m^3/s)	Percent Increase (%)
W23	7.4	13.6	84
W25	29.7	52.6	77
W26	70.1	134.7	92
W28	31.2	55.5	78
W29	42.6	57.2	34



What could Happen: Impacts of Hurricanes (Hurricane Ivan, 2004)

- The Caribbean has observed a 41% increased in the number of high intensity category 4/5 hurricanes since 2000, as compared to the same time period prior.
- General circulation models have projected that the frequency of high intensity category 4/5 hurricanes will increase over the next 100 years further escalating the threat to vulnerable Caribbean SIDs.
- Increased frequency projected is directly attributed to warmer Sea Surface Temperatures (SST) which are the engines that drive and sustain hurricanes.
- Warmer SSTs and warmer average global temperatures are caused by increased anthropogenic GHGs emissions into the atmosphere.



Hurricane Ivan passes through the Caribbean in 2004 devastating Barbados, Cayman Islands, Cuba, Grenada, Jamaica, St. Lucia, St. Vincent\Grenadines & Tobago causing extensive damage in excess of US$3 billion and the deaths of 67 people.

Grenada – at category 3 strength causes more than US$815 million in destruction, damaging 80% of the housing sector and 25 deaths.

Jamaica – at category 4 strength causes an estimated US$360 million in destruction, damaging 47,000 homes and 17 deaths.

Cayman Islands – at category 4 strength causes an estimated US$1.85 billion in destruction, damaging 95% of the housing sector and 2 deaths.