6. CLIMATE EXTREMES AND EARLY WARNING

6.1. BACKGROUND – CLIMATE EXTREMES AND DISASTERS IN A CHANGING CLIMATE

As previously noted in Chapter 3, rainfall in the Caribbean islands and Belize is generally characterised by a wet and a dry season in each year, peaking in September-October and February-March, respectively. At least 70-80% of the rainfall occurs, on average, during the wet season which also largely coincides with the Atlantic Hurricane Season (see Section 4.2). Regional variation is seen, for example, in the coastal Guianas which has two wet and two dry seasons per year but no tropical cyclones, and the ABC Islands (Aruba, Bonaire and Curaçao) which feature a much drier climate, only having substantial rainfall from October through to January. The entire region (with the exception of northern-most portions of The Bahamas) lies within the tropics. Consequently, temperatures are relatively constant throughout the year, although an annual cycle in temperature remains discernible (Section 3.3.). Both daytime and night-time tend to be coolest around January, warm up from around March/April, and peak in August/September.

There is much variability in both the wet and dry season as it relates to the onset, duration, amount, frequency and intensity of rainfall. It is not unusual to experience significant dry spells during the wet season or very wet spells in the dry season (Trotman 1994). When such extreme climate events occur, they can impact heavily on climate sensitive sectors e.g. agriculture and food security, water resources, disaster management, health, energy and tourism (see Chapter 7). It is therefore important to try and understand what drives climate variability in the Caribbean.

A growing body of research is increasingly supporting our understanding of the nature, the drivers and temporal changes of Caribbean climate variability and extremes. For example, rainfall extremes (including droughts) are often a result of the occurrence and phase of global climatic features such as the El Niño Southern Oscillation (ENSO). (This is explored in section 6.3.) In terms of excessive heat, and in particular the occurrence of heat waves, preliminary results also suggest that the ENSO and deviations of SST to the seasonal norm are two of the main large-scale and predictable drivers. This chapter will elaborate on how knowledge of some of these drivers can facilitate the long-range prediction of some climate extremes (i.e. from weeks to years), and what efforts are underway in the region to monitor these extremes as well as to predict the likeliness of their occurrence or their impact. Tropical cyclones are also arguably one of the most costly natural hazards in the Caribbean. The chapter will examine briefly the extremely active 2017 Atlantic Hurricane Season.

The need to understand and forecast Caribbean climate extremes will only grow under projected climate change. Figure 6.1 uses changes in temperature to illustrate the potential impact on climate extremes.

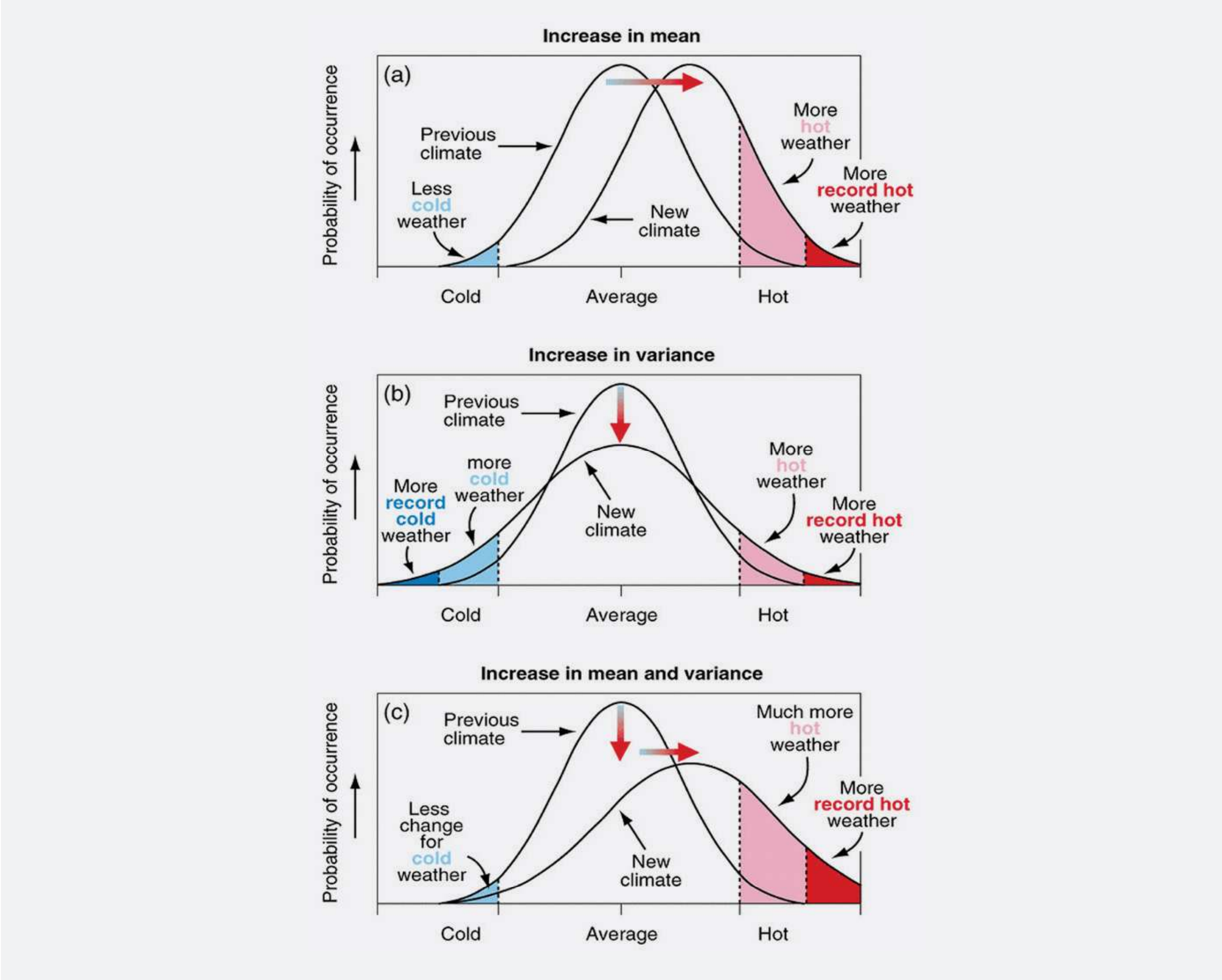


Figure 6.1: Schematic showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature. Source: IPCC (2001).

In a warming world, the atmosphere (and the oceans) is expected to warm as a whole over time, and day-to-day temperature variations - i.e. variability related to weather patterns - are expected to become larger[9]. Figure 6.1a shows how the frequency (or probability) of a given day recording a given temperature changes when the average temperature shifts to a higher value. As seen, very cold days become less frequent and very hot days become more frequent. Figure 6.1b shows what happens to the frequency of temperatures if only the variability (expressed by the variance) increases. In such a scenario, the frequency of having near-average temperatures decreases, and the frequency of extremely low and extremely high temperatures increases. Figure 6.1c shows what happens when both the average and the variability increases (as is most likely to happen in the future). In that case, the frequency of very cold days would decrease, but the frequency of very hot days would increase. The combined shift of average temperature rise and an increase of variability appears to already be observed in the Caribbean (see Section 3.3.4), with a continuation of the trend projected to continue under global warming (Section 5.2.3).

Although there is less certainty about the projections of future rainfall trends, chapter 5 suggests decreasing rainfall totals, particularly for the Lesser Antilles toward the end of the current century. This suggests an increasing drought risk (Cooper and Bowen 2001; Taylor et al. 2018).

9 In statistical terms, day-by-day variations often follow a so-called normal distribution. This means that, if all recorded temperatures were ranked from lowest to highest, the average of all those temperatures would be also be the most frequently observed and a temperature of a number of degrees cooler or higher than that average would each occur equally frequently, but both less frequently than the average. The more extreme the temperature, the less frequently it occurs.

6.2. MONITORING AND PREDICTION

One strategy which has been incrementally implemented in the Caribbean over the past 20 years to improve our preparedness to climate extremes is the development and operation of climate early warning systems. Two major components of climate early warning systems are monitoring and prediction. The former is enabled by a network of weather observing stations that track essential climate variables such as rainfall and temperatures. Skilful climate prediction is then made possible through the development and operationalisation of statistical or physical/dynamical prediction models that depend on a good understanding of the drivers of variability in climate extremes. This section will elaborate on ongoing operational climate monitoring and prediction initiatives in the Caribbean, which are led out of the Caribbean Institute for Meteorology and Hydrology (CIMH) - a World Meteorological Organization designated Regional Climate Centre (RCC) for the Caribbean.

6.2.1. CLIMATE MONITORING IN THE CARIBBEAN

Meteorological drought (i.e. rainfall deficits accumulating over periods of weeks to years) conditions can be easily tracked since rainfall is the most widely recorded variable in climate records in the Caribbean. Meteorological drought is a slow-onset, impactful hazard which translates in time to agricultural, hydrological and socio-economic drought. Partly in response to the technological advances but also coinciding with a perceived amplification of impacts of climate variability, a strong regional focus on drought monitoring and forecasting emerged in the Caribbean leading to the establishment of the Caribbean Drought and Precipitation Monitoring Network (CDPMN). CIMH launched the CDPMN in January 2009 (Trotman et al. 2009; CIMH and FAO 2016) as a body that would seek to operationally monitor drought (and excessive precipitation), as well as provide prognostic drought information. With growing recognition of the increasing impact of heat in the region, CIMH also started operational monitoring of temperature in 2014.

6.2.2. THE CARIBBEAN CLIMATE OUTLOOK FORUM AND ITS SEASONAL CLIMATE OUTLOOKS

As a consequence of the significant impacts suffered by many, mostly tropical regions from the 1997-1998 El Niño event and the lack of effective early warning and preparedness, regional climate outlook fora were established under the auspices of the World Meteorological Organization (WMO). The Caribbean Climate Outlook Forum (CariCOF) was first held in 1998 with the task being to prepare three-month precipitation outlooks for the region indicating the probability of below-, near- or above-normal rainfall. Since 2000, CIMH has undertaken the preparation of the outlooks, with input from a wider group of regional meteorologists and climatologists since 2012. Since 2012, the CariCOF fora have been preceded by a training workshop on seasonal forecasting for National Meteorological and Hydrological Services (NMHSs) and CIMH staff. Since 2014, two CariCOFs have been held per year - just prior to the wet and the dry seasons. At the first staging in 2019, 22 countries and dependencies of France, the United Kingdom and the United States in the Caribbean participated in CariCOF's monthly seasonal forecasting activities.

The CariCOF climate outlooks examine the relative climate risk on sub-seasonal to seasonal timescales. The seasonal forecasts look at how certain weather conditions, including extreme events, become more likely or less likely during a given period of interest of typically one to six months. They, therefore, are not aimed at predicting the exact timing of a pending hazard. Each month the CIMH and the NMHSs participating in CariCOF prepare regional seasonal climate outlooks of precipitation (since 2012) and temperature (since 2013) at 0- and 3-month lead times, along with a short- to mid-term drought outlook (since 2014) (see Section 6.3), and wet days and wet spells outlooks (since 2015). The products are compiled into a newsletter that is disseminated monthly with updated information. The newsletter and outlook products can be accessed on the WMO Caribbean RCC's web page (http://rcc.cimh.edu.bb).

It is anticipated that the CariCOF's next generation of climate outlook products will be more user-driven and co-designed (such as the drought outlooks), as well as more sector-targeted, tailored and co-delivered (see Section 6.6). The next generation of generic outlook products will also aim to address other extremes such as flash flood potential (see Section 6.4) and excessive heat alerting (see Section 6.5). Coincidentally, through the sectoral Early-Warning Information Systems Across Climate Timescales (EWISACTs) programme (see Chapter 8), sector-specific climate monitoring and forecasting information products are already being derived through translation and repackaging of the generic CariCOF products which are being co-designed, co-developed and co-delivered with sectoral partners, particularly in the agriculture, health and tourism sectors. This move to user-driven and to sectorally tailored climate early-warning information will contribute to building the Caribbean region's climate capacity and, by extension, climate risk resilience. Chapter 8 expands on the EWISACTs programme.

The following sections describe specific regional activities and developments with respect to monitoring and forecasting dry (Section 6.3), wet (Section 6.4) and hot (Section 6.5) extremes.

6.3. DROUGHT AND DRY SPELLS

6.3.1. CARIBBEAN VULNERABILITY TO DROUGHT

As of 2013, seven of the world's top 36 water-stressed countries (including e.g. Antigua and Barbuda, Barbados and St. Kitts and Nevis) are from the Caribbean (WRI 2013) and have less than 1000 m^3 freshwater resources per capita (CIMH and FAO 2016). Even within non-water-scarce countries, local communities and cities may be chronically water-scarce, especially under water-stressed conditions. Further stress is likely with the expansion of the tourism industry, population growth, urbanization, increasing societal affluence, ineffective water management practices and strategies, and declining water quality due to anthropogenic activities and climatic factors. It should be noted that, more so than rainfall itself, water availability in the islands varies seasonally as evaporation rates tend to be higher even as rainfall totals are lower in the dry season. The per capita usage of water by the tourism industry is higher than for the domestic population. Tourist arrivals in the Caribbean tend to concentrate around boreal winter, coinciding with the region's dry season. This situation seasonally increases the demand for water and, therefore, water stress. Consequently, drought early warning in the Caribbean should at least focus on the seasonal to interannual timescale.

6.3.2. DRIVERS OF DROUGHT AND DRYNESS IN THE CARIBBEAN

The activity of deep atmospheric convection - which fuels rain and thunderstorms - is low around February and March, and dry spells i.e. a large number of consecutive dry days, are commonplace during the dry season. The oceans also tend to annually cool down until reaching their lowest temperatures in February (Section 3.3.1), resulting in less evaporation of ocean water and drier air. A drier atmosphere over land takes up available soil moisture in an accelerated way compared to moist air, resulting in a tendency for evaporation rates to increase in the dry season. The result is that water availability tends to decrease during the dry season because of reduced rainfall and increased evaporation. During the wet season in much of the Greater Antilles and parts of Belize, drier spells called "mid-summer drought" are common around July-August (Section 3.2.1), which also tend to temporarily increase dryness there.

The dominant driver of regional drought in the Caribbean is El Niño, which initially tends to stabilize the atmosphere and later on increase vertical wind shear, both of which are inhibitive for deep convection. Anomalously low rainfall amounts are particularly common when sea surface temperatures are unusually warm in the eastern tropical Pacific and cool in the Tropical North Atlantic (Enfield and Alfaro 1999; Giannini et al. 2000; Giannini et al. 2001; Taylor et al. 2002; Stephenson et al. 2008; Taylor et al. 2011). Furthermore, when the North Atlantic Oscillation is in a positive mode, i.e. the Azores-Bermuda High Pressure system is larger and stronger than average (Charlery et al. 2006; Gamble et al. 2007), the atmosphere is more stable, thereby inhibiting deep convection. At the same time, stronger trade winds are blowing over the Tropical North Atlantic resulting in a cooling effect on the ocean's surface, with less evaporation taking place in ensuing months. If the winds are carrying Saharan dust across the Atlantic, rainfall tends to be further reduced. Other drivers of drought include the strength of the Caribbean low level jet on seasonal timescales (Cook and Vizy 2010; Taylor et al. 2012) and the Atlantic Multi-decadal Oscillation on an inter-decadal time scale (Stephenson et al. 2014).

6.3.3. DROUGHT MONITORING

The CDPMN drought monitoring system which was launched in 2009 immediately showed its value during one of the worst regional droughts which occurred in 2009-2010, by providing CARICOM governments with situation analyses and advice from January 2010 (CIMH and FAO 2016). The principal monitoring tool relied on a drought index called the Standardized Precipitation Index (SPI) (McKee et al. 1993), as recommended by WMO (Hayes et al. 2011) and Deciles (Gibbs and Maher 1967). SPI monitoring maps were coupled with the three-monthly Caribbean Precipitation Outlook using an SPI calculator[10] and used to inform and advise on how the drought conditions were expected to evolve during 2010. Since then and to present, the SPI and decile monitoring maps are updated each month by the CDPMN and offer depictions of the severity of ongoing meteorological drought.

The CDPMN has enhanced their products by providing monitoring maps covering a range of different timescales. The SPI and decile maps cover five timescales: ranging from 1 month, 3 months, 6 months and 12 months, respectively (CIMH and FAO 2016; Farrell et al. 2010; Trotman et al. 2009; Trotman et al. 2017), to more recently 24 months. Given that agricultural drought results from a lack in soil moisture, which can fluctuate greatly within 1 to 3 months, a 3-month SPI is relevant. By contrast, very large water reservoirs (including aquifers) are affected by long-term rainfall deficits that last beyond six months, making a 12-month SPI more relevant. Figure 6.2 depicts the six-month SPI (also referred to as SPI-6) values calculated from rainfall deficits and excesses from October 2009 to March 2010 across the Caribbean, at the time drought impacts peaked during the 2009-2010 event (Farrell et al. 2010; CIMH and FAO 2016; Trotman et al. 2017). With an SPI value of -2 corresponding to a return period of such rainfall deficits of 40 to 50 years, it is to be noted that much of the Lesser Antilles was subject to exceptional drought resulting in widespread and severe drought impacts (Farrell et al. 2010).

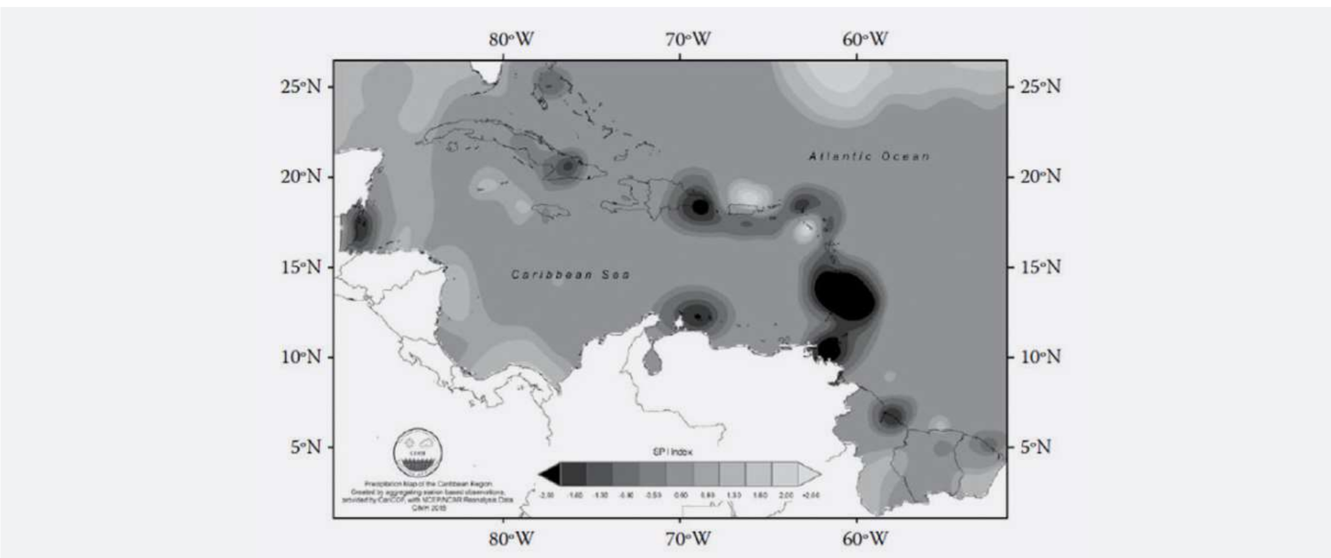


Figure 6.2: A 6-month SPI map (October 2009 to March 2010), where negative values point to increasingly severe dryness. Source: CDPMN

As more temperature records have become available through climate data sharing efforts among participating meteorological services to the CariCOF, efforts are underway to develop and operationalise a drought index that not only includes rainfall deficits and surpluses, but also the effect of anomalous temperatures on moisture loss through evapotranspiration. As such, the CDPMN has released its Standardized Precipitation-Evapotranspiration Index (SPEI) monitoring products on an experimental basis.

6.3.4. DROUGHT FORECASTING AND VERIFICATION

Led by CIMH, the CDPMN and CariCOF have developed drought prediction products on an operational basis, including the CariCOF drought outlooks[11]. Central to the drought outlooks are drought alert maps, which detail the expected impact level and suggest a corresponding preparedness action level. A brief overview of the methods

10 The SPI calculator can be acquired from the US National Drought Mitigation Center (NDMC).

11 The CariCOF drought outlooks can be downloaded from http://rcc.cimh.edu.bb/drought-outlook/ .

utilised to produce such maps is given in CIMH and FAO (2016). Different drought alert levels are generated depending on the forecasted percentage probability that the SPI over six or twelve months exceeds a value beyond which drought is expected to be impactful. Because more rainfall occurs during the wet season than in the dry season, drought impacts are expected to become significant beyond a higher threshold in the former season. SPI threshold values of -0.8 and -1.3 were adopted for the dry and wet seasons respectively, corresponding to CDPMN's drought severity scale of at least moderately dry and severely dry, respectively. Each month, two drought alert maps are produced – an SPI-6 based map for a moving 6-month period ending three months down in time, and an SPI-12 based map with a 12-month period of interest ending either in November for maps generated during the wet season or in May for maps done in the dry season.

Alerts of no drought concern, drought watch, drought warning and drought emergency speak to anticipated risk levels by the end of a forecast period. The drought outlooks therefore form actionable information for decision-support systems for the different sectors (Trotman et al. 2017). If action is to be premised on the outlooks, then the drought prediction system must demonstrate some skill. A recent verification exercise suggests that the forecasting system is able to identify at least 85% of impactful long-term droughts as far as six months in advance (Trotman et al. 2017). The same preliminary investigations found the forecast was able to predict the recent region-wide drought event of 2014-2016 (see Box 6.1) to be approximately as severe as the 2009-2010 drought. The confidence of the system increases when the severity of the expected drought increases, because risk increases with the probability and the severity of a pending impact. Since there is increasing confidence in the forecasts when the level of drought risk increases, the validation exercise therefore shows that there is merit in providing drought prediction information in terms of alert levels.

6.3.5. DRY SPELLS

The Caribbean's vulnerability due to dry spells is most obvious for rain-fed agricultural crop production. A lengthy dry spell during some significant stages of a crop's life cycle can severely limit its productivity due to water stress. On the other hand, dry periods can initiate flowering and increase productivity in some crops, as long as they are not extensive, or, as in the case of sugar cane, enhance sugar concentration. The risk of recurrent dry spells can be exacerbated by heatwaves (see Section 6.5) which increase evapotranspiration rates. Knowing a crop's dry spell tolerance thresholds – in terms of duration and frequency – can provide useful information on the risk of failure or low productivity of a crop. Depending on the type of soil, crops can likely be productive when facing up to 7 to 15 consecutive days without significant rainfall, by utilising available water retained in the matrix of the soil. A number of these spells across those sensitive phases of the growing season could result in unwelcomed reductions in yield. In fact, for even high water-retaining clay soils, a dry spell of more than 15 days could prove debilitating at least at any time within the growing season.

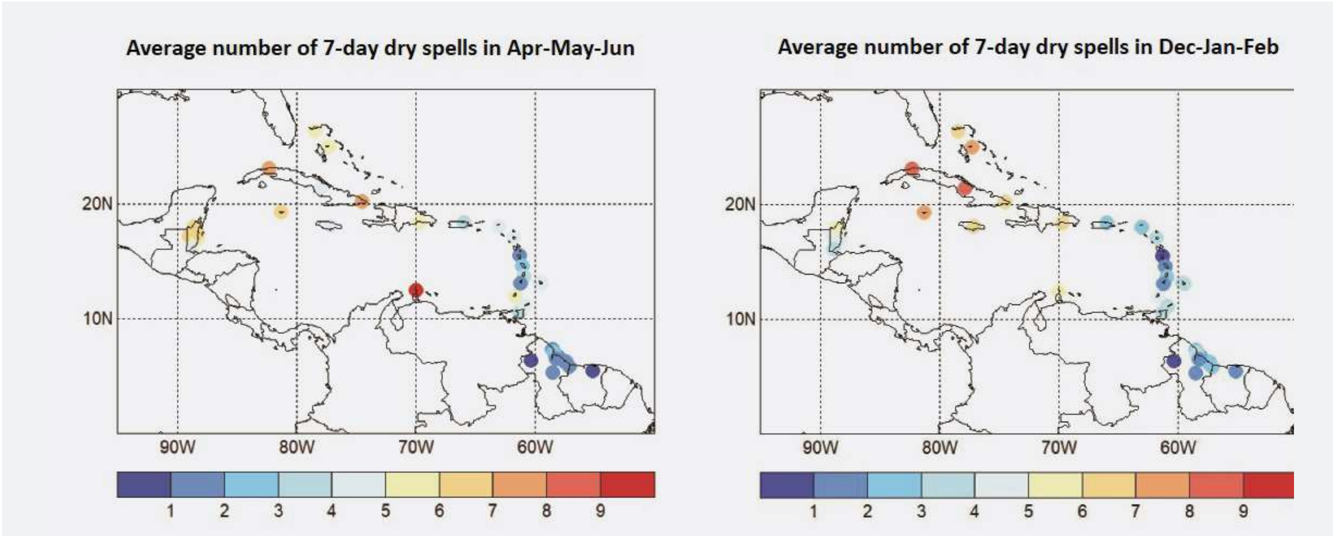


Figure 6.3: Map shows the average number of 7-day dry spell that occur during April May June (left) and December Jan February (right). The climatological period spans 1985 to 2014. Source: CIMH

Given the risk of dry spells to rain-fed agriculture in the Caribbean and a fair understanding of what causes them, there has been a push to develop an early warning system for regional dry spells. It is premised on the notion that the typical growing season of many horticultural crops is about 3 to 4 months, and a crop would find it difficult to produce high yields with either three (averaging one per month) or more 7-day dry spells or one or more 15-day dry spells within the three-month period. Caribbean rainfall records (see Figure 6.3) show many areas in the Greater Antilles where, even during the wet season, such dry spells are frequent and therefore pose a high risk for many plant species. Conversely, other locations such as northern Guyana and Dominica are relatively low risk areas for dry spells, even during the dry season. The CariCOF dry spells outlooks provide forecast maps of the probability of having at least (i) three 7-day dry spells and (ii) one 15-day dry spell in a given three month period[12]. The maximum number of 7- and 15-day dry spells within the same upcoming three-month period is also forecast. The added value of seasonal forecasts of dry spell frequency is in determining whether a particular planting season may pose too much water stress in a given year, whereas it may not in most other years.

12 For now, with the products still being in experimental stage, the same 0-month lead period is employed as for the precipitation outlooks and the wet days and wet spells outlooks.

INFORMATION BOX 6.1

THE 2014-2016 CARIBBEAN DROUGHT

Caribbean droughts within the last decades have all coincided with El Nino years, including the 2014-2016 event (see Section 4.4.2). By the end of 2014, drought impacts were observed in countries like Antigua and Jamaica. Anguilla, Antigua and Barbuda and Sint Maarten recorded below-normal rainfall from January to March 2015. Dryness during early 2015 was likely amplified by strong dust transport across the Atlantic occurred. There was rapid strengthening of the El Niño by May 2015 and by the end of the end of 2015, it was one of the two strongest El Niño events since 1950 [NOAA 2018]. By July 2015, the significant reduction in rainfall across the region resulted in dry conditions being recorded in Aruba, Barbados, Dominica, Dominican Republic, Guadeloupe, Jamaica, St. Kitts, and St. Lucia. Wet season rains brought temporary drought relief in late August/September 2015 at some locations. By late November, drought conditions were re-established, with record-low October to December rainfall being observed at several locations. 2015 became the driest year on record at many locations, including in Antigua, Tobago, Barbados, Jamaica and St Lucia (Stephenson et al. 2016), or second driest since 1973 in parts of St. Lucia and third driest since 1881 at one location in Jamaica and since 1951 in St. Croix. By the end of the dry season in 2016 much of the eastern Caribbean observed a deficit of between 20% and 60% of their cumulative rainfall for the “Water Year” June 2015 to May 2016.

The 2014-2016 drought was deemed the worst on record for Antigua with its total duration of meteorological drought being the second longest since 1928 with, by far, the greatest rainfall deficit. Trotman et al. (2017) provides an overview of reported impacts of the 2014-2016 regional drought on a diversity of socio-economic sectors, which varied by country. Throughout the Caribbean, there were many reports of reduced agricultural crop production, loss of livestock, increase in bushfires, reports of empty water reservoirs and ensuing water restrictions, as well as, reports of reduced hydropower generation, hotel cancellations and, in one nation a temporary stop in provision of water to cruise ships.

6.4. EXCESSIVE RAINFALL, EXTREME WET SPELLS AND FLASH FLOODS

The Caribbean wet season is accompanied by copious rainfall attributable to weather disturbances and weather systems (including tropical cyclones) that produce intense showers. Wet spells with intense showers occurring in a rapid succession (i.e. over a small number of consecutive days) characterise wet seasons in the Caribbean. Though the recurring heavy rains can be beneficial for replenishing major water reservoirs, extremely intense showers often lead to flash flooding. Flash floods occur when the rainfall accumulation rate exceeds the rate of soil infiltration and surface drainage.

The impacts from flash floods can range from water damage to infrastructure and property to crop losses to contamination of water supplies by waste, toxic material or biological contaminants. Flash floods can also increase landslide risk, for instance by destabilising slopes and through erosion. Two recent notable examples of flash floods impacting the region are the 2015 floods in Dominica from Tropical Storm Erika (see Box 6.2) and the 2013 'Christmas floods' between 24 and 26 December in Dominica, St. Lucia and St. Vincent and the Grenadines.

Flash flood risk management can benefit from early warning information on wet spells . Some of the hazards associated with flash floods can be partly or largely mitigated by appropriate land management practices and technologically simple solutions such as ensuring drainage channels are cleared of silt and debris. Others can be mitigated to a large extent by improving preparedness through education on the hazards and risks associated with them, as well as by the provision and uptake of early warning information. The remainder of this section focuses on (flash) flooding triggered by wet spells in the Caribbean. Specifically, the chapter addresses how early warning information on wet spells could be designed as a step toward addressing flash flood risk.

6.4.1. FLASH FLOOD POTENTIAL

In addition to climate data, flash flood risk prediction models incorporate non-climate data such as geology, exposure of the population and assets, and the appropriateness of infrastructure. This restricts operationalizing the forecasting of flash flood risk due to limited non-climatic data for developing, calibrating and validating the models throughout much of the region. A simpler alterative approach is to focus on climate alone as a trigger for flash flood risk and to estimate the flood potential. Flash flood potential specifically estimates the potential number of flash floods to be expected. Forecasts of flood potential can be later integrated with risk assessments and risk mitigation and preparedness plans in order to drive evidence-based decision-making.

6.4.2. EXTREME WET SPELLS

To provide early warning for flash flood potential at seasonal timescales, seasonal forecasts of wet spell frequency require threshold rainfall intensities that correlate well with flash flood occurrence. The threshold rainfall rate depends on exposure, geology, soil water infiltration capacity and infrastructure – in particular drainage – and is location-specific. There is limited facility to determine such thresholds for each individual location at risk of flash flooding, and such an effort would demand an increase in the amount and density of rainfall stations at each location at risk. To overcome this challenge a more time efficient, proxy-based, statistical solution is being pursued, the outcome of which would allow inference of implications due to flooding rather than accurately quantifying the risk. For instance, if the assumption is that a rainfall threshold to be exceeded to produce a flash flood is a function of its local climate (i.e. very wet in a given season, with frequent episodes of extreme rainfall), then a soft threshold of the percentile type could be adopted. So instead of selecting a generic threshold value (e.g. 100 mm in two days), the top X% of rainfall accumulations over an n-day period is calculated, i.e. the (100-X)th percentile. An obvious limitation of such an assumption is that flood potential is only a function of the relative wetness of a certain period at a given location compared to its usual rainfall. Hence, when working with percentile-based thresholds, it becomes critical to utilise only thresholds that are high enough to increase flood probability in reality.

Starting from June 2015, the CariCOF added a 3-day extreme wet spells outlook to its list of monthly operational forecast products. The 3-day extreme wet spells frequency forecasts driving these outlooks cover a three month period with 0 months lead time[13]. A methodological setup puts the wet spell forecast alongside the 0-month lead seasonal precipitation forecasts in order to make an expert judgement on implications that follow from a combination of forecasted events. In terms of thresholds being used, a 3-day extreme wet spell is a period of three consecutive days over which the total rainfall sum exceeds the 99th percentile of all three day periods in a historical, climatological record[14]. The actual rainfall sums associated with this threshold vary from around 50mm in Aruba (the driest territory within CariCOF), to between 80mm and 120mm in most other areas, and in excess of 160mm in the wettest mountainous areas of e.g. Dominica or Jamaica.

To provide early warning for flash flood potential at seasonal timescales, seasonal forecasts of wet spell frequency require threshold rainfall intensities that correlate well with flash flood occurrence. The threshold rainfall rate depends on exposure, geology, soil water infiltration capacity and infrastructure – in particular drainage – and is location-specific.

6.4.3. CARICOF WET DAYS AND WET SPELLS OUTLOOKS AND FLASH FLOOD POTENTIAL EARLY WARNING

The effectiveness of the early warning for flash flood potential depends, in part, on how the occurrence of extreme wet spells and flash floods correlate. Efforts are currently underway at the CIMH to thoroughly examine this. For example, Table 6.1 shows five examples of flash floods during the period September to November 2016 in the countries of Barbados and Dominica. Table 6.1 suggests that there may be a very close correlation between the hazard – i.e. flash flood – and the trigger – i.e. extreme wet spell. If this verifies for much larger samples across many Caribbean countries, then extreme wet spell frequency within a season may be a good potential proxy for expected flash flood occurrence.

Further testing revolves around the skill of the extreme wet spell forecasts in discriminating periods with lower or higher relative flash flood risk, respectively. Figure 6.4 presents the September to November 2016 precipitation outlook (Figure 6.4a) and extreme wet spells frequency shift forecast map (Figure 6.4b) both issued in August, alongside the observed SPI-3 values for the same period (Figure 6.4c) as issued in December 2016. Though the rainfall totals in the Lesser Antilles were neither forecast (Figure 6.4a) nor observed (Figure 6.4c) to be well above-normal for the area as a whole, extremely high SPIs of >2.0 over Barbados and St. Vincent suggest local extreme rainfall. However, the extreme wet spell forecast map (Figure 6.4b) did indicate medium confidence of a small increase in the frequency of extreme wet spells, of which historically up to two occur in Barbados and up to two or three in St. Vincent. With two such extreme wet spells observed in Barbados and three in St. Vincent, an increased

13 A 0-month lead forecast means that a forecast made towards the end of a certain month will cover the period starting on the first day of the following month (e.g. a 3-month forecast with 0 month lead made towards the end of June will cover the forecast period of July, August and September).

14 The climatological reference period used to define the historical norm is 1981-2010, as mandated by the WMO. However, there is an insufficient amount of manned weather station based records of daily rainfall dating back to at least 1981 to allow a good geographic of the calculation of wet days and wet spells and, hence, the wet days and wet spell forecasts that depend on them. Since rainfall was shown not to have changed significantly in most areas of the Caribbean (see Chapter 3), shifting the climatological period by 5 years to 1985-2014 - for which a decent geographic coverage can be produced - should not significantly affect the forecast product.

flash flood potential for September to November 2016 was well forecast. The forecast thus enabled a qualitatively accurate assertion that there would have been enhanced concern of flash flood risk during those three months.

There are promising indications that the forecasting system proposed may be well calibrated and have useful skill. Confirming this in a statistically robust way will involve comparing hindcasts of past extreme wet spells to a database of flash flood occurrences in the past. This is currently underway, and if successful, will allow the CariCOF to build a validated flash flood early warning product at the seasonal timescale.

Table 6.1: Flash floods in Barbados and St. Vincent and the Grenadines (SVG) between September and November 2016. The 99th percentile of 3-day rainfall totals is 92mm at CIMH in Barbados, and 110mm at ET Joshua in St. Vincent). With two hits, no misses and no false alarms for Barbados, and with three hits, no misses and one false alarm, the occurrence of extreme wet spells at the two weather stations correlates well with – and appears to be a good proxy for – flash flood occurrence in their respective surroundings in this very small sample.

LOCATION	DATE	WEATHER STATION 3-DAY RAINFALL	EXTREME WET SPELL?
BARBADOS	28 Sep 2016	CIMH: 109mm	Yes
SVG		ET Joshua: 150mm	Yes
SVG	8-10 Nov 2016	ET Joshua: 306mm	Yes
BARBADOS	29 Nov 2016	CIMH: 171mm	Yes
SVG		ET Joshua: 110mm (27-29 Nov)	Yes

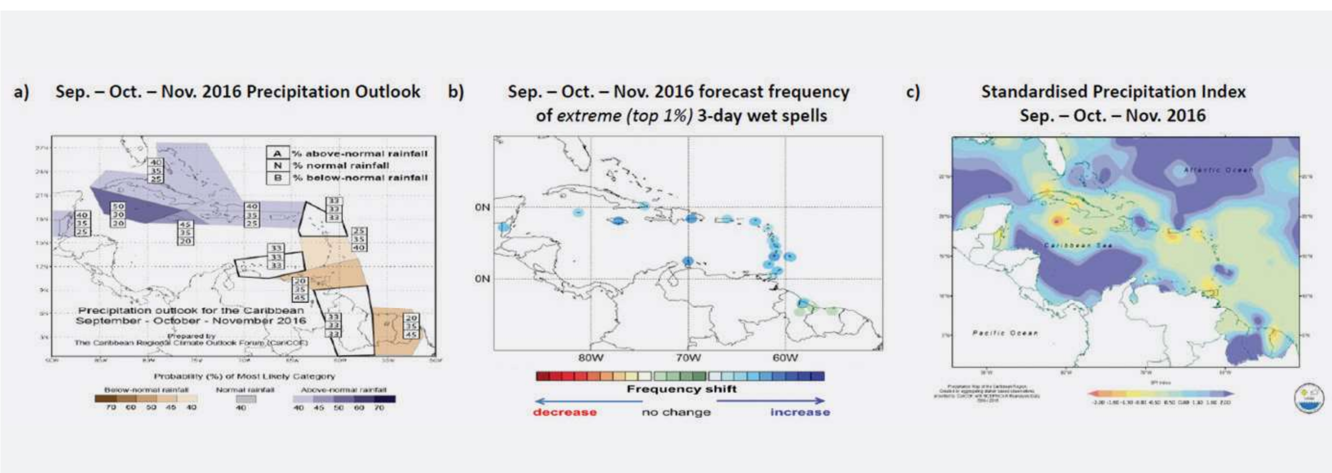


Figure 6.4: The forecasted and the observed rainfall patterns across the Caribbean for September to November 2016. In panel (a) the Precipitation Outlook depicts the average probabilities of the three-month rainfall total to be above-normal (i.e. wetter than usual), normal (i.e. the usual), or below-normal (i.e. drier than usual) for different areas across the Caribbean. Panel (b) shows a forecast for each weather station of the shift in the numbers of extreme wet spells as compared to the historical norm. Panel (c) is the CDPMN's three-month Standardised Precipitation Index map. Source: Caribbean Regional Climate Centre at CIMH (rcc.cimh.edu.bb)

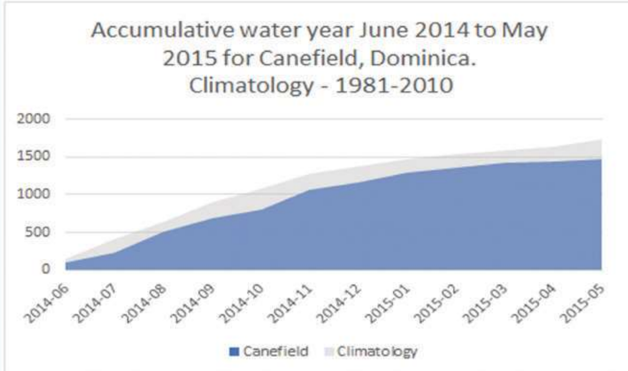
INFORMATION BOX 6.2

AMPLIFICATION OF RISK DUE TO THE IMPACT OF SUCCESSIVE DROUGHT AND WET SPELLS

As mentioned in Box 6.1, the 2014-2016 Caribbean drought impacted most of the region. By the beginning of the 2015 wet season, the Commonwealth of Dominica was suffering from an ongoing drought. A long-term drought started with below-normal rainfall recorded during 2014 wet season and was amplified between May and July 2015, when the dry season seemed to never end. The drought was one of the worst experienced since 1999 and saw the cumulative rainfall water year for June 2014 to May 2015 for two rainfall stations in Dominica, Canefield and Douglas-Charles being 85% (see Figure B6.1a) and 72% of average, respectively. Soils began to crack due to a deficit in soil moisture.

As Dominica was in its 8th month of record dryness, Tropical Storm Erika struck Dominica on the night of Monday, August 25, 2015. It dumped over 320.5 mm of rain in 12 hours, with 225.0 mm in less than six hours. Erika's rainfall contributed to half of the monthly rainfall total measured for August. Rainfall in August, however, did not end the drought, with cumulative rainfall by the end of the year still showing large deficits (see Figure B6.1b).

a)



b)

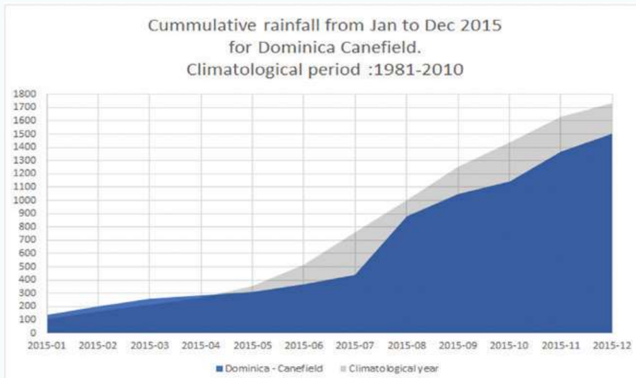


Figure B6.1: Charts shows the cumulative rainfall totals for (a) the water year June 2014 to May 2015 and (b) January to December 2015 in relation to the historical norm (i.e. climatology) for Canefield, Dominica. The climatological period spans 1982 to 2010. Source: CIMH

With excessively dry cracked soil and slow infiltration rates due to soil compaction from the drought, the short and intense downburst of rainfall from Erika caused excessive surface runoff. There were many landslides and rock fall which covered villages and blocked major roads. Approximately twelve major rivers broke their banks and caused severe flooding taking out vital bridges, and disrupting water, electricity and telecommunications. This disaster resulted in thirty confirmed deaths and 271 homes damaged or destroyed (Pasch and Penny 2016). Nine villages were declared as “Special Disaster Areas” with Petite Savanne being the most significantly affected. As of August 31, many roadways on the island remained impassable, several bridges were destroyed or unsafe, and many communities remained without electricity or potable water.

Up to September 8, 360 people were staying in seven different shelters across five communities. Most of the country lacked access to water, and there were concerns over waterborne diseases (PAHO and WHO 2015). The Dominican Water and Sewage Company Limited (DOWASCO) stated that 100% of the national water system was affected by the disaster. 54 cases of gastroenteritis, 8 cases of acute respiratory illness, 11 cases of undifferentiated fever and 1 case of tetanus were reported. Residents in 3 communities were using unsafe streams as water supply, and water infrastructure and water quality remained a problem in 2 other communities. Up to a year after the event, there were cases of post-traumatic stress disorder observed in many youths (Tavernier 2016).

The events ensuing from the drought and TS Erika in 2015 are indicative of a climate in which multiple hazards may, whether or not catastrophically, impact Caribbean nations. The case thereby forms an example of enhanced vulnerability to compounded risk of climate hazards related to extremes that coincide or follow in rapid succession. If the Caribbean is to work towards climate resilience in the face of climate change, it will have to take this risk caused by an anticipated increase in extremes into close consideration.

6.5. EXTREME TEMPERATURE AND HEAT WAVES

Heat is an increasing concern globally and in the region. Global Warming increases both frequency and intensity of heat waves over time in many locations. Chapter 3 showed that for the Caribbean there has been an increase in intensity, duration and frequency of warm and hot days and nights between 1961 and 2010.

Heat stress impacts, in increasing order of severity, can comprise general discomfort, heat rash to heat cramps, heat exhaustion, heat stroke and death. The mounting evidence of increasing heat stress implies that the availability and adoption of appropriate mitigation and adaptation mechanisms to excessive heat are warranted. There is need for heat action plans, which comprise heat preparedness measures and heat early warning systems (HEWSs). The development of an operational HEWS at weather time scales and a program of seasonal preparedness measures - including heat preparedness systems at the seasonal time scales - for the Caribbean can offer a timely and resource efficient strategy to manage excess heat risk now and for the future. At the global level, this has been called for by both the World Health Organization and the World Meteorological Organization. The current thrust provided by the Global Framework for Climate Services, which has adopted Dominica as a pilot country for climate services for health, makes such development in the Caribbean even more timely.

The following section describes a first attempt at developing a predictive framework to form part of an operational, seasonal heat preparedness system for the Caribbean. The focus is initially on the seasonal to sub-seasonal scale (S2S) i.e. between two weeks and six months, which is the focal time scale of most operational climate early-warning systems. As such, it is meant to alert, with ample lead-time for effective mitigation and/or adaptation response, periods during which excess heat will be likely.

6.5.1. TEMPERATURE MONITORING

CIMH developed temperature monitoring maps in 2015. The maps depict the monthly, 3-monthly, 6-monthly, and 12-monthly anomalies of the average temperature near the surface. When put side-by-side with maps of historical average temperatures the maps give a first order indication of heat intensity experienced during that period, and how the heat during the given period differed from the norm. Figure 6.5 is an example of a map and shows the mean temperature anomaly for 2016, the hottest year on record at many Caribbean locations. It is noteworthy that even though the anomalies depicted in Figure 6.5 were extreme in terms of rarity, the small magnitude of the anomalies temperatures can easily lead to a false conclusion that excessive heat may not be a major issue in the Caribbean.

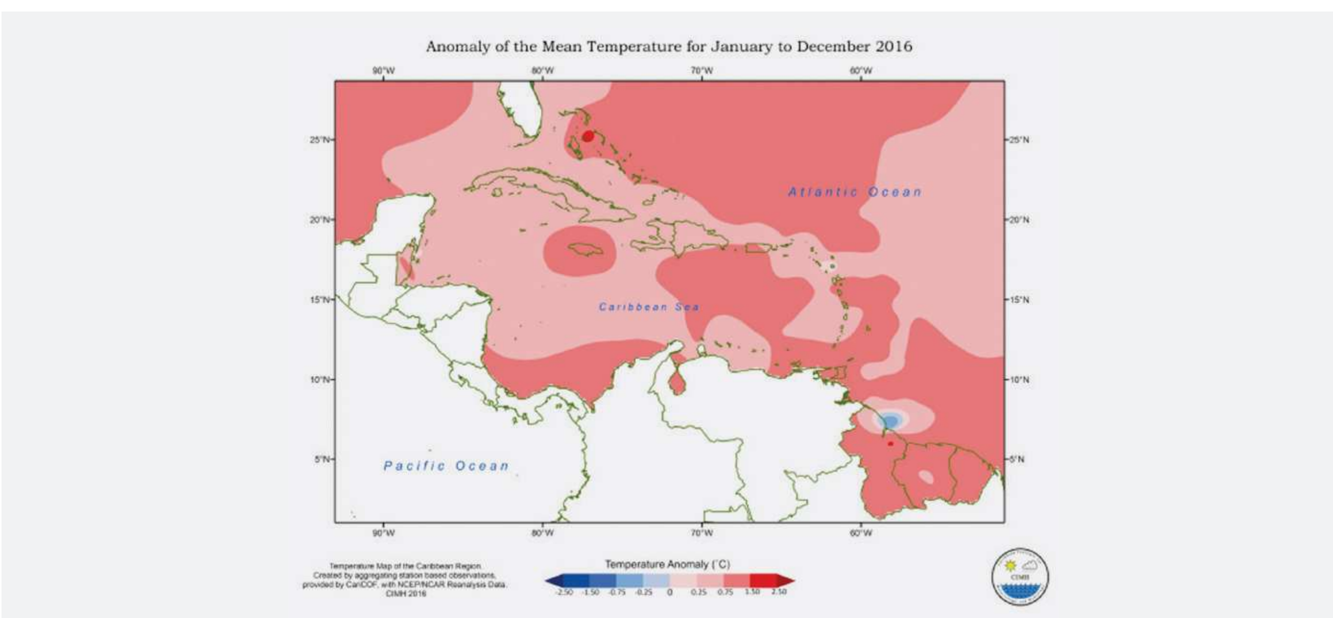


Figure 6.5: A 12-month mean near-surface air temperature anomaly map for 2016. Source: CIMH

6.5.2. DEVELOPING A PROTOTYPE HEAT OUTLOOK FOR THE CARIBBEAN

The first step in developing a heat prediction framework is the selection of an appropriate metric of heat stress which will be of value to the user of the forecast product. That is, a suitable metric should be related to relevant outcomes in a sector that may be impacted by heat e.g. health, energy or agriculture. For example, while elevated maximum temperature is the most common condition used to classify a heat wave, humidity, wind speed, solar radiation and duration of hot weather are known to mediate the effect of heat on human health in complex ways.

A heat prediction system must also be operationally feasible, accounting for requirements of resource efficiency and practicality. Many heat early warning systems opt for simple measures of heat impacts based on temperature alone, or on temperature and humidity, as though more sophisticated indices of heat burden exist (e.g. the Universal Thermal Climate Index[15]) and may more accurately reflect the true heat burden, they also tend to require a wealth of data that are unavailable in much of the Caribbean region. Studies comparing a variety of heat stress indicators have concluded that the simple measures can be as, or even more, effective than more complex measures at predicting general heat stress across a population (Vaidyanathan et al. 2016; Nissan et al. 2017). Ease of understanding is also a major advantage when developing a system that is intended for use across different sectors of society.

From the point of view of food security in the Caribbean, it is noteworthy to mention that a number of regional studies are emerging which show a clear link between poor livestock productivity and heat stress, with species specific metrics and thresholds becoming available (see for e.g. Lallo et al. (2018)). It seems plausible that heat outlook products tailored for small livestock, and heat susceptible poultry, can readily be developed premised on metrics such as the Temperature Humidity Index which relies on both temperature and air humidity data, which have been regionally recorded in many territories for at least two decades.

Recent research (IRI 2017) has also revealed that extreme heat in the Caribbean is a local phenomenon, with nearby islands, and sometimes even nearby stations, often observing heat waves on different days. Consequently, skilful predictions for the hottest days will likely only be possible at lead-times of typical weather forecasts (up to a few days). However, less extreme hot days (defined by exceedance of the 90th percentile of summertime maximum temperatures over a period of at least two days) appear to be more coherent across particular sub-regions of the Caribbean, and are therefore likely to be a better choice for sub-seasonal to seasonal forecasts. Further research is required to determine appropriate heat metrics for different applications.

CariCOF's experimental seasonal heat outlooks are delivered each month during the heat season from May to October i.e. over the six months during which all areas in the Caribbean experience at least two or three months with a regular recurrence of heatwave days. The outlooks present the heat forecasts as probabilities of the number of heat wave days exceeding thresholds such as 14 days, 30 days, and or 60 days. Figure 6.6 is an example of an experimental forecast for the summer of 2018. Figure 6.6a & 6.6b suggests that the summer of 2018 was not forecast to be particularly warm as compared to the average for all summers between 2001 and 2015. This was in stark contrast with, for example, the recent summers of 2015 and 2016, which were very warm across most of the region (in some places record warm), in part driven by the 2014-2016 El Niño. It should be noted, however, that heatwaves are common from July to September in the entire region (see Figure 6.6c). The forecast (Figure 6.6d) then suggested a 50% chance or more that there will be "**at least 7 heatwave days** from July to September 2018 in the Greater Antilles and for some locations in the Windward Islands, with a few of these stations [possibly] recording 14 heatwave days or more" (CIMH, 2018). The final heat outlook formulated the following statement on the expected implications with respect to heat:

15 A comprehensive list may be found in: World Meteorological Organization / World Health Organization (2015). Heatwaves and Health: Guidance on Warning-System Development. WMO-No. 1142. ISBN 978-92-63-11142-5

"Heat stress [is expected] in the vulnerable population and small livestock until October (or November in the Guianas), but [is] unlikely to the same extent as in recent years. By consequence, cooling needs until October are reduced compared to recent years. Nevertheless, the occurrence of a few heatwaves in many locations is likely to temporarily increase heat stress in human populations or livestock" [CIMH, 2018]

Note that at present to obtain a reasonable assessment of expected heat stress as well as associated implications (as indicated by Figure 6.6) it is necessary to compare a significant amount of information. It is also recognized that more detail is needed to adequately express expected levels of heat stress. CIMH and its research partners - in particular the International Research Institute for Climate and Society and the University of the West Indies - and sectoral partner institutions have committed to working towards providing more tailored heat early warning information so that in turn CariCOF can provide detailed implications for at least the health and the poultry and small livestock sectors initially, but potentially also the energy sector (in terms of energy demand for cooling), amongst others.

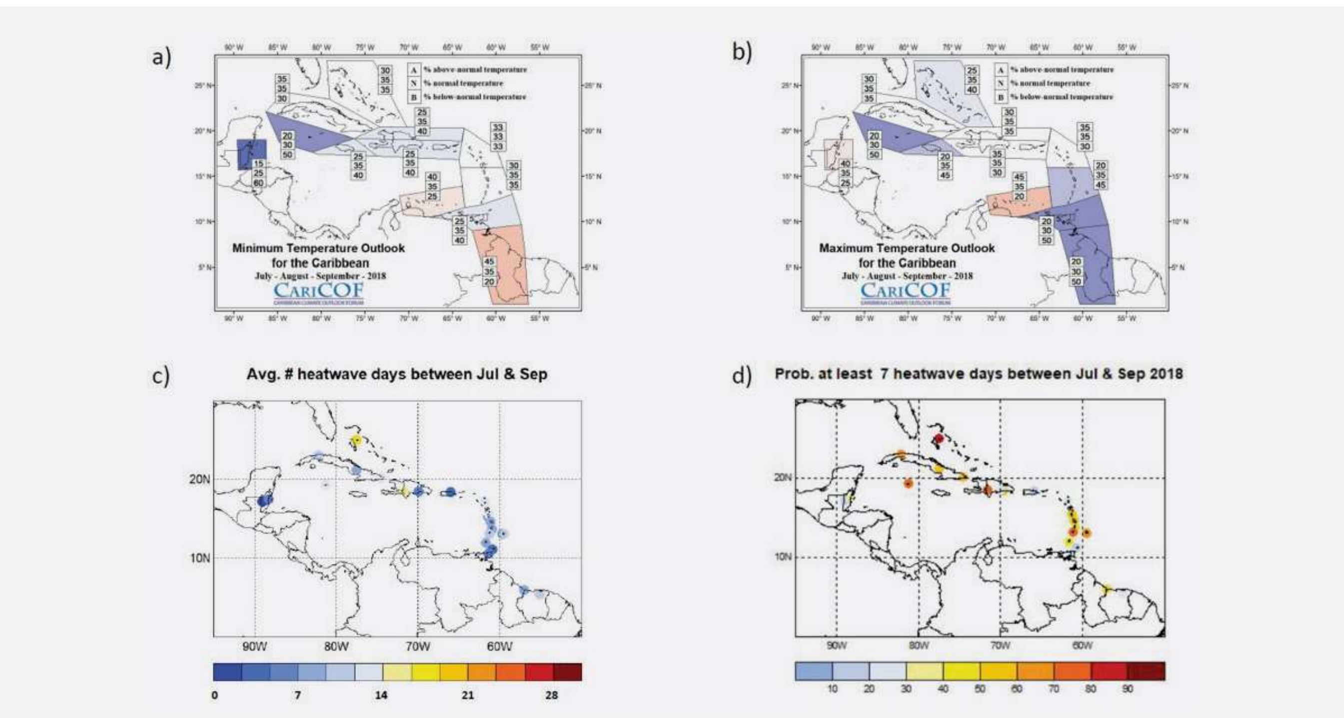


Figure 6.6: Excerpts from the CariCOF July to December 2018 Experimental Heat Outlook. Panels (a) and (b) depict the July to September minimum (nighttime) and maximum (daytime) temperature outlook maps in terms of the forecast probability of warmer than usual (above-normal), usual (normal) or cooler than usual (below-normal) temperatures as averaged over those three months. Panel (c) shows the historical average number of heatwave days during the July to September period, and (d) provides the forecast probability that at least 7 heatwave days would occur between July and September 2018. Source: CIMH (2018)

6.6. THE FUTURE OF EARLY WARNING ON CLIMATE EXTREMES IN THE CARIBBEAN

6.6.1. SECTOR DRIVEN INFORMATION ON CLIMATE EXTREMES

Climate information holds great potential to inform often complex decision-making across a wide range of climate-sensitive sectors in the Caribbean, and the general public, thus reducing their vulnerability to climate impacts, particularly from climate extremes. Arming climate-sensitive sectors in the Caribbean with specialised early warning information on climate extremes is now a priority for the Caribbean. This mandate has been taken on by the CIMH, as the Caribbean RCC, in its current and future research efforts. In association with its sectoral and other technical partners, the aim is to increasingly address the lack of localised, integrated empirical indices and models linking climate and sector-specific outcomes in a range of sectors.

The health sector is useful for illustrating the need for prioritised sector information. Among the health-climate challenges faced by the Caribbean is the recent unprecedented public health crisis of co-occurring epidemics due to Aedes aegypti mosquito borne viruses. Illness due to the dengue (DENV), chikungunya (CHIKV) and Zika (ZIKV) viruses has historically placed a high socio-economic burden on Caribbean countries. A conservative estimate for example, suggests that dengue costs the Caribbean about US$321 million annually. Moreover, the Caribbean remains the area within the Americas with the highest cost per capita (International dollars $8.70) (Shepard et al. 2011), and about 9,000 years of lost time due to ill health and premature deaths as a result of dengue (Carrington 2013). Results from a Barbados case study found that information on climate extremes such as drought positively influenced dengue relative risk at longer lead-times of up to five months while excess rainfall increased the risk at shorter lead times between 1-2 months (Lowe et al. 2018). Subsequently, a modelling approach that utilises the CariCOF drought and temperature forecasting methods was built and tested for its skill in predicting dengue cases, with the new approach significantly outperforming a modelling approach that does not account for climate extremes. There is scope for this modelling approach to now be employed in the designing of an operational dengue risk forecasting system for Barbados. With further investigation, the modelling approach could potentially also be extended to other arboviruses and to other islands in the Caribbean (Lowe et al. 2018).

There are other sectors which are being targeted using the same approach. For example, building energy demand models that include considerations of enhanced cooling need during periods of excessive heat exposure e.g. due to heatwaves, will better inform energy producers and distributors than perhaps current models do. Such investigations are ongoing at CIMH, in collaboration with the University of the West Indies.

6.6.2. DATA AND CAPACITY BUILDING NEEDS

In order to capitalise on the potential benefits of improved preparedness through longer lead time and outlooks for pending hazards such as flooding, flash floods, drought, dry spells and heat waves, significant and sustained investment is needed. A recent comparative study of the climate information production capacity of 22 NMHSs in the Caribbean (Mahon et al. 2019) shows need for (i) investments that result in enhanced and specific climate and sectoral data collection; (ii) hazard specific monitoring and prediction systems; (iii) policies and plans to respond to the early warning information; (iv) expansion or shifting of institutional mandates; and (v) education and outreach activities to allow the intended audience to respond to early warning information. Each of these capacity building needs to contain technical components and rely on data and evidence driven information. Building such capacity will furthermore require intensive engagement of a broad range of public and private, sectoral stakeholders.

To alleviate major bottlenecks in the provision of reliable, actionable early warning information services for climate extremes, critical investment needs are:

Climate data: sufficient long spanning, good quality, freely accessible and exchangeable, hazard-relevant climate data records other than records of monthly rainfall totals. A relatively good spatial and temporal coverage exists for monthly rainfall across the region, with 169 records routinely utilised and exchanged across NMHSs within the context of CariCOF. These enable drought early warning systems to be developed (Section 6.3.4). However, most NMHSs are not in the position to produce sufficient records at daily or hourly resolution for rainfall, temperature, humidity, wind speeds, etc., needed to deliver monitoring or prediction services related to hazards such as flash floods, dry spells, heat waves. Commonly, those variables are only measured at the manual station located at the territory's major airport(s), and long-term records are maintained at even fewer of those airports. Having records of hourly or daily rainfall from locations that are geographically and geologically very different from those at the airports are needed. However, obtaining such data can be very costly. In the case of manned stations, much of the cost, apart from the initial deployment of instruments, arises from travel time needed to reach the station to make measurements, and also to maintain the instruments. In case of Automatic Weather Stations (AWSs), travel time is not as critical a factor. However, in order for the AWSs to routinely report correct values for the variables they measure, maintenance costs tend to increase, as do costs related to greater time spent on data quality control.

Data sharing: A data sharing policy is needed for data at a sub-monthly resolution, e.g. hourly and daily data. Through the years, data sharing agreements for weather forecasts have been forged, but this is not yet the case for climate data. Often, this stems from the notion that, since NMHSs or other stakeholder institutions bear the significant cost of maintaining instrumentation and sustaining observations of weather and climate variables, they should protect the ownership of their climate data which is deemed as valuable. Moving the region forward requires NMHSs to be able to access data "owned" by other institutions within their country, and data "owned" by other stakeholder institutions in neighbouring countries. This requires the development of data sharing policies. Data sharing policies usually struggle to advance because it is not clear that there are viable cost-recovery options for data production and maintenance.

Instrumentation: Install, maintain and augment instrumentation for weather stations. Perhaps for the same reason i.e. a lack of clarity of cost-recovery in climate data generation, insufficient investment is currently made at the national level in most, if not all countries in instrumentation. This is in spite of some initiatives that are providing automatic weather stations in many Caribbean countries.

Climate Monitoring and Prediction Systems: Provide operational monitoring and prediction information of extremes such as wet spells, dry spells and heatwaves. Whereas the CDPMN operationally monitors drought, and the Caribbean RCC operationally monitors temperatures at monthly, seasonal and (inter-)annual timescales, operational systems that monitor extremes at hourly or daily timescales in near-real time, critical to hazards early warning, are not yet widely available. It is also very challenging for individual NMHSs to operate national level monitoring systems. At the regional scale, a programmatic approach to investment is likely needed as innovative techniques can be developed that reduce the time demand on human resources to generate monitoring information, e.g. through automation. Furthermore, a programmatic approach allows for institutions such as CIMH to build the procedural capacity of NMHSs to adopt good practices in operations that are very time efficient, through training campaigns. Recent examples of such have been pre-CariCOF training workshops in the generation, communication and quality verification of seasonal climate outlooks, as well as similarly themed in-country training workshops on drought monitoring and prediction, climate products development, and climate information presentation. Such trainings have equipped even the smallest NMHSs in the region with the basic tools needed to produce seasonal climate outlooks, with national seasonal precipitation outlooks now produced in a regionally standard way every month by a large majority of NMHSs. Finally, investments into the sustainability of the CariCOF programme and, specifically, in its technical training capacity can therefore help support the regional roll-out of climate prediction systems geared at early warning of climate extremes.

At the regional scale, a programmatic approach to investment is likely needed as innovative techniques can be developed that reduce the time demand on human resources to generate monitoring information, e.g. through automation.

Research: A good understanding is needed of Caribbean Climate and its drivers. Though the body of literature related to this is steadily growing, the equivalent literature related to understanding climate extremes is trailing. There is need for investment in academic research on historical, ongoing and future trends in climate extremes, the drivers of such extremes as well as in R&D into designing resource efficient and reliable monitoring and prediction systems.

In terms of institutional capacity, a major need identified is expansion of the legal mandates of NMHSs to include the provision of climate services. Chapter 8 provides further discussion on how the Caribbean sectors approach the climate services agenda.

Finally, Caribbean NMHSs often have small operational budgets, with budget expenditures per capita in this region ranging from a low of US$1.63 to a high of US$8.23 per capita (2013 year dollars) (Mahon et al. 2018). As a result, it is not uncommon for NMHSs to have difficulty in maintaining suitable expertise for the delivery of climate services. While all Caribbean NMHSs have been able to push forward with their climate services agenda, with a few of them - invariably the larger ones - pushing forward at an accelerated rate, there is a notably large gap between countries' financial resources and human resource allocation dedicated to climate services delivery when compared to their very positive perceptions of the value of and the need for the roll-out of a climate services agenda.

INFORMATION BOX 6.3

THE 2017 ATLANTIC HURRICANE SEASON

From as early as May, several monitoring and forecast agencies predicted that the 2017 Atlantic Hurricane Season's activity would likely be near-normal to above-normal. In most cases the extent of the activity was revised upwards during the season. On August 5th, the US National Oceanic and Atmospheric Administration (NOAA)'s Climate Prediction Center predicted a total of 14 to 19 named storms, 5 to 9 hurricanes and 2 to 5 major hurricanes. They further warned their audience that the 2017 Season could be one of the most active since 2005. Their forecasts were corroborated by the August 4th updates produced by Colorado State University's group.

The 2017 Atlantic hurricane season saw a total of 17 named storms of which 10 were hurricanes and 6 further intensified to major hurricanes. Low vertical wind shear and warmer than usual sea surface temperatures were two of the drivers behind the extremely active season. Some notable things about the season were:

- It was the third year in a row in which the first named storm occurred before June 1st.
- On 19th June, 2017, Tropical Storm Bret caused damage and loss of life in Trinidad, an island thought to be south of the Hurricane Belt.
- It was the sixth most active on record based on the accumulated cyclone energy (ACE) index[16].
- In the Atlantic, September was the most active month on record, with 10

16 The ACE is a hurricane season activity metric that depends on two variables, namely duration and maximum wind speeds. The index reflects how energy generated by all storms accumulate over time. While the ACE can be also easily computed for an entire season (by summing the ACE of each individual storm), this index does not, however, take storm size, rainfall or storm surge indicators into consideration.

consecutive named storms and an ACE of 175.

» Hurricane Ophelia was the farthest east that a major hurricane was observed in the Atlantic.

Perhaps, the three of the most notable systems of the season were Hurricanes Harvey, Irma and Maria all of which attained category 5 status. Irma and Maria severely affected the eastern Caribbean.

Hurricane Irma – Irma was an impressive "Cape Verde" type hurricane[17].

History: On Wednesday, August 30th, the NOAA - National Weather Service's National Hurricane Center (NHC) had indicated that tropical storm Irma had formed in the eastern Atlantic. By Tuesday 5th September, the system was a powerful category 5 hurricane heading toward the Leeward Islands. By 2AM Eastern Caribbean Time (ECT) on Wednesday September 6th, the eye of Irma had passed over the island of Barbuda. The system then moved on to make landfall in St. Martin and Virgin Gorda of the British Virgin Islands. On the 7th September, the centre of Irma passed to the north of Puerto Rico and the Dominican Republic. By 8pm ECT on September 7th, Irma had passed south of Turks and Caicos and was headed toward Bahamas and Cuba. Dr. Phil Klotzbach[18] noted that (i) Irma's highest wind speeds averaged 180 mph – the third strongest winds of all time for Atlantic hurricanes –, sustained for a world record 37 hours; (ii) Irma single-handedly generated an ACE of 67.5, more than some entire seasons and the highest ACE on record by a tropical cyclone in the tropical Atlantic (7.5-20°N, 60-20°W), excluding cyclones crossing the Caribbean Sea.

The three of the most notable systems of the season were Hurricanes Harvey, Irma and Maria all of which attained category 5 status. Irma and Maria severely affected the eastern Caribbean.

Impacts[19]: In the Caribbean islands 37 deaths were attributed to Irma. Barbuda, Saint-Martin/St. Maarten and the British Virgin islands all took direct hits from Hurricane Irma while St Barthelemy was impacted by the southern eyewall and Anguilla by the northern eyewall. On Barbuda, Irma was at peak intensity and the winds left 95% of the structures damaged or destroyed, while crippling the water and communication sectors. Property damage there was estimated at US $150-300million and the island became deserted for the first time in 300 years. In Saint-Martin (the French side of the island of St. Martin), 90% of structures were damaged and estimates of losses total US $1billion, versus 70% of structures damaged, including a severely damaged airport in St. Maarten (the Dutch side). On nearby Saint-Barthélemy, economic loss was estimated to be over US $480million. In Anguilla, most properties were damaged, including schools, homes and the only hospital,

17 Cape Verde hurricanes are hurricanes that canonically develop in the Main Development Region of the Atlantic not too far from the Cape Verdean islands, mostly from disturbances coming off of Africa. Those hurricanes typically migrate east to west or north-west across the Tropical North Atlantic Ocean for several days before reaching the Antilles or passing north of this island chain. Cape Verde type hurricanes can grow to some of the most devastating hurricanes

18 The scientist in charge of CSU's Atlantic Hurricane Season outlook. He took over the work of famous hurricane specialist Bill Gray - whose outlooks people were perhaps most familiar with - after his passing. The information presented here was found on https://twitter.com/philklotzbach as accessed on 30th June 2018.

19 This section is based on the NHC Irma report as of 30th May, 2017 [Cangialosi et al., 2018].

with estimated economic losses of at least US $190million. In the Turks and Caicos Islands damage to structures and the islands communication was sustained, causing estimated total losses of at least US $500million. Nine persons lost their lives in Cuba, and ten people died in the United States. Irma's trail of damage and losses continued until it finally dissipated over Georgia on September 12th.

Hurricane Maria–Like Irma, Hurricane Maria was a Cape Verde type. Some of the same islands threatened by Irma had to issue new warnings only a few days later after Irma.

History: By 2PM ECT on September 16th, the US National Hurricane Center had indicated that the tropical depression in the Atlantic had been upgraded to Tropical Storm Maria. On September 18th, the system explosively intensified into a Category 5 Hurricane, attainting this strength hours before landfall in Dominica. After this, Maria weakened slightly due to land interaction with Dominica then regained strength to peak at 175mph. Maria weakened slightly before landfall over Puerto Rico and further weakened as it crossed the island. By September 22nd, the system emerged from Puerto Rico and re-intensified before passing east of the Turks and Caicos Islands. Some notable facts on Maria are: (i) it increased in sustained wind speeds from 85mph to 165mph in 24hours; (ii) it had a record low minimum pressure of 908mb for the Eastern Caribbean; (iii) it was the first category 5 hurricane on record to affect the island nation of Dominica; (iv) it dumped 22.8inches (579.1mm) of rainfall on Dominica and 38 inches (965.2mm) at one location on Puerto Rico.

Impacts[20]: In the Caribbean, the direct deaths from Maria totalled 108. Dominica sustained catastrophic damage, with total losses estimated at US $1.31billion, or over 220% of GDP. The agriculture sector was severely impacted and most roofs were either damaged or blown off. Roads were impassable and the communication system was destroyed. In Guadeloupe, an estimated 80,000 homes lost electricity, most of the banana crops were destroyed and officials estimated loss at US$120 million. The US Virgin Islands which was still recovering from Irma experienced heavy rainfall accumulations and mudslides. On the island of Puerto Rico, Maria was the most destructive hurricane in modern times. The energy sector was crippled due to downed power lines and extensive damage to infrastructure. This resulted in the loss of electricity to the island's 3.4 million inhabitants. The winds also destroyed the islands only radar system, reducing the capacity of the National Weather Service's local office to deliver early warning for any pending adverse weather post-hurricane. Unprecedented river flooding in an entire alluvial valley resulted in the rescue of hundreds of families from roof tops. Officials estimated total losses in the US Virgin Islands and Puerto Rico at US$ 90 billion, making Maria the third costliest hurricane in US history, trailing only Harvey (2017) and Katrina (2005).

20 This section is based on the NHC Maria report as of 10th April, 2017 [Pasch et al., 2018].


Revenue Structure
Cost trends
Jul
Aug
Sep
Oct
Nov
Dec