THE UNIVERSITY
OF THE
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NDRM
Natural Disaster Risk Management
in the CARIFORUM

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THE STATE OF THE CARIBBEAN CLIMATE

Prepared by
The Climate Studies Group Mona
The University of the West Indies

For
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ACE	Accumulated Cyclone Energy
ACP	African, Caribbean and Pacific Group of States[1]
AEW	African Easterly Waves
AMC	Applied Meteorology and Climatology
AMO	Atlantic Multi-decadal Oscillation
AR5	Fifth Assessment Report
ASO	August – September - October
AWP	Atlantic Warm Pool
AWS	Automatic Weather Station
BMCs	Borrowing Member Countries
BRCCC	Building Regional Climate Capacity in the Caribbean
CACB	Caribbean Agro-Climatic Bulletin
CAMI	Caribbean Agro-Meteorological Initiative
CANARI	Caribbean Natural Resources Institute
CAP	Common Alerting Protocol
CARDI	Caribbean Agricultural Research & Development Institute
CARIBSAVE	Partnership of CCCCC and Oxford University
CariCOF	Caribbean Climate Outlook Forum
CARICOM	Caribbean Community
CARIFORUM	Forum of Caribbean Group of African Caribbean Pacific States
CariSAM	Caribbean Society for Agricultural Meteorology

CARISURV	Caribbean Health Surveillance System
CARIWIG	Caribbean Weather Impacts Generator
CAROGEN	CariCOF Outlook Generator
CARPHA	Caribbean Public Health Agency
CCCCC	Caribbean Community Climate Change Centre
CCCMA	Canadian Centre for Climate Modelling and Analysis
CCID	Caribbean Climate Impacts Database
CCORAL	Caribbean Climate Online Risk and Adaptation Tool
CCRIF SPC	Caribbean Catastrophe Risk Insurance Facility Segregated Portfolio Company
CDB	Caribbean Development Bank
CDD	Consecutive Dry Days
CDEMA	Caribbean Disaster Emergency Management Agency
CDKN	Climate and Development Knowledge Network
CDP	Caribbean Dewetra Platform
CDPMN	Caribbean Drought and Precipitation Monitoring Network
CEPF	Critical Ecosystem Partnership Fund
CHCB	Caribbean Health-Climatic Bulletin
CHTA	Caribbean Hotel and Tourism Association
CIMH	Caribbean Institute for Meteorology and Hydrology
Climpag	Climate Impacts on Agriculture
CLLJ	Caribbean Low Level Jet

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[1] The African, Caribbean and Pacific Group of States is now called The Organisation of African, Caribbean and Pacific States (OACPs).

CMEP	Commonwealth Marine Economies Programme
CMIP	Coupled Models Intercomparison Project
CMO	Caribbean Meteorological Organisation
CNN	Cable News Network (USA)
CNRM	National Centre for Meteorological Research
CO2	Carbon Dioxide
CPO	Caribbean Precipitation Outlook
CRU	Climatic Research Unit
CSGM	Climate Studies Group Mona
CSIS	Climate Services Information System
CTA	Technical Centre for Agricultural and Rural Cooperation
CTCB	Caribbean Tourism Climatic Bulletin
CTO	Caribbean Tourism Organization
CWWA	Caribbean Water and Wastewater Association
DOWASCO	Dominican Water and Sewage Company Limited
DSS	Decision Support Systems
DSSAT	Decision Support System for Agrotechnology Transfer
EC	European Commission
ECLAC	Economic Commission for Latin America and the Caribbean
ECT	Eastern Caribbean Time
EDS	Early Dry Season (December to April)
EM-DAT	Emergency Events Database
ENSO	El Nino-Southern Oscillation
EOC	End of Century
EPA	Environmental Protection Agency
ERFS	Early Rainfall Season (May-June)
ESRL	Earth System Research Laboratory (NOAA)
ET0 Map	Drought and Evapotranspiration Map
EU	European Union
EWISACTs	Early Warning Information Systems across Climate Timescales
FAO	Food and Agriculture Organisation of the United Nations
FAOSTAT	FAO Corporate Statistical Database
FMA	February - March - April
GA Airport/ GAIA	Grantley Adams International Airport (Barbados)
GCM	Global Climate Model / General Circulation Model
GDP	Gross Domestic Product
GFCS	Global Framework for Climate Services
GFDL	Geophysical Fluid Dynamics Laboratory (NOAA)
GIA	Global Isostatic Adjustment
HEC-GeoHMS	Geospatial Hydrologic Modeling Extension
HEC-HMS	The Hydrologic Modeling System
HEWSs	Heat Early Warning Systems
ICDC	Integrated Climate Data Centre
IGDS	Institute for Gender and Development Studies (Mona Unit – Jamaica)
IPCC	Intergovernmental Panel on Climate Change
IRI	International Research Institute for Climate and Society
ITCZ	Inter-Tropical Convergence Zone

KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
LMI	Lifetime Maximum Intensity
LRFS	Late Rainfall Season (September –November)
m	metres
MBIA	Maurice Bishop International Airport (Grenada)
MJJ	May - June - July
mm	millimetres
MOSAICC	Modelling System for Agricultural Impacts of Climate Change
MOU	Memorandum of Understanding
MRESL	Mean Reconstruction sea level (data set)
MSD	Mid-Summer Drought
MSJ	Meteorological Service of Jamaica
MSL	Mean Sea Level
NAH	North Atlantic High
NASH	North Atlantic Subtropical High
NCEP	National Centres for Environmental Prediction
NCOFs	National Climate Outlook Forums
NDJ	November - December - January
NDRM	National Disaster Risk Management
NHC	National Hurricane Center
NMHS	National Meteorological and Hydrological Services
NOAA	National Oceanographic and Atmospheric Administration
OAR	Oceanic and Atmospheric Research

OAS	Organization of American States
OECS	Organization of Eastern Caribbean States
OI SST V2	Optimum Interpolation Sea Surface Temperature
OTEC	Ocean Thermal Energy Conversion
PAHO	Pan American Health Organization
PET	Potential Evapotranspiration
PoA	Plan of Action
PPE	Perturbed Physics Experiment
PRECIS	Providing Regional Climates for Impact Studies
R&D	Research and Development
R95p	Rainfall exceeding 95th percentile
RADA	Rural Agriculture Development Agency
RCC	Regional Climate Centre
RCMs	Regional Climate Models
RCOF	Regional Climate Outcome Forum
RCP	Representative Concentration Pathways
ReCORD	Regional Climate Observations Database
RJR	Radio Jamaica Rediffusion
RX1	Monthly Maximum One Day Rainfall Amount
RX5	Monthly Maximum Consecutive Five Day Rainfall Amount
scPDSI	self-calibrating Palmer Drought Severity Index
SDSM	Statistical Downscaling Model
SIDS	Small Island Developing State
SIMCLIM 2013	ArcGIS-based Climate Simulation Model

SLR	Sea Level Rise
SM	Supplementary Materials
SMASH	Simple Model for the Advection Storms and Hurricanes
SMS	Subscriber Messaging Service
SOCC	State of the Caribbean Climate
SOJC	State of the Jamaican Climate (2015)
SON	September-October-November
SPEI	Standardized Precipitation-Evapotranspiration Index
SPI	Standardized Precipitation Index
SRES	Special Report on Emissions Scenarios
SREX	Special Report on Extremes
SST	Sea Surface Temperature
STP	Science and Technology Programme
TC	Tropical Cyclones
TCTT	Telecommunications Company of Trinidad and Tobago
TIMS	Tourism Information Management System (CTO)
TNA	Tropical North Atlantic
TTMS	Trinidad & Tobago Meteorological Service
UDel	University of Delaware

UIP	User Interface Platform
UNDP	United Nations Development Programme
USD	United States Dollars
UTCI	Universal Thermal Climate Index
UVI	Ultraviolet Index
UWI	University of the West Indies
UWI-DFD	University of the West Indies' Department of Food Production
VCB Airport	V.C. Bird International Airport (Antigua and Barbuda)
WAMIS	World Agro-Meteorological Information Service
WEAP	Water Evaluation and Planning
WEC	World Energy Council
WFP	World Food Program
WMO	World Meteorological Organization
WRA	Water Resources Authority
WRI	World Resources Institute
WTTC	World Travel and Tourism Council
WWC -3	The Third World Climate Conference

EXECUTIVE SUMMARY

In the Caribbean, weather and climate events recurrently impact economic performance, productivity, livelihoods and quality of life. The record-breaking 2017 hurricane season stands as one of several recent examples that strongly underscore the economic, physical and social vulnerability of Caribbean nations to climate-related phenomena. Evidence-based and proactive decision-making will be fundamental to the transformation process from vulnerable to resilient Caribbean societies.

This State of the Caribbean Climate (SOCC) Report was prepared to strengthen the strategic planning and decision-making processes that will be required to accelerate resilience-building efforts in the Caribbean, specifically within the 19 Borrowing Member Countries (BMCs) of the Caribbean Development Bank (CDB). By providing significant climate data, information, analysis and references, distributed across 10 chapters, the SOCC Report is expected to become the premise for actionable recommendations that will support climate proofing at national and regional levels.

The structure and content of this report facilitate provision and analysis of climate data and information in a manner that takes cognizance of the similarities and differences among Caribbean nations. Chapters 1 and 2 provide the introductory background and methods and sources of data collection, respectively. Chapters 3 to 6 describe historical and future climate by focusing on key variables, e.g., temperature and rainfall, as well as extreme climate phenomena such as droughts, floods, sea level rise and hurricanes. The impacts of these climate variables and extremes on key sectors have been summarized in Chapter 7. Chapter 8 details the Caribbean approach and experience in developing climate services for improving national and regional response mechanisms. An overview of the key report findings and recommendations for the way forward are set forth in Chapter 9, and a list of all the references (by chapter) used in the preparation of this document is presented in Chapter 10.

While this report provides a significant repository of climate data and information (some of which have been summarized in the table below), there are a number of critical data-related gaps and challenges that need to be addressed as the region seeks to employ evidence-based approaches to decision-making. These data challenges are linked to inadequate coverage of weather and climatological stations that will (i) facilitate analysis at sectoral, national and regional scales (ii) enable automatic reporting, and (iii) improve continuous monitoring and analysis of key variables for sufficiently long timescales (greater than 30 years). Also to be addressed in support of better decision-making are (i) inadequate data collection and monitoring systems at the sectoral level that limit the understanding of climate-sectoral linkages (ii) the need for higher resolution modelling outputs as well as more impacts-based modelling, and (iii) coordination and capacity challenges that have reduced the effectiveness of climate action in the region.

Table ES 1: Summary of Climate Trends and Projections for the Caribbean

HISTORICAL TREND[2]	PROJECTION[3]
RAINFALL	
» Caribbean region has a defined dry (December to April) and wet (May to November) season. » Caribbean countries can be divided into six rainfall zones, based on the pattern of rainfall received. » Central Caribbean (Zones 3 and 4) receives smaller rainfall amounts (2-17 mm/month) while the far western and southern Caribbean (Zones 1 and 6) receive rainfall amounts ranging from 2 to 27 mm/month. » More than 70% of the rainfall occurs in the wet season for each zone. » In the long-term historical record (1900-2014), the Caribbean has not gotten wetter or drier (no significant observed linear trend). » Decadal variations account for 7% of the observed variability in Caribbean rainfall. Year-to-year (interannual) variations account for up to 91%. » The number of consecutive dry days is increasing, as well as the amount of rainfall during rainfall events.	» The Caribbean as a whole will gradually dry through to the end of the century. Drying is expected to be less in the far north Caribbean and more in the south and southeast. » Global Climate Models (GCMs) suggest for the central and southern Caribbean basin, drying up to 20 per cent for annual rainfall, while Regional Climate Model (RCM) based projections suggest up to 25 and 35 per cent less rainfall by the end of the century » GCMs suggest that mid-2020s will see up to 2% less rainfall in the annual mean. By the 2050s, the region is in the mean up to 6% drier, and by the end of century, the region may be up to 17% drier. » The Caribbean drying trend is likely driven by drying in the late wet season (September-November). » Dry season rainfall generally shows small increases or no change. » RCMs suggest sub-regional variation in projections with some parts of the region being more significantly impacted by drier conditions than others. A general pattern is for Belize in the far west Caribbean (Zone 1) and the Lesser Antilles and southern Caribbean (Zones 5 and 6) to be the most severely impacted once drying has begun, as well as the central Caribbean (Zone 4) to a lesser extent. » Changes to mean annual rainfall in the far north and north Caribbean (Zones 2 and 3) may suggest slightly wetter conditions through to mid-century, which change to drier conditions by the end of century. It is important to note however, that even for the far north Caribbean, the rainy seasons are projected to dry from as early as the 2020s. » Small to large increases in consecutive dry days are projected across the region.
AIR TEMPERATURES	
» Most of the variability observed (~65%) in temperature in the Caribbean is due to a significant upward (linear) trend. » Increase in temperature in Caribbean is consistent with global warming trend. » There is an increasing trend in very warm days and nights for the Caribbean as a whole.	» The Caribbean as a whole will gradually warm through to the end of the century. » Minimum, maximum and mean temperatures increase irrespective of scenario through the end of the century. » The mean temperature increase (in °C) from GCMs will be 0.48-0.56°C by the 2020s; 0.65-0.84°C by the 2030s, 0.86°-1.50°C by the 2050s, and 0.83-3.05°C by the end of the century with respect to a 1986-2005 baseline over all four RCPs. » RCMs suggest higher magnitude increases for the downscaled grid boxes - up to 4°C by end of century. » Temperature increases across all seasons of the year. » There are regional variations in warming evident in the RCM results. The far western Caribbean (Zone 1) and the southern Caribbean (Zone 6) show slightly higher warming than the rest of the region. » Projections based on statistical downscaling show an increase for both warm days and warm nights by the end of the century - warm days ranged between 51 and 251 days, and warm nights between 24 and 360 days for RCP 8.5. » The trend is for a decrease in both cool days and nights. The range for cool days was between 1 and 41 days, and between 1 and 32 days for cool nights for the end of century under RCP 8.5.

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[2] Historical trends are based on observations made over 1900-2014.

[3] GCM-generated projections are relative to a 1986-2005 baseline, RCM-generated projections are relative to a 1961-1990 baseline.

HISTORICAL TREND[2]	PROJECTION[3]
SEA SURFACE TEMPERATURES	
» Range from 25°C to 30°C over the period of the year and follows a normal distribution pattern, with the lower temperatures in December/January and the highest temperatures in July.	» Recent warming trend in SSTs will continue in the future. » Under a business-as-usual scenario, SSTs increase by 1.76 ± 0.39°C per century in the wider Caribbean. » The mean annual SST range (~ 3.3°C) currently observed in the Caribbean Sea is projected to contract to 2.9°C in the 2030s, and to 2.3°C in the 2090s. By the end of the century, years of coolest projected SSTs fall within the range of the warmest years in the present.
SEA LEVELS	
» There is a general increasing trend in the sea level of the Caribbean region: » A regional rate of increase of 1.8 ± 0.1 mm/year between 1950 and 2009. » Higher rate of increase in later years: 1.7 ± 1.3 mm/year between 1993 and 2010. » Caribbean Sea level changes are near the global mean. » Larger sea level increases observed for post 2000 period during which hurricane intensity and sea level interannual variability have both increased.	» For the Caribbean, the combined range for projected SLR spans 0.26-0.82 m by 2100 relative to 1986-2005 levels. The range is 0.17-0.38 for 2046 – 2065. Other recent studies suggest an upper limit for the Caribbean of up to 1.5 m under RCP8.5. » Regional variation in SLR is small with the north Caribbean tending to have slighter higher projected values than the southern Caribbean. By the end of the century, sea level rise is projected to reach or exceed 1m across the Caribbean.
HURRICANES	
» Significant increase in frequency and duration of Atlantic hurricanes since 1995. » Increase in category 4 and 5 hurricanes; rainfall intensity, ass°Ciated peak wind intensities, mean rainfall for same period.	» No change or slight decrease in frequency of hurricanes. » Shift toward stronger storms by the end of the century as measured by maximum wind speed increases of +2 to +11%. » +20% to +30% increase in rainfall rates for the model hurricane's inner core. Smaller increase (~10%) at radii of 200 km or larger. » An 80% increase in the frequency of Saffir-Simpson category 4 and 5 Atlantic hurricanes over the next 80 years using the A1B scenario.

As the region considers how to respond in light of the implications of the key findings of this report and the uncertainty of future climate threats, there are three simple key messages or guiding principles that should undergird decision-making.

KEY MESSAGE 1: PLAN FOR THE CURRENT CLIMATE – BUT BE GUIDED BY LESSONS OF THE PAST.

It is important that the Caribbean region learns the lessons of the past and use them to guide current and future decision-making processes. Chapters 3 and 4 present the historical (long-term) characterization of Caribbean climate, by focusing on variables such as rainfall and temperature (sea surface and air) and climate extremes such as droughts, floods, sea level rise and hurricanes. The region has struggled with addressing these climate-related threats in an anticipatory manner, and this has increased individual and collective vulnerability. One key example of this is the frequently reactive manner in which slow-onset events such as droughts are addressed. Despite significant efforts such as work led by the Caribbean Institute for Meteorology and Hydrology (CIMH) to improve early warning for drought (see Chapter 8), there has been limited implementation of major long-term policy and other adaptation initiatives by decisionmakers to reduce drought's damaging impacts. The lessons of the past dictate that we can no longer afford to wait until an event happens, or is about to happen, before action is taken to deal with climate hazards. It is important that planning and decision-making efforts are (i) proactive, (ii) not curtailed or stalled once the threat is deemed to be past, and (iii) guided by past lessons and available expertise.

KEY MESSAGE 2: PLAN FOR THE FUTURE CLIMATE – BUT DO IT COLLABORATIVELY.

Prioritized collective action, coordinated across sectoral, national and regional levels, will be critical for successful decision-making. The projections for the Caribbean (presented in Chapter 5) are for rising sea levels, hotter temperatures, more variable rainfall with increased drying, increased sea surface temperatures, and more intense hurricanes. These projections, especially in light of the recent extremes discussed in Chapter 6 and the climate impacts in Chapter 7, call for urgent and coordinated action even while the region tries to grapple with existing threats. The climate-related phenomena that so drastically affect Caribbean countries are not locally derived, and as such, our response mechanisms must also be regionally driven and locally applied. The small size of Caribbean islands is one factor pointing to the need to work together to strengthen regional response mechanisms. In identifying those prioritized actions that the Caribbean should take, consideration should be given to (i) the social and economic costs of inaction or delayed action against the value to be derived from resilience efforts, (ii) the levels of resilience that can sustainably be targeted, and (iii) the systems that will need to be in place to support the transition to a more resilient Caribbean.

KEY MESSAGE 3: PRIORITIZE HARNESSING AND ENHANCING REGIONAL STRENGTHS AND EXPERTISE IN SUPPORT OF IMPROVED DECISION-MAKING

Chapter 8 presents an overview of climate services in the region, as well as national and regional mechanisms for supporting same. These efforts, which stand as key examples of regional strengths, have been led by the CIMH in collaboration with a consortium of regional partners. There is significant scope for bolstering these and similar services as well as the implementing institutions so that critical data, information, products and tools to improve decision-making are readily available to end users. As the region tackles climate change, identification and exploitation of regional strengths and opportunities, such as those for integrated, interdisciplinary and targeted research and development programmes as well as climate products and services, must play a substantial role in decision-making.

1. INTRODUCTION

1.1. CONTEXT

The very climate that has for decades underpinned the economies of many Caribbean territories is now proving to be their greatest area of vulnerability. This is in large part due to significant economic dependence upon climate sensitive sectors, like tourism and agriculture, in the face of a changing climate regime. There are, however, several other factors that further contribute to regional climate sensitivity and a heightened vulnerability to climate variations and change. These include limited coastal plains for siting major towns, cities and zones of economic activities (due to the small sizes and/or complex terrain of most Caribbean territories); a strong dependence on rainfall for water; and limited capabilities for hazard forecasting. For much of the Caribbean, there has been an expectation that the climate must follow anticipated and accustomed patterns, and as a result, planning related to both quality of life and economic development is strongly premised on these 'normal' patterns of climate. This is true even when the region experiences 'anomalous' climate phenomena, i.e., even variations from the 'normal' are expected to occur within bounds of familiarity.

Recent years, however, have seemingly brought the emergence of climatic conditions that are not only unfamiliar, but also unprecedented. This has been seen in such phenomena as rising sea levels, more prolonged region-wide droughts, increased heavy rainfall and flooding events, and greater numbers of very hot days and nights in a year. It is not just the magnitude of the change that has proven challenging (e.g., the intensity of the rainfall events leading to flooding, or the length of the droughts), but also the frequency of extreme event occurrence. Such is the case when the region is impacted by a climate extreme even before it has managed to recover from another. Projections of future Caribbean climates indicate that changes already seen are likely to continue and further intensify, exposing the region to an increasing number of extreme climatic events. The Caribbean is, therefore, projected to keep facing the challenges that accompany the adjustment to climate change, for example, from more frequent and/or intense tropical storms and hurricanes.

The 2017 hurricane season provided valuable insight into what the Caribbean might face in the future under climate change. Far surpassing any upper limits of devastation in prior experience, the 2017 hurricane season was among the deadliest on record, and the costliest to date - estimated at over US$350 billion globally (Seria 2018). According to the Caribbean Development Bank (CDB), several of its Borrowing Member Countries (BMCs)[4], shown in Figure 1.1, were affected by the hurricanes of September 2017. Hurricanes Irma and Maria, in particular, challenged prior concepts of familiarity and preparedness, both in terms of the record-breaking speed with which they attained category 5 status, and their relentless onslaught upon the region. The damage caused by these hurricanes led to substantial loss of life, widespread infrastructural damage, destruction of crops and livestock, diminished standards of living, and loss of livelihoods. Recovery from that most devastating of seasons is still proving to be a challenge for the scope of regional experience, and perhaps regional economic power as well. (It is noted that the challenge posed to the region by recurrent hazards of unprecedented nature was being played out even as this document was being finalized. The 2019 hurricane season proved to also be record breaking with Hurricane Dorian (category 5) causing significant devastation in the Bahamas (ECLAC 2019).

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[4] CDB BMCs: Anguilla, Antigua and Barbuda, Bahamas, Barbados, Belize, British Virgin Islands, Cayman Islands, Dominica, Grenada, Guyana, Haiti, Jamaica, Montserrat, St Kitts and Nevis, St Lucia, St Vincent and the Grenadines, Suriname, Trinidad and Tobago, and Turks and Caicos Islands

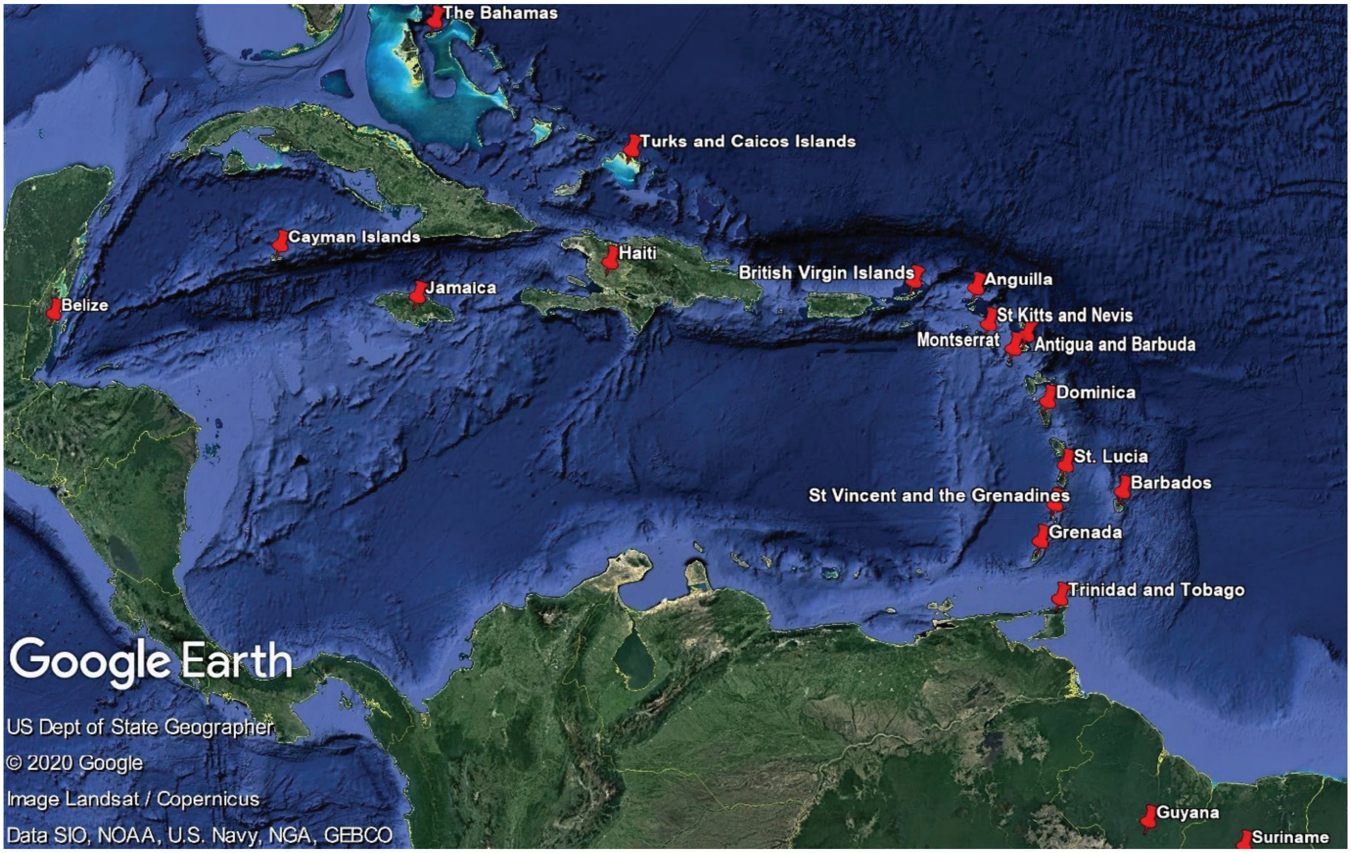

Figure 1.1: Map of the Caribbean showing CDB BMCs (Source: Google Earth 2020)

Given recent experiences and future projections, it seems clear that the Caribbean can no longer afford the cost of the catastrophic consequences of climate change, nor can it afford not to respond to climate change. Therefore, regional efforts aimed at augmenting climate resilience are necessary given that the Caribbean's vulnerability to climate variability and change is projected to only increase. Such resilience will require a multi-faceted, strategic, and sustainable approach which will only be possible with the support of decision-makers in government and industry.

This document serves as a contribution to the regional resilience building effort through the provision of historical and future climate information for use by regional decision-makers. In order to mainstream climate variability and change into regional planning and decision-making, it is necessary to have an understanding of: (i) the baseline or mean climate of the region, (ii) how that climate has changed in the recent past and how it is projected to change in the future, (iii) how those changes are expected to have an impact at local levels, and (iv) potential measures that have already been implemented or will be required to reduce vulnerability to climate change. This document, compiled under the auspices of the State of the Caribbean Climate (SOCC) Project, provides the climate-related information decisionmakers will need as they seek to proactively plan and effectively respond to a changing climate.

1.2. THE STATE OF THE CARIBBEAN CLIMATE PROJECT

The CDB has long been cognizant of the need for increased knowledge about climate change and its effects. In 2017, the organisation provided a grant of 445,056 euros to The University of the West Indies (UWI), Mona through financing from the European Union (EU), to implement the Project "State of the Caribbean Climate Report: Information for Resilience Building". Funding for the project came as a result of a 2014 agreement with the EU for the CDB to execute projects within the African Caribbean Pacific (ACP)[5]-EU Natural Disaster Risk Management

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[5] The African, Caribbean and Pacific Group of States is now called The Organisation of African, Caribbean and Pacific States (OACPs).

(NDRM) Programme in the CARIFORUM states[6]. The main objective of the five-year NDRM Programme is "to contribute to reducing the vulnerability to long term impacts of natural hazards, including the potential impacts of climate change, thereby achieving regional and national sustainable development and poverty reduction goals in the CARIFORUM States." (Jambou 2015).

The State of the Caribbean Climate Project contributes to the goals of the NDRM Programme by seeking to increase awareness about, and use of, updated and reliable climate data in CDB BMCs. The Climate Studies Group, Mona (CSGM), within the Department of Physics at The UWI, is directly responsible for technical implementation of the project across its three main components listed below:

Preparation of the "State of the Caribbean Climate Report". This is intended to be a comprehensive 'first-stop' reference report that details the state of knowledge of climate variability and change at the time of its compilation. This report is expected to become the premise for actionable recommendations to improve the region's resilience across all levels and sectors. Two validation workshops for targeted end-users, one in Jamaica and one in St. Lucia, formed part of the report finalization process. Section 1.3 presents further details on the report.

Conducting interactive "Climate SMART Series" workshops. These were targeted at key governmental representatives within BMCs of the CDB as well as relevant regional organisations. The workshops focussed on: (a) building knowledge and awareness of climate change and its impacts on climate-sensitive sectors, and (b) guiding the BMCs to effectively use the data in the State of the Caribbean Climate Report to assess the effects of climate variability and change on specific sectors, and integrate climate data into development planning and strategies.

Development of an online platform. This will permanently host content relating to the State of the Caribbean Climate Report. The platform will also host workshop materials, and other relevant climate resources, thereby increasing the reach and capacity-building potential of the Project.

In the delivery of the State of the Caribbean Climate Report the CSGM partnered with the Caribbean Institute for Meteorology and Hydrology (CIMH) to produce two chapters (see the author listing in the front material). This report has also significantly benefitted from collaborative dynamical downscaling modelling work done with the Cuban Instituto de Meteorología (INSMET) under the auspices of the Caribbean Climate Modellers Consortium.

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[6] Caribbean Forum of African, Caribbean and Pacific States.

1.3. ABOUT THIS DOCUMENT

The State of the Caribbean Climate Report (hereafter SOCC Report) contains updated and reliable climate data for the Caribbean region, including observed climate variability and trends, recent extreme climatic events and impacts, a compilation of potential impacts of climate change for climate sensitive sectors, and an examination of the value of climate information. The report is geared towards increasing decision-makers' basic understanding of climate variability and change, facilitating evidence-based planning and policy, and implementing prioritised actions tailored to respond to climatic threats as well as sector-specific sensitivity contexts. Ultimately, this SOCC Report is expected to be used to support disaster risk reduction, facilitate the formation of climate change adaptation strategic plans, and aid work programme development, all of which will contribute to the increased resilience of vulnerable Caribbean countries and communities.

Although general assessment reports for the Caribbean do exist, there are often limitations to their access and use, particularly in the following ways: (a) many exist in peer-reviewed literature and are not readily accessible by decision-makers, (b) they are unsuited for policy-makers due to their technical scope, (c) the projections used tend to rely on general circulation models that do not provide sufficiently detailed data and information at spatial scales required by small Caribbean islands, (d) climate variability is not taken into account, and (e) existing climate change projections at the regional level are not based on the most recent science. The SOCC Report seeks to address these limitations.

Despite the fact that there have been significant improvements in the collection and availability of climate data over the last ten years, the data do not often play a critical role in planning and decision-making processes. In some cases, this is due to limitations in (i) understanding and awareness of climate variability and change as it relates to the Caribbean region, and (ii) knowledge of how and where to access climate information and data for the Caribbean. Furthermore, while many Caribbean policymakers have a strong interest in climate change issues, the perception is that such matters are often presented in an overly academic and technical manner, which discourages attempts at both understanding and using the information. The SOCC Project is an attempt to provide tools for bridging these gaps. One goal of the project is to increase basic knowledge and understanding of recent and future climate variability and change in the Caribbean region, in the hope that doing so will yield evidence-based policy and investment actions. In particular, the SOCC Report attempts to do this by amalgamating all current Caribbean region-specific climate-related information for a non-scientific audience. Table 1.1 outlines the structure of the report.

Table 1.1: Structure of the State of the Caribbean Climate Report

CHAPTER	TITLE	SUMMARY
CHAPTER 1	INTRODUCTION	Caribbean context and State of the Caribbean Climate Project.
CHAPTER 2	DATA AND METHODOLOGIES	Methods and sources of data collection.
CHAPTER 3	RAINFALL AND TEMPERATURE	Defining climatology, extremes, and trends.
CHAPTER 4	SEA LEVEL RISE, DROUGHTS & FLOODS, HURRICANES	Historical variability or long-term trends.
CHAPTER 5	CLIMATE SCENARIOS AND PROJECTIONS	Caribbean climate in the future using regional climate models and statistical downscaling.
CHAPTER 6	CLIMATE EXTREMES AND EARLY WARNING	A description of extreme climatic events and the current regional early warning information for improved preparedness to such events.
CHAPTER 7	IMPACTS OF CLIMATE CHANGE ON THE CARIBBEAN	A compilation of potential impacts of climate change for relevant sectors in the Caribbean with references.
CHAPTER 8	ADDING VALUE TO CLIMATE INFORMATION THROUGH SERVICES	Caribbean approach to climate services at national and regional levels.
CHAPTER 9	CONCLUSIONS AND RECOMMENDATIONS	Summary of key report findings and recommendations for the way forward.
CHAPTER 10	REFERENCES	A list of all the references (by chapter) used in the preparation of this document.
APPENDIX 1	CLIMATE RESOURCES	A comprehensive review of credible climate tools, reports, and articles on Caribbean climate.


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2. DATA & METHODOLOGIES

2.1. APPROACH

The general approach taken in compiling this document is as follows:

Literature Review. A literature review was conducted of authoritative works and recent studies on climate change and climate variability for the Caribbean region. These included national reports such as the State of the Jamaican Climate 2015 (CSGM 2017), National Communication submissions from Non-Annex I Parties and Biennial Update Report submissions under the United Nations Framework Convention on Climate Change (UNFCCC), the Fifth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC 2013), and other reports and studies produced by the IPCC, Caribbean Community Climate Change Centre (CCCCC), Caribbean Institute for Meteorology and Hydrology, and the Climate Studies Group, Mona. The literature review guided the preparation of, and provided content for, the sections of this report.

Historical Data Analysis. The climate data products used in this work are listed in Table 2.1. Available historical observed data are used to both characterise the climatology of selected climate variables and examine variability and trends for the same climate variables. Variability and trends in sea level rise and the occurrence of tropical storms, hurricanes, and other climate extremes were also examined. The literature review was used to complement the descriptions of the climatology and historical climate variability. Data from a variety of sources were used. The data sources employed are further described in the following subsection (Section 2.2). The analysis of the data is organised by variable and done using tables, graphs, and diagrams with specific emphasis on CDB member states and for the Caribbean as a whole. Data are also presented for climatic zones premised on six rainfall zones identified in the Caribbean (see Section 3.1). The climatic zones group countries within the Caribbean with similar rainfall climatological patterns.

Projections of Future Climate. Climate projections for the Caribbean region were obtained from the outputs of a suite of global climate models (GCMs), two regional climate models (RCMs), and statistical downscaling techniques. Future trends in climate and variability were produced for the Caribbean over three future time slices: 2020s (2020-2029), 2050s (2050-2059), and end of the century (2091-2100) with respect to a historical baseline. For GCM data, country scale projections were generated using representative concentration pathway scenarios or RCPs (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) consistent with the IPCC's Fifth Assessment Report (AR5). RCPs are explained in Section 2.3.

Comparisons to past trends are shown, where appropriate. For RCM analyses, data were extracted from the PRECIS (Providing Regional Climates for Impact Studies) RCM, with 25 km grid resolution covering respective rainfall zones consisting of CDB member states and using a perturbed physics ensemble (see Section 2.3). Similar future time slices were reported on. Whereas the coarser resolution GCM data were used to capture mean climate changes for the Caribbean divided into six rainfall zones, the RCM data were only used to extract projection data for selected geographic regions. Projections of extreme indices were also derived from rainfall and temperature data obtained from stations with long-term time series using statistical downscaling techniques and GCM data.

In producing future projections, the data are analysed to provide, as best as possible, a picture of the state of the climate of the Caribbean at the regional, country, and sub-country (~25 km) levels for the near-term to end-of-century. Again, the literature review was used to provide complementary pictures of the future with respect to other climatic variables, for example, with respect to sea level rise and future tropical storms and hurricanes.

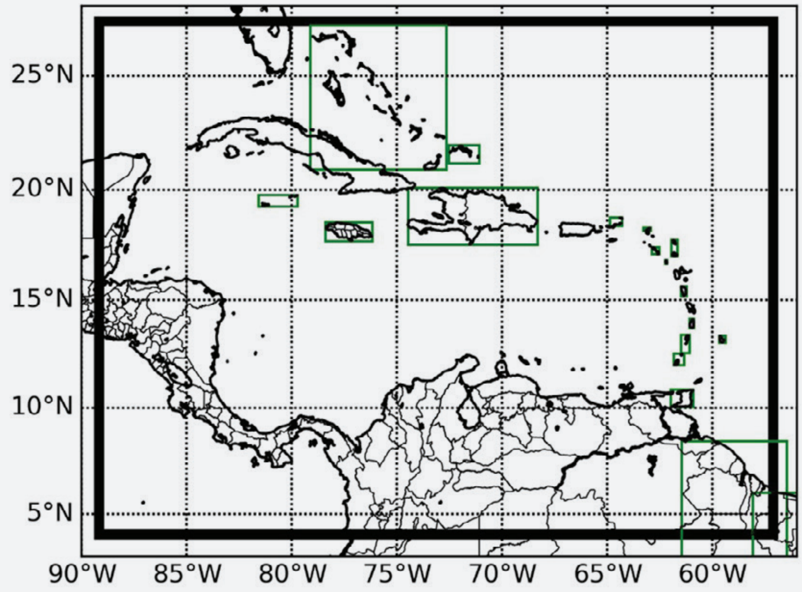


Figure 2.1: Representation of the Caribbean. CDB member states are shown in green boxes.

Impact Tables, Vulnerability Profiles, and Maps. The likely impacts of climate variability and change on key sectors are summarized from an extensive literature review and presented in tabular form. Sectors addressed under other CDB initiatives were targeted (water, agriculture, tourism, health, human settlements, and coastal resources). Also presented are impacts tables for crosscutting themes such as poverty, society, gender, and development

2.2. DATA SOURCES

As noted above, multiple sources are used in compiling the narrative of this report. Table 2.1 shows the primary climate data sources which are relied upon to produce the climatologies, and the general analyses of past and future climatic trends for which they are used. Links to each source are also shown.

Table 2.1: Data sources used in the compilation of historical climatologies and future projections

HISTORICAL DATA				
Temperature	Climatology + Historical Trends	Station data	» CAROGEN Monthly data for stations across the Caribbean region. Data availability varies from country to country. Stations are listed in Table 3.2.	» Observed weather station data from Caribbean Institute for Meteorology and Hydrology: Retrieved from http://carogen.cimh.edu.bb/
		Gridded Dataset	» University of Delaware (UDel): Monthly global gridded high resolution (0.5°) station (land) data for air temperature from 1900-2014.	» University of Delaware, Center for Climatic Research; Willmott et al. (2014): Retrieved from Global Precipitation Archive
	Trends	Gridded Dataset	» CRU TS 3.24: fully interpolated dataset with high resolution (0.5°). Monthly gridded fields based on monthly observational data, which are calculated from daily or sub-daily data by National Meteorological Services and other external agents.	» University of East Anglia Climatic Research Unit; Harris et al. (2014): Retrieved from KNMI Climate Explorer http://climexp.knmi.nl/plot_atlas_form.py
			» IRI Climate and Society Map Room Tool used to present an approximate timescale decomposition of the Caribbean region's precipitation and air temperature time series for the twentieth century.	» Columbia University International Research Institute for climate and society; Map Room: Retrieved from http://iridl.ldeo.columbia.edu/maproom/
Rainfall	Climatology + Historical Trends	Station data	» CAROGEN Monthly data for stations across the Caribbean region. Data availability varies from country to country. Stations listed in Table 3.2.	» Observed weather station data from Caribbean Institute for Meteorology and Hydrology: Retrieved from http://carogen.cimh.edu.bb/
		Gridded Dataset	» University of Delaware (UD): Monthly global gridded high resolution (0.5°) station (land) data for rainfall from 1900-2014.	» University of Delaware, Center for Climatic Research; Willmott et al. (2014): Retrieved from Global Precipitation Archive
	Trends	Gridded Dataset	» CRU TS 3.24: Fully interpolated dataset with high resolution (0.5°). Monthly gridded fields based on monthly observational data, which are calculated from daily or sub-daily data by National Meteorological Services and other external agents. Based on analysis of several individual weather station records in the Caribbean.	» University of East Anglia Climatic Research Unit; Harris et al. (2014): Retrieved from KNMI Climate Explorer http://climexp.knmi.nl/plot_atlas_form.py
			» IRI Climate and Society Map Room Tool used to present an approximate decomposition of the Caribbean region's precipitation anomaly time series for the twentieth century.	» Columbia University International Research Institute for climate and society; Map Room: Retrieved from http://iridl.ldeo.columbia.edu/maproom/
Sea Levels	Trends	Gauge data	» As reported in literature	» Various sources

HISTORICAL DATA

Sea Surface Temperature	Trends	Gridded Dataset	» NOAA/OAR/ESRL PSD V2 High Resolution 0.25° monthly dataset	» National Oceanic and Atmospheric Administration (NOAA), Earth System Research laboratory; Optimum Interpolation (OI) SST V2: Retrieved from https://www.esrl.noaa.gov/psd/
Hurricanes	Historical Trends		» Atlantic hurricane reanalysis project of the National Oceanic and Atmospheric Administration	» Observed storm data available from: http://www.aoml.noaa.gov/hrd/data_sub/re_anal.html

FUTURE DATA*

Temperature & Rainfall	GCM Data	Gridded Dataset	» CMIP5 (IPCC AR5 Atlas subset)- This is the dataset used in the IPCC WG1 AR5 Annex I “Climate Change Atlas”. » Only a single realization from each of over 20 models is used. » All models are weighted equally, where model realizations differing only in model parameter settings are treated as different models.	» Retrieved from KNMI Climate Explorer: http://climexp.knmi.nl/plot_atlas_form.py
	RCM Data	Gridded Dataset	» PRECIS Perturbed Physics experiments performed for the Caribbean. » Dynamical Downscaling using the RegCM4.3.5 Model.	» Perturbed physics data available from the Caribbean Community Climate Change Centre: http://www.caribbeanclimate.bz/general/clearinghouse-search-tool.html
Sea Levels	GCM Data	Gridded Dataset	» Ensemble mean and 95% percentile of 21 CMIP5 models. Data taken for projections to the end of century (2100). Data relative to 1986-2005.	» Model data: Retrieved from Integrated Climate Data Center: http://icdc.cen.uni-hamburg.de/las/getUI.do
Hurricanes			» As reported in literature.	» Various sources.

*Additional information on model data is provided in Section 2.3.2.

2.3. OBTAINING FUTURE PROJECTIONS FROM MODELS

2.3.1. EMISSION SCENARIOS

It is largely Representative Concentration Pathway (RCP) based future data that are reported on in this document. The GCMs from which data were extracted for use in this study were run using the full range of RCPs, namely RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (see Box 2.1). However, the PRECIS RCM was run multiple times using the A1B Special Report Emission Scenario (SRES) (Nakicenovic et al. 2000). As will be explained later, more sub-island scale data are currently available for a future Caribbean for the RCM run using the SRES scenario (6 possible futures), hence its use. The statistical downscaling also relied on the output of a GCM run using RCP2.6, 4.5, and 8.5.

With respect to comparability between the two sets of scenarios used in this document, the SRES A1B is comparable to RCP6.0 in carbon dioxide concentrations and global temperature change by century's end and RCP8.5 through mid-century. Both RCP6.0 and the A1B scenarios are marked by an increase in carbon dioxide emissions through to (A1B) or after (RCP6.0) mid-century, followed by a decrease approaching 2100 (see Figure 2.2). By 2100, carbon dioxide concentrations for both scenarios are very similar (over 600 ppm) as is the mean global temperature anomaly (just under 3 °C). In this document, the RCM data reported on using the A1B scenario are representative of a high emissions (or worst case) future scenario for the first three time slices and a medium-high emissions scenario for the end of century time slice.

INFORMATION BOX 2.1

SO WHAT IS A SCENARIO?

In distinguishing between SRES and RCP scenarios, it is noted that SRES scenarios (reported on in the IPCC's Fourth Assessment Report (IPCC 2007)) represent plausible storylines of how a future world will look. The SRES scenarios explore pathways of future greenhouse gas emissions, derived from self-consistent sets of assumptions about energy use, population growth, economic development, and other factors. They however explicitly exclude any global policy to reduce emissions to avoid climate change. SRES scenarios are grouped into families (e.g. A1, B1, A1B, etc.) according to the similarities in their storylines. In this document data from one RCM run using the A1B scenario are reported on. The A1B scenario is characterized by an increase in carbon dioxide emissions through mid-century followed by a decrease. A1B is often seen as a compromise between the A2 (high emissions) and B1 (lower emissions) scenarios.

In the IPCC's Fifth Assessment Report (AR5) (IPCC 2013), however, outcomes of climate simulations use new scenarios referred to as *"Representative Concentration Pathways"* (RCPs) (van Vuuren et al. 2011). These RCPs represent a larger set of mitigation scenarios and were selected to have different targets in terms of radiative forcing (cumulative measure of human emissions of greenhouse gases from all sources expressed in Watts per square metre) of the atmosphere at 2100. They are therefore defined by their total radiative forcing pathway and level by 2100: RCP2.6. RCP4.5, RCP6.0 and RCP8.5 (Figure 2.2). The four RCPs include one mitigation scenario leading to a very low forcing level (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6), and one scenario with very high greenhouse gas emissions (RCP8.5).The RCP scenarios are also considered plausible and illustrative, and do not have probabilities attached to them.

In comparing the SRES and RCP scenarios it is noted that whereas the SRES scenarios resulted from specific socio-economic scenarios from storylines about future demographic and economic development, regionalization, energy production and use, technology, agriculture, forestry and land use (IPCC 2000), the RCPs are new scenarios that specify concentrations and corresponding emissions, but not directly based on socio-economic storylines like the SRES scenarios. The RCPs can thus represent a range of 21st century climate policies, as compared with the no-climate policy of the Special Report on Emissions Scenarios (SRES). Of the 4 RCPs, many do not believe RCP2.6 or RCP4.5 are feasible without considerable and concerted global action cause, and that the world is currently on an emission pathway equivalent to RCP6.0 or higher (Meinshausen et al. 2015).

> *The four RCPs include one mitigation scenario leading to a very low forcing level, two stabilization scenarios, and one scenario with very high greenhouse gas emissions*

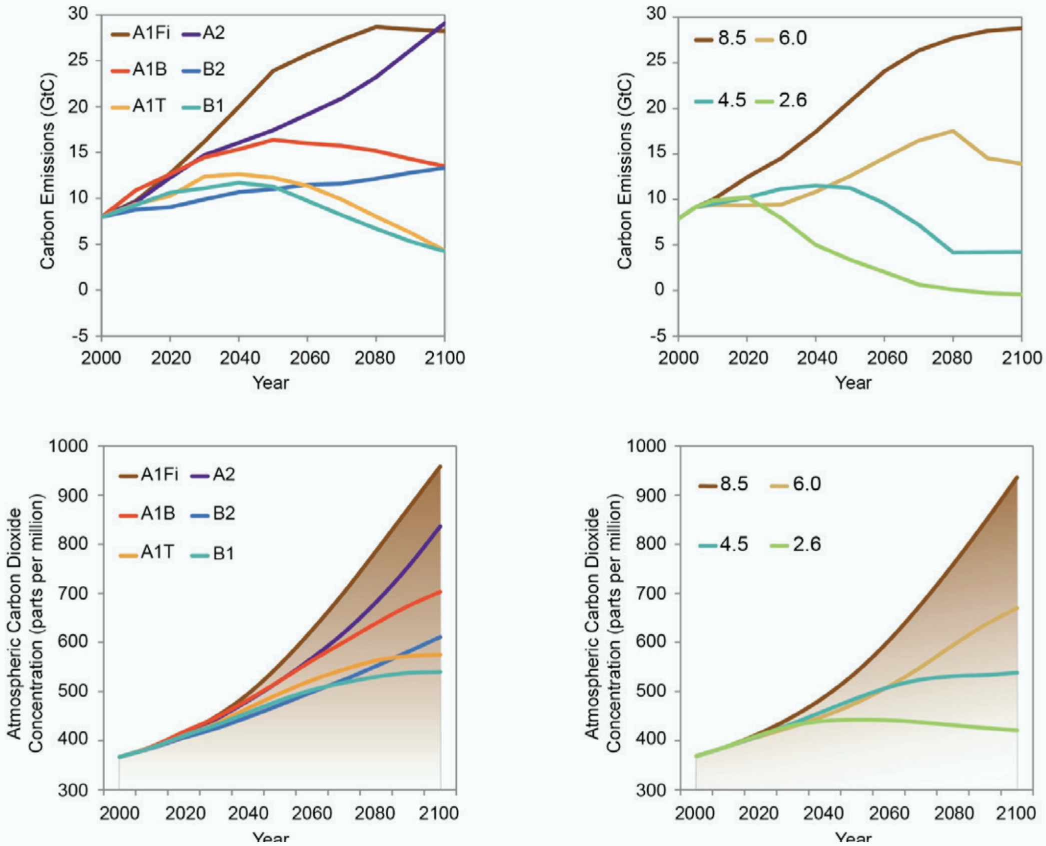


Figure 2.2: Two families of scenarios commonly used for future climate projections: the Special Report on Emission Scenarios (SRES, left) and the Representative Concentration Pathways (RCP, right). The SRES scenarios are named by family (A1, A2, B1, and B2), where each family is designed around a set of consistent assumptions: for example, a world that is more integrated or more divided. The RCP scenarios are simply numbered according to the change in radiative forcing (from +2.6 to +8.5 watts per square metre) that results by 2100. This figure compares SRES and RCP annual carbon emissions (top), carbon dioxide equivalent levels in the atmosphere (bottom).

Figure source: Climate Change Impacts in the United States: The Third National Climate Assessment.

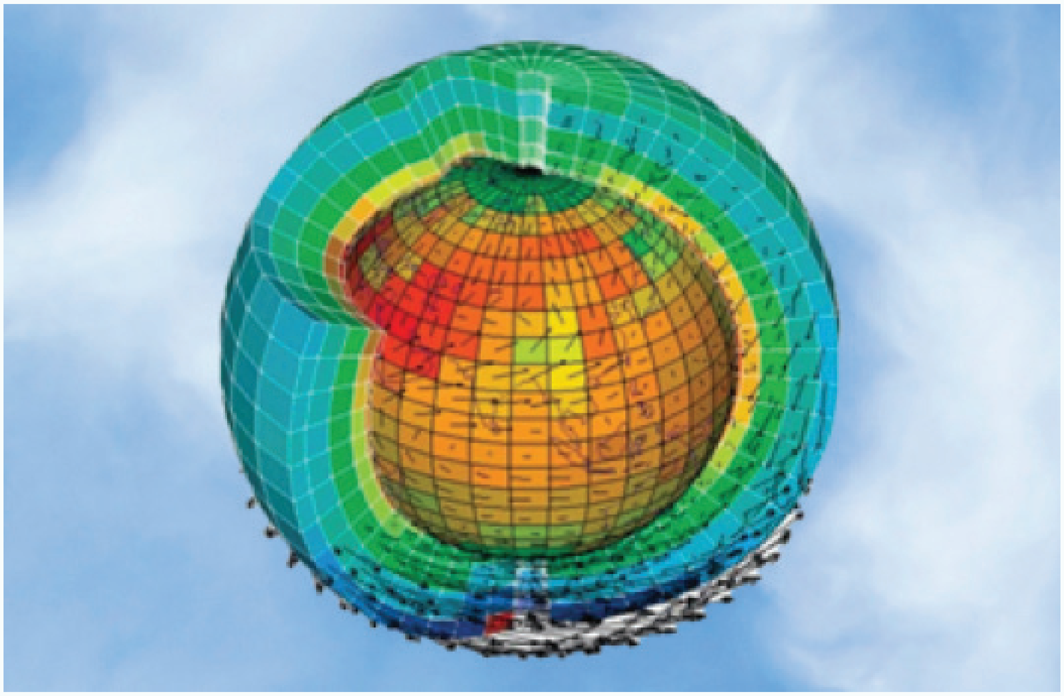
2.3.2. GCMS AND RCMS

Data from both Global Circulation Models (GCMs) and Regional Climate Models (RCMs) are used in this study (see Box 2.2).

INFORMATION BOX 2.2

WHAT'S THE DIFFERENCE BETWEEN GCMS AND RCMS?

Climate Models are useful tools for providing future climate information. GCMs are mathematical representations of the physical and dynamical processes in the atmosphere, ocean, cryosphere and land surfaces. Their physical consistency and skill at representing current and past climates make them useful for simulating future climates under differing scenarios of increasing greenhouse gas concentrations. (See the previous section for the discussion on scenarios.)



Global Climate Models (GCMs) have relatively coarse resolutions relative to the scale of required information because of the computational requirements to model the entire globe. Unfortunately, the size of the Caribbean islands versus the grid spacing of the GCMs on which data are reported means that some islands are represented by at most a few grid boxes. There is therefore a need for downscaling techniques to provide more detailed information on a sub-country level. The additional information which the downscaling techniques provide do not however devalue the information provided by the GCMs especially since (1) to a large extent the Caribbean's climate is driven by large-scale phenomenon (2) the downscaling techniques themselves are driven by the GCM outputs, and (3) at present the GCMs are the best source of future information on some phenomena, for example, hurricanes. Dynamical downscaling employs a regional climate model (RCM) driven at its boundaries by the outputs of the GCMs. Like GCMs, the RCMs rely on mathematical representations of the physical processes, but are restricted to a much smaller geographical domain (the Caribbean in this case). The restriction enables the production of data of much higher resolution (typically < 100 km).

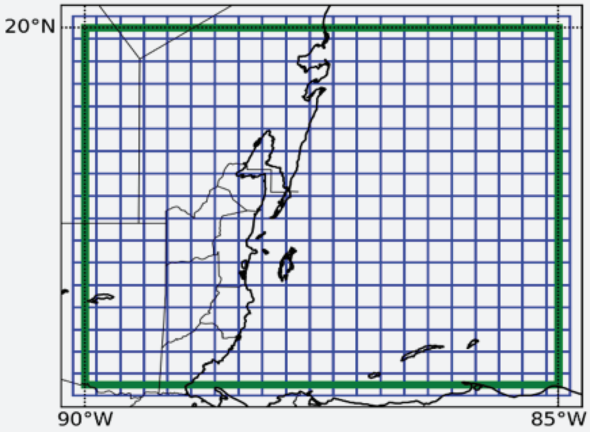
GCM projections of rainfall and temperature characteristics for the Caribbean were extracted from the subset of CMIP5 (Coupled Models Intercomparison Project 5) models used to develop the regional atlas of projections presented as a part of the IPCC's Fifth Assessment Report (AR5) (IPCC 2013). Data from more than 20 GCMs are analysed and projected annual change extracted for the GCM grid boxes over the Caribbean islands. The average for each zone containing CDB states is generated from the GCM data. This analysis provides a context within which to interpret other subzone and country scale projections derived from the RCM. Save for sea level rise (SLR), projections through the end of the century are generated, and values were averaged over the 2020s, 2050s, and end-of-century (EOC) as previously noted. Extraction was done for four RCPs. SLR projections are generated for the Caribbean as a whole and the six defined zones. The projections are presented in figures and summary tables in Chapter 5.

Available dynamically downscaled data for CDB member states are obtained from the PRECIS RCM – the PRECIS model (Jones et al. 2004) run at a resolution of 25 km. Table 2.2 summarizes key characteristics of the RCM and the experiments performed.

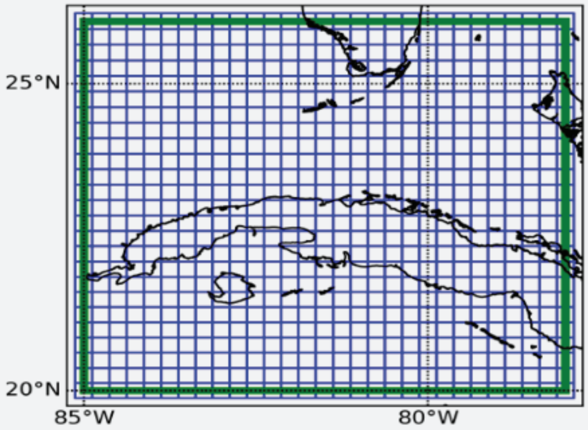
Table 2.2: Summary of RCM characteristics and experimental setups.

	PRECIS
RESOLUTION	0.22°x0.22° or ~ 25 km
KEY FEATURES	» Hydrostatic primitive equations grid point model. » 19 levels in the vertical. » Dynamical flow, the atmospheric sulphur cycle, clouds and precipitation, radiative processes, the land surface and the deep soil are all described in the model.
FORCING GCM	HadGM
AVAILABLE ENSEMBLE	6 members through the 2050s and 3 members for end of century projections using a perturbed physics approach. All ensemble members simulate SRES A1B.
VALIDATION FOR THE CARIBBEAN	Campbell et al. (2011) and Taylor et al. (2013)
REFERENCE	Hadley Centre (UK) http://www.metoffice.gov.uk/precis/intro

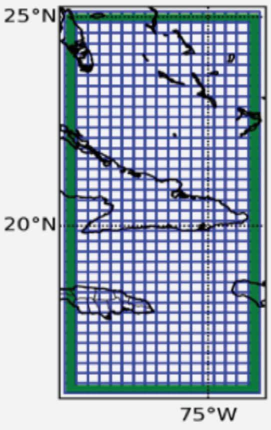
Although the PRECIS model runs are premised on the SRES A1B scenario, its results are reported because of the availability of an ensemble of up to six members from the Hadley Centre's Perturbed Physics Experiments (PPEs). PPEs are designed by varying uncertain parameters in the model's representation of important physical and dynamical processes. They capture major sources of modelling uncertainty by running each member using identical climate forcing and the methodology is an alternative to using different driving GCMs developed at different modelling centres around the world to create a multi-model ensemble. The range of climate futures projected by the Hadley Centre's PPE is considered equivalent to or greater than those based on the CMIP multi-model ensemble. As noted previously, the SRES A1B mirrors RCP 8.5 through the first three time slices and RCP6.0 by end of century. Therefore, the projections from the PRECIS model that are reported in this document represent future projections from an ensemble of simulations run using a high emissions scenario.



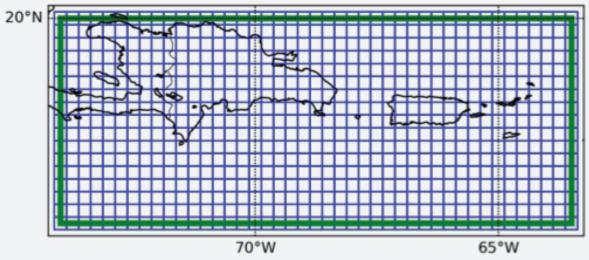
PRECIS 25-km grid box representation over zone 1



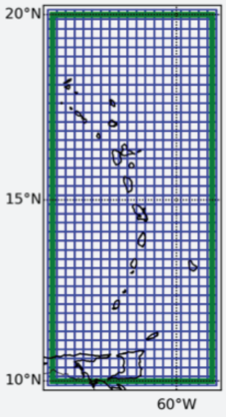
PRECIS 25-km grid box representation over zone 2



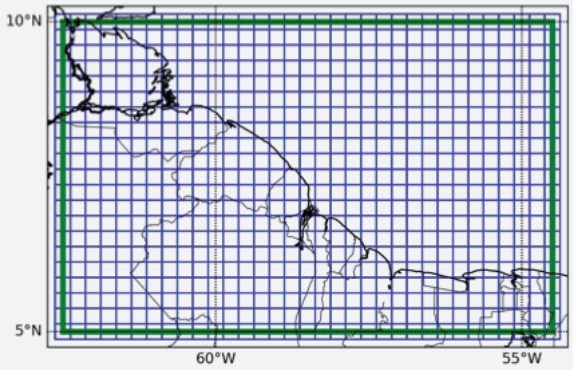
PRECIS 25-km grid box representation over zone 3



PRECIS 25-km grid box representation over zone 4



PRECIS 25-km grid box representation over zone 5



PRECIS 25-km grid box representation over zone 6

Figure 2.3: PRECIS 25-km grid box representation over six Caribbean rainfall zones.

Figures 2.3 shows how the rainfall zones in the Caribbean are represented by the PRECIS RCM. Future data for temperature (mean, maximum, and minimum) and rainfall for each grid box are extracted for the available ensemble of perturbations. The mean, minimum, and maximum change on seasonal and annual time scales for each variable and for each future time slice are then determined. However, though these data were extracted for all grid boxes for each CDB member state shown in Figure 2.3, the volume of data precluded the presentation of tables of projections for each grid box. Instead, only maps showing the mean projected changes across the perturbation ensemble are presented. Additionally, mean, minimum and maximum changes are presented in tables for the Caribbean divided into six blocks, roughly coinciding with the region's six rainfall zones (see Section 3.1).

2.3.3. SDSM

Statistical downscaling is a second means of obtaining downscaled information. It is premised on the view that the climate of a location is influenced by two types of factors: the large-scale climatic state and the regional/local features (such as topography, land-sea distribution, and land use). The approach first determines a statistical model that relates large-scale climate variables (called predictors, such as relative humidity and wind velocity) to regional or local variables (called predictands, such as rainfall and temperature). The large-scale output of a GCM simulation is then fed into the model to estimate future local or regional characteristics, such as station rainfall and temperature. Statistical downscaling can provide site-specific information that is critical for many climate change impact studies. A guidance document on how climate scenarios may be developed from this approach is available at http://www.ipcc-data.org/guidelines/dgm_no2_v1_09_2004.pdf.

In this document, results obtained using the Statistical DownScaling Model (SDSM) developed at Loughborough University in the United Kingdom are reported. SDSM is a freely available software tool that facilitates rapid development of multiple low cost, single-site scenarios of daily weather and surface variables under present and future climate forcings (http://co-public.lboro.ac.uk/cocwd/SDSM/sdsmmain.html). The model is a combination of a weather generator approach and a transfer function model. A weather generator allows the generation of a number of synthetic present or future weather series given observed or model predictors. The transfer function approach establishes a mathematical relationship between local scale predictands and large-scale predictors. In SDSM, the transfer function is obtained using linear regression.

Predictors on daily time-steps and for a grid box closest to the study area are obtained from two datasets: (1) the NCEP Reanalysis for 1961-2005, and (2) the CanESM2, a coupled GCM developed by the Canadian Centre for Climate Modelling and Analysis (CCCMA) of Environment Canada for a historical period 1961-2005 and for a continuous 2006-2100 for RCP2.6, 4.5 and 8.5. Correlation analysis, partial correlation analysis, and scatter plots are used to identify a useful subset of predictors from the original suite of 26 predictors. A mathematical relationship is then created between the predictand and predictor subset in a process known as model calibration. These first steps are executed using the first half of the available data. All the analyses with observed data are constrained by the availability of data and their overlap with the span of the predictor dataset (1961-2005). For example, analyses using rainfall, maximum temperature and minimum temperature data measured at Jamaica's Norman Manley International Airport could only be conducted for 1993-2005, with the first half of the data used for model calibration. Annual models are created for temperature and seasonal models were created for rainfall. The stochastic component of SDSM is used to generate 20 simulations of weather series using the mathematical model established in the previous step, with observed predictors over the second half of the data used as inputs. These series are averaged and can be compared with the observation data set using a number of metrics to validate the model. Once the models are identified as reliable representations of historical climate, they are fed with data from the CanESM2 model to generate future weather series for analysis. The periods examined are 2016-2035 and 2036-2075.

2.3.4. PRESENTING THE DATA

In presenting the future projection data, absolute change is provided for most variables, for example temperature, while percentage change is presented for rainfall. For temperature and rainfall, the data are averaged over three-month seasons: November-January (NDJ), February-April (FMA), May-July (MJJ) and August-October (ASO), which are roughly consistent with the Caribbean dry season (December-April) and wet season (May- November) (Taylor et al. 2002). The mean annual change

3. RAINFALL & TEMPERATURE

3.1. INTRODUCTION

In this chapter the historical monthly climatology (i.e. the mean value for each month over a period of several years) as well as recent trends in mean and extremes of rainfall and temperature are presented. The results provided are for indices averaged over (i) the Caribbean region as a whole (see Figure 3.1 for domain definitions), (ii) six defined climatic zones (also see Figure 3.1), and (iii) the 19 BMCs of the CDB listed in Table 3.1.

Table 3.1: The 19 Borrowing Member Countries (BMCs) of the Caribbean Development Bank (CDB).

	COUNTRIES	CAPITAL	LATITUDE	LONGITUDE	RAINFALL ZONE	DATA PERIOD
1	ANGUILLA	The Valley	18.220833	-63.051667	5	1993 to 2017
2	ANTIGUA AND BARBUDA	St. John's	17.116667	-61.85	5	1971 to 2017
3	BARBADOS	Bridgetown	13.105833	-59.613056	5	1971 to 2017
4	BELIZE	Belmopan	17.251389	-88.766944	1	1979 to 2017
5	BRITISH VIRGIN ISLANDS	Road Town	18.431389	-64.623056	4	-
6	CAYMAN ISLANDS	George Town	19.3034	-81.3863	-	1971 to 2017
7	DOMINICA	Roseau	15.301389	-61.388333	5	1971 to 2017
8	GRENADA	St. George's	12.05	-61.75	5	1986 to 2017
9	GUYANA	Georgetown	6.801111	-58.155278	6	1971 to 2017
10	HAITI	Port-au-Prince	18.533333	-72.333333	4	1971 to 2017
11	JAMAICA	Kingston	17.983333	-76.8	3	1971 to 2017
12	MONTSERRAT	Plymouth	16.706417	-62.215839	5	-
13	ST KITTS AND NEVIS	Basseterre	17.3	-62.733333	5	1972 to 2017
14	ST LUCIA	Castries	14.016667	-60.983333	5	1971 to 2017
15	ST VINCENT AND THE GRENADINES	Kingstown	13.157778	-61.225	5	1979 to 2017
16	SURINAME	Paramaribo	5.852222	-55.203889	6	1971 to 2017
17	THE BAHAMAS	Nassau	25.06	-77.345	3	1971 to 2017
18	TRINIDAD AND TOBAGO	Port of Spain	10.666667	-61.516667	5	1971 to 2017
19	TURKS AND CAICOS ISLANDS	Cockburn Town	21.459	-71.139	-	-

Figure 3.1 outlines the general geographical region (Caribbean domain) which is the focus of this report as well as the locations of the 19 BMCs listed in Table 3.1 and their capital cities (red dots). For averaging over the entire Caribbean, the purple box roughly defines the boundaries used (approximately 5N to 25N and 60W to 90W). The Caribbean-wide index is defined to be consistent with the analysis of previous studies (see for example Giannini et al. 2000; Taylor et al. 2002), thereby facilitating easy comparisons with their findings. The Caribbean region is also divided into six rainfall zones (numbered 1 to 6) with similar rainfall patterns. The zones used in this study are adapted from a number of other studies which use a variety of statistical techniques to group countries with similar rainfall climatological patterns (see for example the studies of Jury et al. 2007; McLean et al. 2015; Stennett-Brown et al. 2017; Martinez et. al. 2019). Figure 3.1 also displays the annual climatology of rainfall (bar graphs in blue) and temperature (line graph in red) for each of the six defined zones. The graphs show that there are general similarities as well as distinct features in both the temperature and rainfall patterns for each of the six zones. In the following sections the data sets and the climatologies for the Caribbean and the six zones are further discussed.

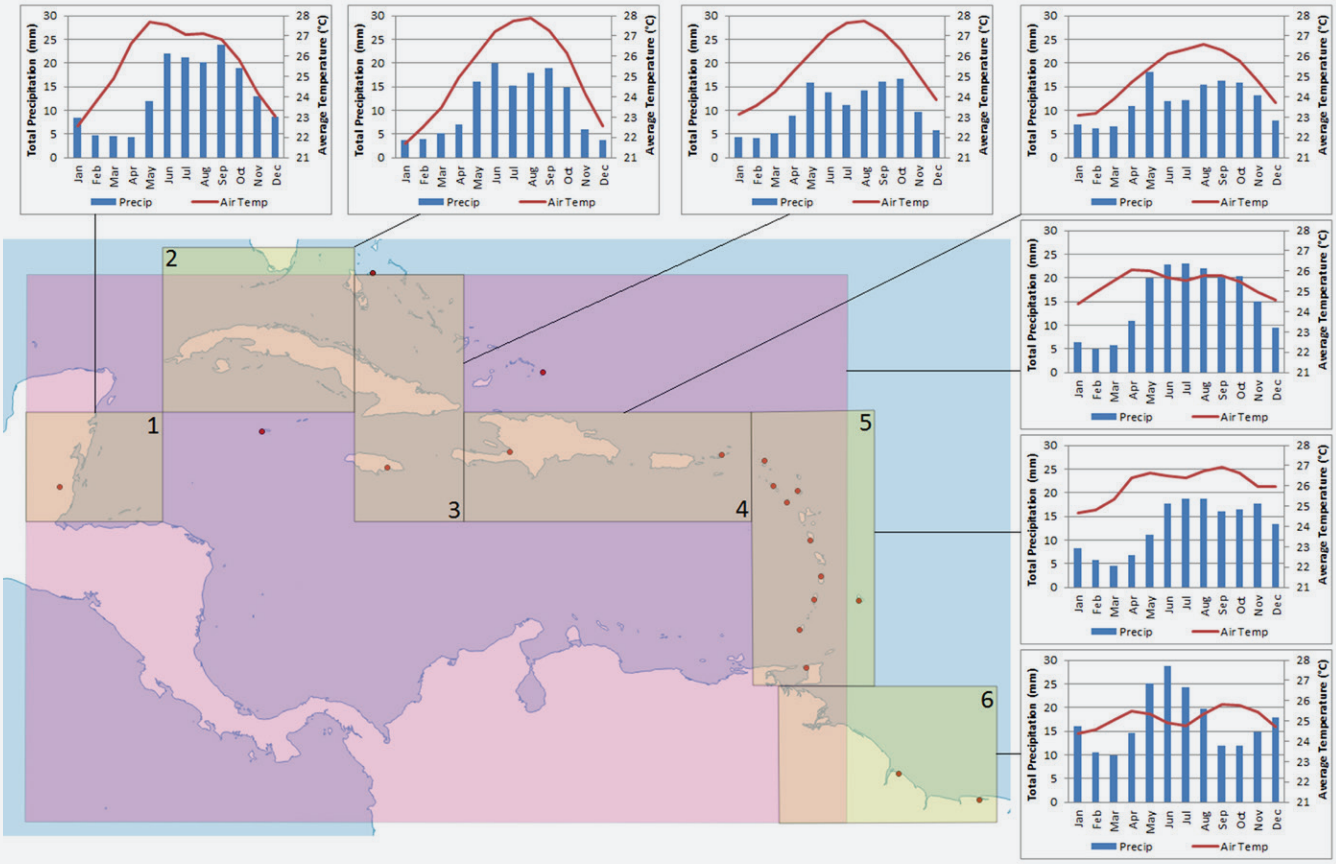


Figure 3.1: Map showing: (i) The Caribbean Domain, (ii) The 6 Rainfall Zones, (iii) The location of the CDB BMCs and their capital cities and, (iv) The Rainfall and Air Temperature Climatologies for each of the six defined zones (averaging period: 1980-2014).

3.2. CARIBBEAN RAINFALL

In this section, the rainfall climatologies of the Caribbean region and the six rainfall zones are discussed. The section also presents an analysis of historical precipitation looking at both: (i) the time scale decomposition of the rainfall time series, (ii) trends in the amount of rainfall received in the Caribbean as a whole and in each zone, and (iii) trends in precipitation extremes defined using extreme indices.

Data from the University of Delaware (UDel) dataset (Willmott et al. 2001) averaged over the period 1980-2014 were used to produce the climatological rainfall (and temperature) graphs for the Caribbean as a whole and for the six zones. (Details of the datasets used in all analyses are provided in Chapter 2.) The UDel dataset was chosen for its relatively high resolution and because it contained both rainfall and temperature data. Time scale decomposition of the historical rainfall data was done utilising the International Research Institute (IRI) Climate and Society Map Room Tool (Greene et al. 2011). This tool utilises the Climate Research Unit (CRU) dataset ((Harris et al. 2014)) due to its longer available time series.

Country-specific analysis was conducted using station data from a single station in each country listed in Table 3.1. The use of a single station is to be borne in mind when interpreting the country results. The station data were obtained through the CAROGEN portal (see again Chapter 2).

3.2.1. RAINFALL CLIMATOLOGY

Figure 3.2 presents the rainfall climatology pattern of the Caribbean averaged as a whole and for the six defined rainfall zones given in Figure 3.1. The following things are noted:

- The figure shows that the Caribbean has a wet season which runs from May to November and a dry season that runs from December to April. Rainfall during the wet season accounts for approximately 70% of each zone's total precipitation.
- Across most zones, the wet season has a distinctive bi-modal pattern with a rainfall peak in May or June and another which falls between September and December (Zone 6). This gives rise to the four rainfall periods often used to describe the climate of the Caribbean, namely: the Early Dry Season (December-April), the Early Rainfall Season (May-June), the Mid-Summer Drought or MSD (July-August), and the Late Rainfall Season (September-November). The bi-modal pattern and the resulting dry and wet seasons are defining climatological features of the Caribbean region.
- The timing of peaks in rainfall varies depending on rainfall zone. Zone 6 (the far south Caribbean inclusive of Guyana) tends to have a rainfall peak in December/January and again in June, which makes its bimodality slightly different from the rest of the region. Zone 5 (Lesser Antilles) tends to be almost unimodal with rainfall steadily rising and peaking in July/August. This is also reflected in the station data (see Table 3.2) for the countries falling within Zone 5. This may in part explain why when the region is averaged as a whole in this and other studies, the bi-modal pattern is sometimes not evident. The latter may also be in part a function of the averaging period used.
- Overall, the central Caribbean (Zones 3 and 4) receives smaller rainfall amounts ranging from approximately 2 to 17 mm/month while the far western and southern Caribbean (Zones 1 and 6) receive rainfall amounts ranging from approximately 2 to 27 mm/month.

Table 3.2 gives the mean monthly rainfall for stations in the individual countries. Data availability varies by country, and as such the periods used in calculating the climatologies are given in Table 3.1. The individual country climatologies pattern the climatological variations of the zones in which they fall, i.e. there is consistency between the timing of the peaks in rainfall and the driest periods.

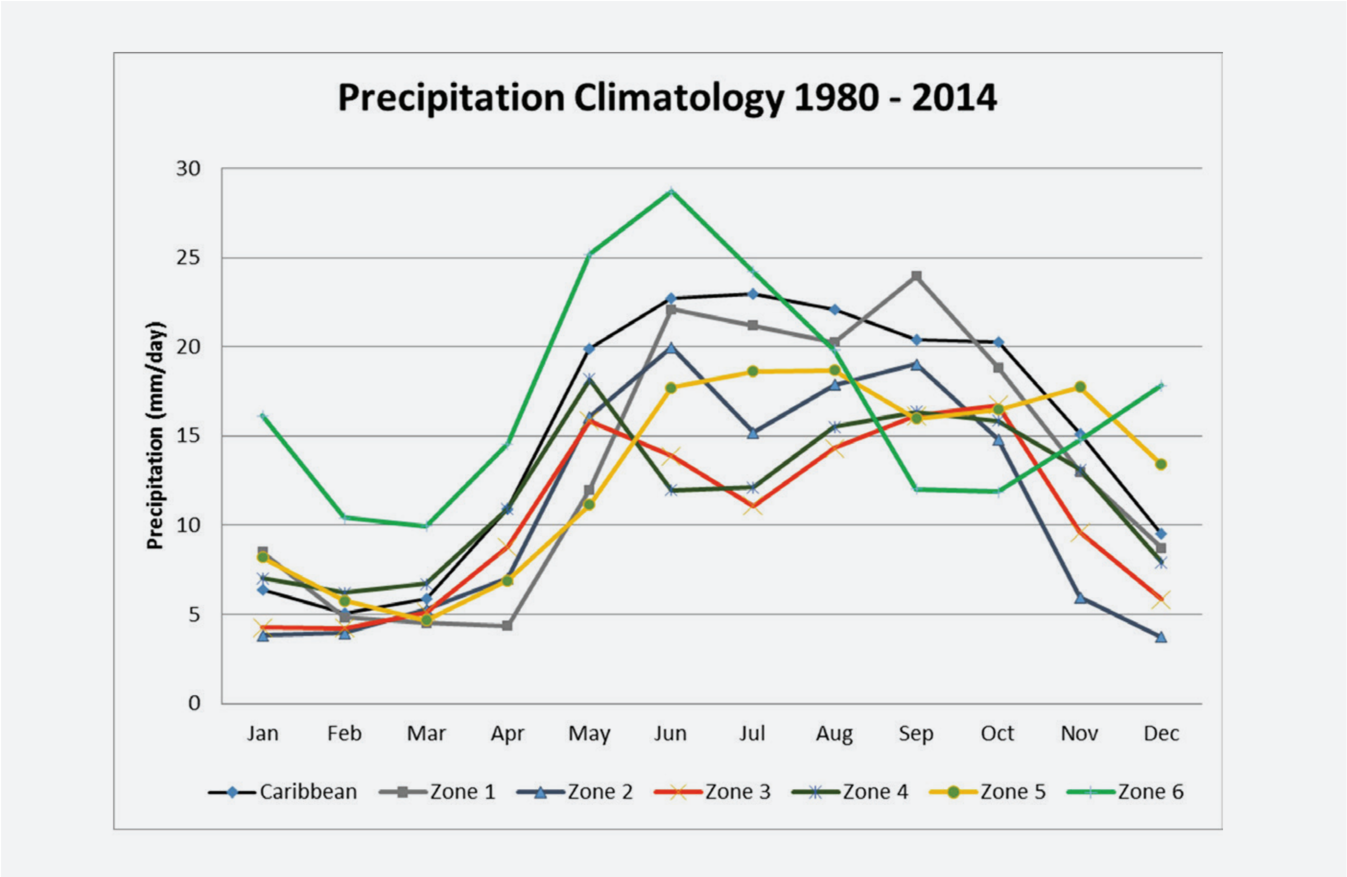


Figure 3.2: Climatological rainfall pattern (1980 to 2014) for the Caribbean and the six defined rainfall zones. Data source: UDel.

Table 3.2: Rainfall climatologies calculated from station data across selected Caribbean countries. Time periods used to calculate the means are indicated in column 3. Data source: CAROGEN.

		PRECIPITATION MONTHLY TOTAL CLIMATOLOGIES (MM)											
STATION	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ANGUILLA													
Metro	1993 to 2017	49	31	44	44	69	47	66	80	98	121	92	78
ANTIGUA AND BARBUDA													
VCB Airport	1971 to 2017	46	38	37	60	62	49	63	88	113	135	116	83
BARBADOS													
GA Airport	1979 to 2017	68	38	38	46	40	87	101	147	110	162	140	89
BELIZE													
Belmopan	1979 to 2017	118	53	39	26	74	227	245	282	254	220	190	130
BRITISH VIRGIN ISLANDS													
-	-	-	-	-	-	-	-	-	-	-	-	-	-

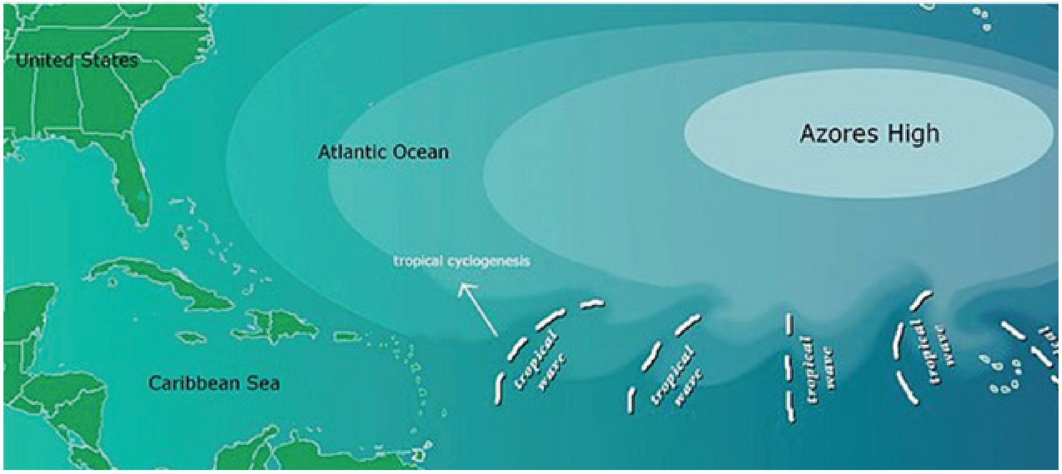
PRECIPITATION MONTHLY TOTAL CLIMATOLOGIES (MM)

STATION	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
CAYMAN ISLANDS													
Metro	1971 to 2017	36	29	27	21	107	126	113	141	193	183	110	62
DOMINICA													
Douglas-Charles	1971 to 2017	129	90	104	121	192	159	207	242	271	313	293	189
GRENADA													
Maurice Bishop	1986 to 2017	50	28	21	16	29	121	110	144	119	125	162	82
GUYANA													
Georgetown	1971 to 2017	164	81	80	127	293	297	272	161	87	75	143	237
HAITI													
Port-au-Prince	1971 to 2017	30	36	84	130	152	117	60	94	107	130	67	17
JAMAICA													
Norman Manley	1971 to 2017	10	12	22	26	47	46	25	37	18	95	62	19
MONTSERRAT													
-	-	-	-	-	-	-	-	-	-	-	-	-	-
ST KITTS AND NEVIS													
Metro	1972 to 2017	60	57	51	53	66	66	66	94	101	117	131	79
ST LUCIA													
Hewanorra Airport	1973 to 2017	72	49	48	48	56	98	145	165	157	159	165	99
ST VINCENT AND THE GRENADINES													
ET Joshua Airport	1979 to 2017	128	90	87	87	90	200	266	225	235	233	249	152
SURINAME													
Cultuurtuin	1971 to 2017	149	138	131	201	314	280	271	159	78	101	130	180
THE BAHAMAS													
Lynden Pindling	1971 to 2017	35	40	36	48	109	192	162	211	167	147	55	23
TRINIDAD AND TOBAGO													
Piarco Airport	1971 to 2017	65	41	28	32	87	245	238	255	190	216	209	157
TURKS AND CAICOS ISLANDS													
-	-	-	-	-	-	-	-	-	-	-	-	-	-

Box 3.1 provides a brief synthesis of some of the large-scale dynamical features that give rise to the mean Caribbean rainfall pattern.

INFORMATION BOX 3.1

WHAT DETERMINES WHEN THE CARIBBEAN IS WET AND DRY?



An interplay between a number of large-scale climatic features gives rise to the annual climatology of the Caribbean. For example, one of the important large-scale features that strongly modulates the Caribbean rainfall climatology is the semi-permanent subtropical anticyclone known as the North Atlantic Subtropical High (NASH) or Azores High. Variations in the intensity of the Azores High due to its annual northward trek during the warmer summer months significantly impact the strengths of the easterly trade winds as well as subsidence across the Caribbean region. The influence of the Azores High is strongest during the Caribbean dry season and again briefly during July/August (coincident with the mid-summer drought) generally bringing dry conditions. Variations in the NASH, then, roughly define the dry and wet seasons in the Caribbean.

A second important feature which helps define the rainfall seasons across the Caribbean is the Atlantic Warm Pool (AWP) (see Section 3.3.1). The AWP appears in boreal spring in the far northwestern Caribbean, thereafter expanding across the Caribbean Sea through to August-September before contracting and disappearing by the end of the year. The appearance, peak and disappearance of the AWP roughly coincide with diminishing influence of the NASH, thereby helping to define the Caribbean rainfall season. A third feature of importance is the Inter-Tropical Convergence Zone (ITCZ). Its two branches in the Atlantic and the Eastern Pacific ITCZ have a seasonal migration which lags the north-south movement of maximum solar radiation. At their northernmost and southernmost extents, the branches influence rainfall amounts, particularly in the southern and western Caribbean mainland territories. In general, the seasonal changes in the NASH, AWP and ITCZ broadly account for the rainfall climatology in the Caribbean through their influence on the strength of the trades, the warmth of the SSTs, and subsidence.

Other regional influences which modulate sub-regional patterns include: (i) the Caribbean Low-Level Jet (CLLJ) which strongly influences the mid-summer drought (MSD); (ii) African Easterly Waves which traverse the Atlantic Basin from mid-June to early October and account for more than half of all Atlantic hurricanes and major hurricanes; (iii) the passage of north American cold fronts over the Northern Caribbean, particularly during the Caribbean dry season; and (iv) localized mechanisms such as sea breezes due to strong easterly winds induced by the NASH, which together with orographic lifting result in rainfall on the leeward side of Caribbean islands and the Caribbean coast of Central America.

A number of studies provide an overview of the interplay of all the above mechanisms including Giannini et al. 2000; Taylor and Alfaro 2005; Wang and Lee 2007; Maldonado et al. 2018; and Martinez et al. 2019.

3.2.2. RAINFALL TIME SCALE DECOMPOSITION AND TRENDS

Figure 3.3 shows monthly rainfall amounts for the Caribbean region for the period 1900 - 2014. The figure depicts a slight downward trend in rainfall which is, however, not statistically significant. There is a significant decadal variability (groups of years which are wet versus groups of years that are dry e.g. the 1940s and 1950s versus the 1960s and 1970s respectively), as well as (and even more so) significant interannual (year-to-year) variability. These results mirror the findings of Jones et al. (2015), which also provide an extensive analysis of long-term trends in Caribbean rainfall. Jones et al. (2015) note that annual and decadal variability appear to be the dominating influences in the Caribbean rainfall time series.

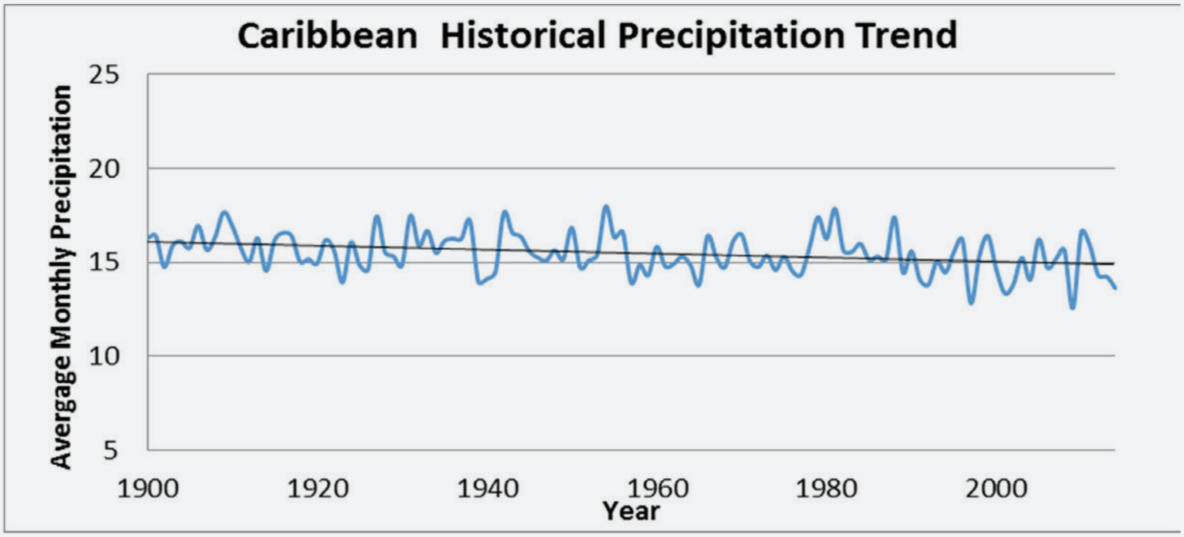


Figure 3.3: Historical Rainfall Trends (1900 to 2014) for the Caribbean. Source data: UDel.

Figure 3.4 shows the decomposition of the Caribbean region's rainfall anomaly time series for the twentieth century[7], that is, the rainfall record is broken down to show the relative contributions over time of the long term linear trend versus decadal and interannual variations. The figure shows the extracted patterns of variability and the statistics describing their relative contribution. Figure 3.4 confirms the previously noted conclusions about interannual and decadal variability being the dominant timescale of variability in the Caribbean rainfall record. The following are also noted:

» In the long term record, the Caribbean is not getting wetter or drier. The linear trend accounts for 0% in the observed variability and is not significant at the 5% significance level.

» Decadal variations account for 7% of the observed variability.

» Year-to-year (interannual) variations account for 91% of the observed rainfall pattern.

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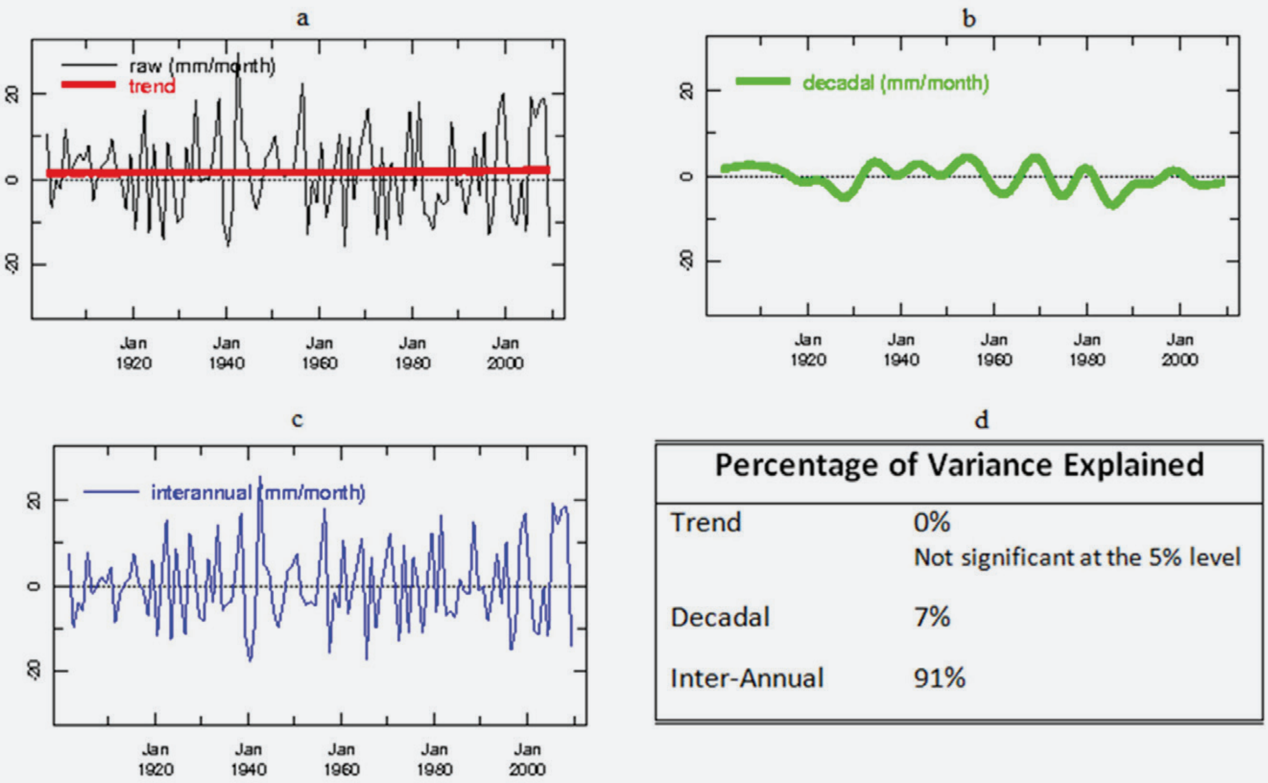
[7] The Figure was created using the IRI Climate and Society Map Room Tool available at http://iridl.ldeo.columbia.edu/maproom.



Percentage of Variance Explained	
Trend	0% Not significant at the 5% level
Decadal	7%
Inter-Annual	91%

Figure 3.4: Historical Rainfall Anomaly Time Scales Decomposition for the Caribbean as a whole. Images generated using IRI Climate and Society Map Room Tool. Source rainfall data: CRU.

Figure 3.5 presents similar plots to that of Figure 3.3, but for the six rainfall zones. Zones 1-4 show slight downward trends, while Zones 5 and 6 show no appreciable trend. For four of the six zones the linear trends were statistically not significant. As was also true for the Caribbean-wide index, the patterns for each zone show decadal and interannual variability as the dominant influences in the time series. When the decomposition of the time series for each zone is done (Table 3.3), it is noted that:

- Linear trends account for 0% to 7% of the variability across all zones and are insignificant at the 5% confidence level except for Zone 5.
- Decadal signals account for 7% to 16% of the variability.
- 64% to 91% of the rainfall patterns are as a result of inter-annual variations.

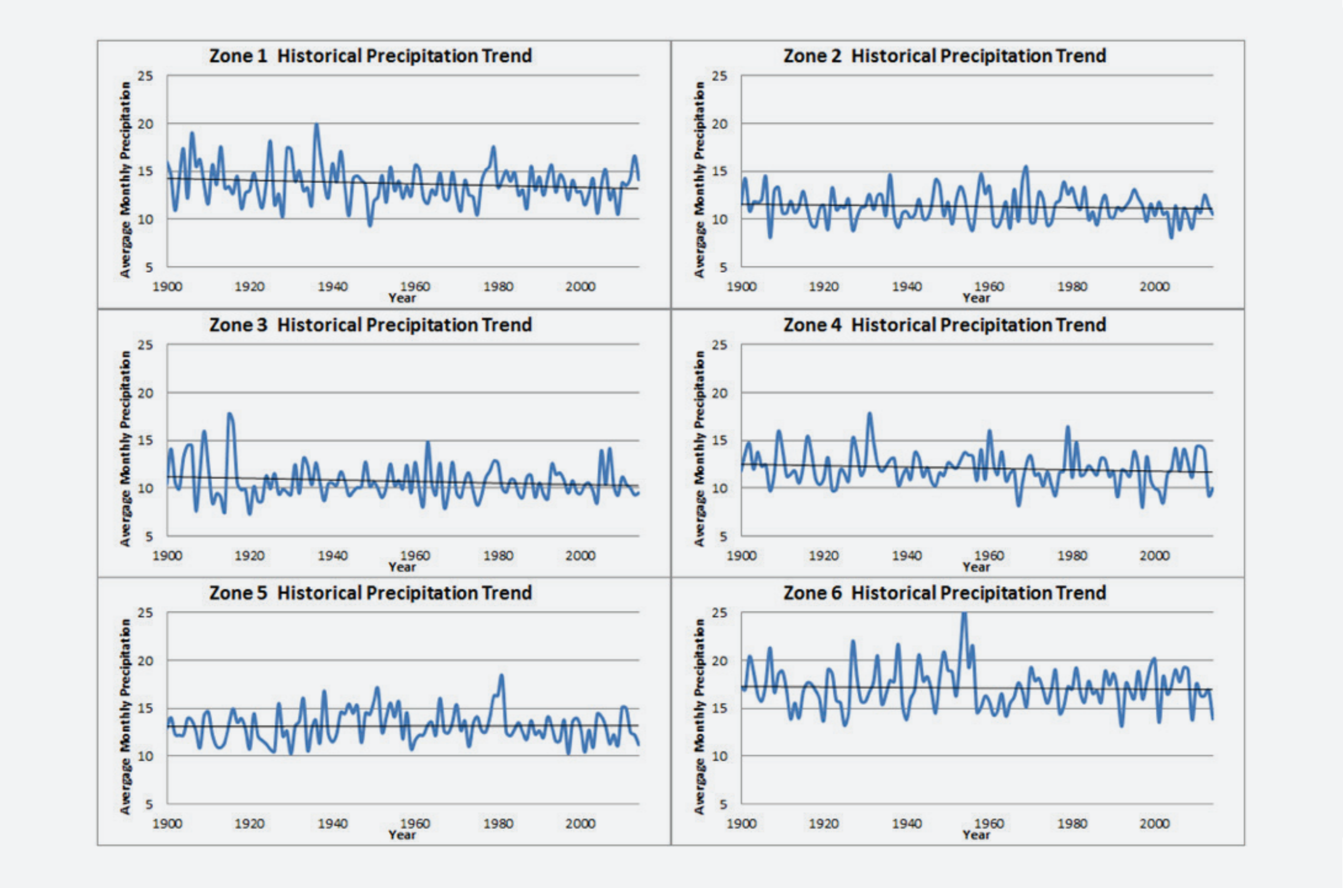


Figure 3.5: Historical Precipitation Trends (1900 to 2014) for the six defined rainfall zones.

Table 3.3: Precipitation Time Series Decomposition Numbers

REGION	PERCENTAGE OF PRECIPITATION VARIANCE EXPLAINED		
	TREND	DECADAL	INTER-ANNUAL
CARIBBEAN	0% Not significant at the 5% level	7%	91%
ZONE 1	0% Not significant at the 5% level	15%	83%
ZONE 2	1% Not significant at the 5% level	12%	81%
ZONE 3	1% Not significant at the 5% level	8%	82%
ZONE 4	0% Not significant at the 5% level	10%	80%
ZONE 5	**7%** **Significant at the 5% level**	16%	64%
ZONE 6	3% Not significant at the 5% level	10%	79%

3.2.3. RAINFALL EXTREMES AND TRENDS

Extreme indices are often used to provide more information about the mean climate of the region. Figure 3.6 gives the annual average for four common rainfall extreme indices derived for, and averaged over, the period 1980-2011: (i) Maximum Number of Consecutive Dry Days (CDD) (ii) Rainfall Amount on Very Wet Days i.e. when total rainfall exceeded the 95th percentile (R95p), (iii) Monthly Maximum One Day Rainfall Amount (RX1), and (iv) Monthly Maximum Consecutive Five Day Rainfall Amount (RX5). The plots are derived for the stations listed in Table 3.2.

Over the period under analysis, CDD fell in the range 10 to 32 days. Countries located in Zones 1 and 3 seem to exhibit largest CDD, with Belize Central Farm having the highest number of consecutive dry days. The southern Caribbean countries, those in Zone 6, had lowest CDD values. Zones 1 and 3 had the highest values for the extreme rainfall indices (i.e. RX1 and RX5). Melville Hall, Dominica recorded the highest values for the heavy rainfall indices i.e. R95p (864 mm), RX1 (152 mm) and RX5 (285 mm) and the lowest value for CDD (10 days).

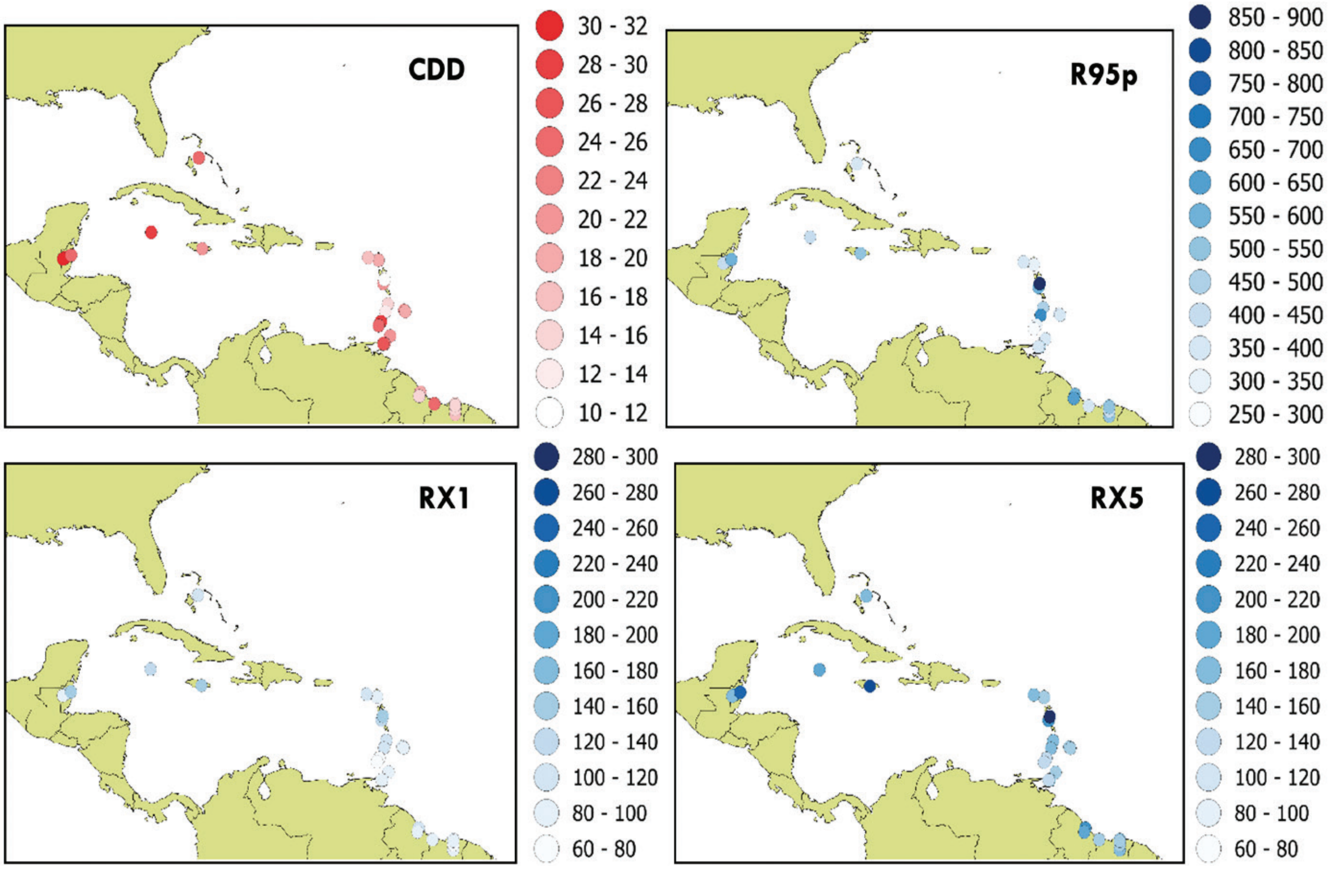


Figure 3.6: Top row: Maximum Number of Consecutive Dry Days (CDD) and Rainfall Amount for Very Wet Days (R95p). Bottom row: Monthly Maximum One Day Rainfall Amount and Monthly Maximum Consecutive Five Day Rainfall Amount (RX5) for the Caribbean region over the period 1980 to 2011. Units are days for CDD and mm for R95p, RX1 and RX5. Data source: CAROGEN.

Table 3.4 gives the slope estimates for the extreme rainfall indices over the period 1980 to 2011. The Caribbean on average showed an increasing trend for all four extreme rainfall indices i.e., the number of consecutive dry days between rainfall events are increasing, as well as the amount of rainfall that falls during rainfall events. When analysed by zones i.e. averaging the station values that fell in a zone, Zone 3 showed an increasing trend for all four extreme rainfall indices, while R95p was increasing for all zones. CDD increased for Zones 1, 3 and 5, however the increase was negligible. Zone 6 showed a decrease in CDD. None of the studied countries fell in Zones 2 and 4.

Table 3.4: Slope Estimates for Extreme Rainfall Indices (1980 to 2011)

REGION	CDD	R95P	RX1	RX5
CARIBBEAN	0.024	3.372	0.094	0.675
ZONE 1	0.073	0.224	-0.506	-0.309
ZONE 2	-	-	-	-
ZONE 3	0.070	5.467	0.583	3.073
ZONE 4	-	-	-	-
ZONE 5	0.075	1.537	0.016	-0.068
ZONE 6	-0.109	6.357	-0.066	-0.700

3.3. TEMPERATURE (SEA SURFACE & AIR)

In this section, sea surface temperature (SST) and near-surface air temperature plots are presented for the region. For SST, a bi-monthly spatial pattern is presented in addition to the spatial long-term trend. For air-temperature, the climatologies of the Caribbean region and the six defined rainfall zones are presented. The section also presents a decomposition of the historical time series of air-temperature as well as an examination of temperature extremes.

The SST dataset utilised is the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) SST V2 High Resolution dataset (Reynolds et al. 2002). The UDel dataset (Willmott et al. 2001) is utilised for air-temperature climatologies and time series trends, while time scale decomposition of the historical air-temperature data was done utilising the International Research Institute (IRI) Climate and Society Map Room Tool (Greene et al. 2011). As previously noted, the IRI tool utilises the Climate Research Unit (CRU) dataset ((Harris et al. 2014)). Station data for individual countries are obtained from the CAROGEN portal. (See again Chapter 2 for a description of all datasets.)

3.3.1. SEA SURFACE TEMPERATURE CLIMATOLOGY AND TRENDS

Figure 3.7 presents mean SST maps for the wider tropical Atlantic, including the Caribbean, for selected months. The appearance, expansion and decline of the Atlantic Warm Pool (AWP) and how it modulates Caribbean basin SSTs are evident in the plots. At the start of the year and during the northern hemisphere winter season, the Caribbean is relatively cool with SSTs of 27°C and below. SSTs gradually increase, with warmer waters first appearing in the western Caribbean (the Gulf of Mexico) and then spreading eastward, eventually reaching the tropical Atlantic coast of the African continent during the summer months. SSTs exceed 29°C across the Gulf of Mexico and the Caribbean basin during summer (peaking in August), with SSTs greater than 27.5°C extending through to the east Coast of Africa. The pattern reverses thereafter, as SSTs gradually cool and the AWP disappears by the onset of the winter months. It is, therefore, to be noted that warm waters greater than the 27.5°C convection threshold exist over much of the north tropical Atlantic during the summer and late rainfall season. This makes for extremely conducive conditions along the path traversed by tropical easterly waves and facilitate their development into tropical storms and hurricanes.

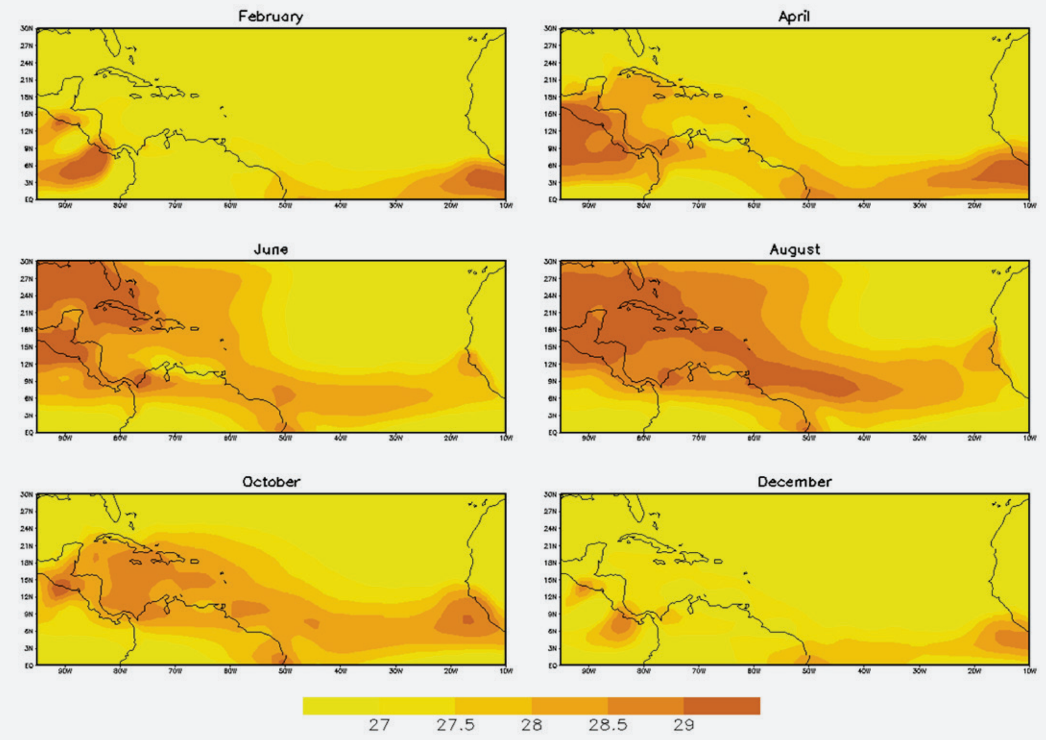


Figure 3.7: Climatology (1982 – 2016) of Sea Surface Temperature (SST) for the Caribbean region and Tropical North Atlantic (TNA). Dataset: NOAA-OI.

Figure 3.8 depicts average SST values for the Caribbean region as a whole and for each of the six defined rainfall zones. SST is coolest in December/January (winter) for all six defined zones, ranging from 25°C to 26.8°C, and warmest in July/August (summer) ranging from 28.6°C to 29.6°C. Except for Zone 2, all other zones and the Caribbean as a whole exhibit a highly correlated SST pattern. The difference shown by Zone 2 can be attributed to its far north location which accounts for a wider extent in its temperature range.

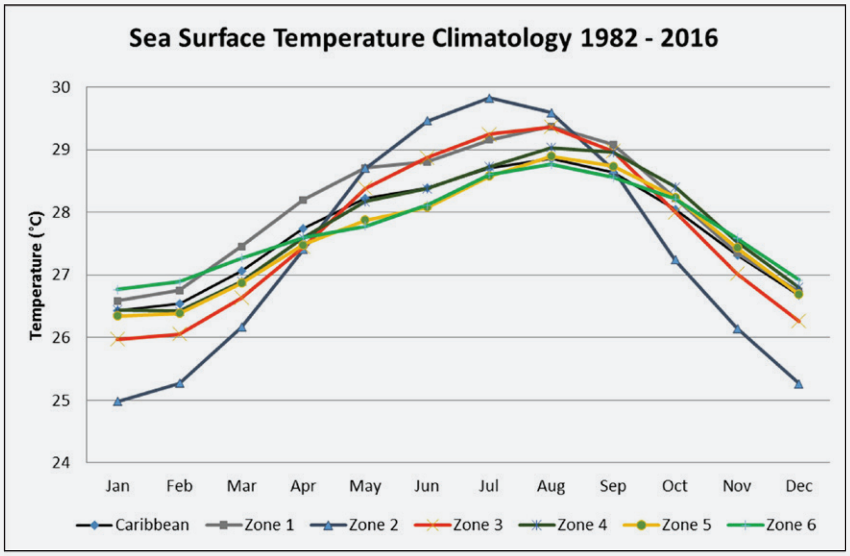


Figure 3.8: Climatology (1982 to 2016) Sea Surface Temperature (SST) for the Caribbean and the six defined rainfall zones. Dataset: NOAA-OI.

Figure 3.9 presents the trend in SSTs for the Caribbean region and surrounding area. Over the period 1982-2016, it shows that SSTs have warmed at a rate of between 0.01°C and 0.04°C annually. Higher rates of warming can be observed in the Gulf of Mexico and the eastern Caribbean extending into the eastern tropical Atlantic. Cooling is only observed in the far northern edge of the domain, in the vicinity of Florida.

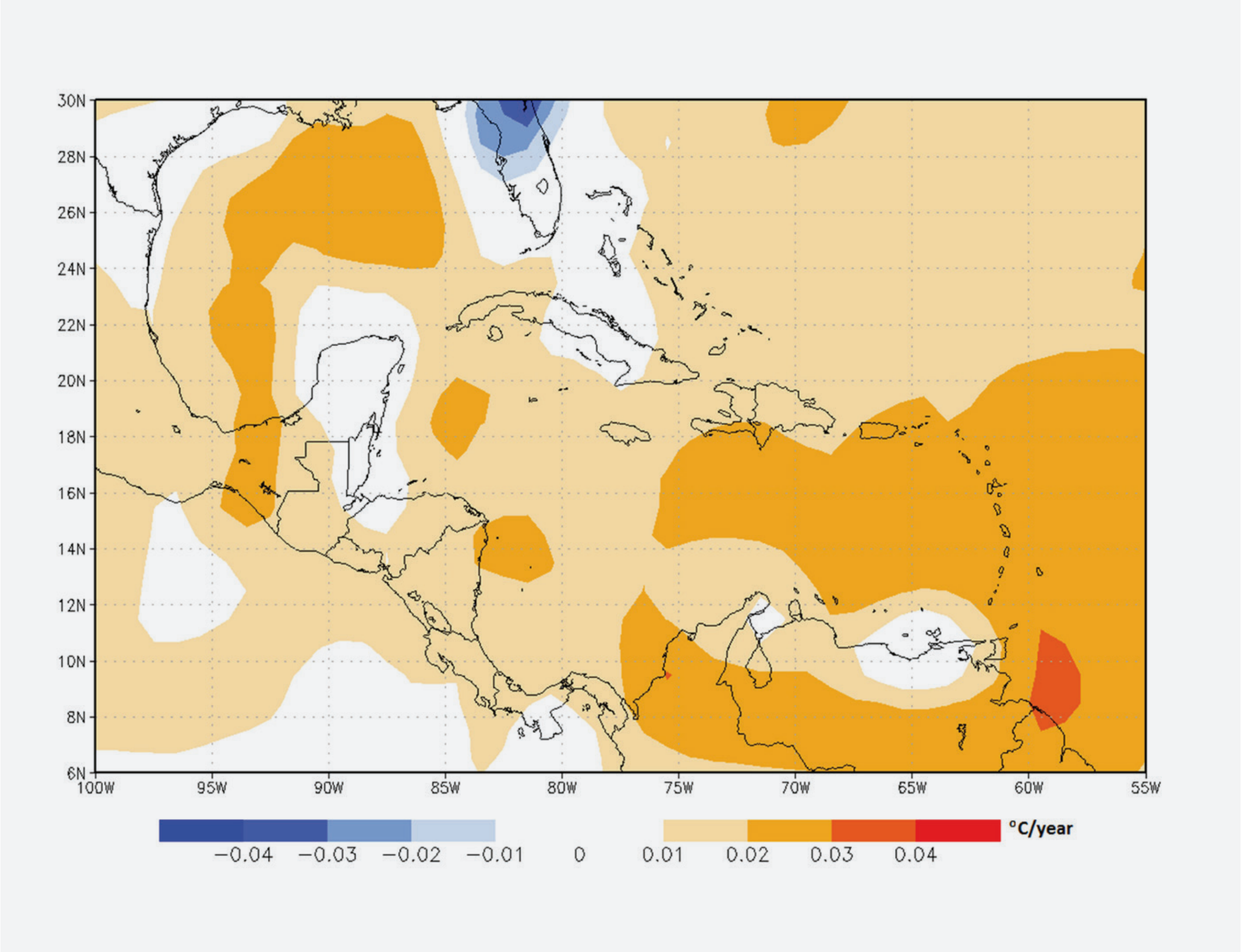


Figure 3.9: Map showing sea surface temperature trends within the Caribbean and surrounding regions over the period 1982 to 2016.

3.3.2. AIR TEMPERATURE CLIMATOLOGY

Figure 3.10 presents the climatologies of air temperature for the Caribbean and the six defined zones. It shows that the average monthly air-temperature in the region generally ranges from approximately 22°C to 28°C throughout the course of the year. Coolest temperatures occur during the winter months for the Caribbean as a whole and across the region, while warmest temperatures generally occur in the summer months, peaking in August. Zones 1 and 6, however, have temperatures peaking in May and September respectively, likely reflecting the respective influences of the Pacific and Atlantic ITCZ. The south-eastern Caribbean (Zone 6), experience slightly lower temperatures than the western Caribbean (Zones 1 to 3).

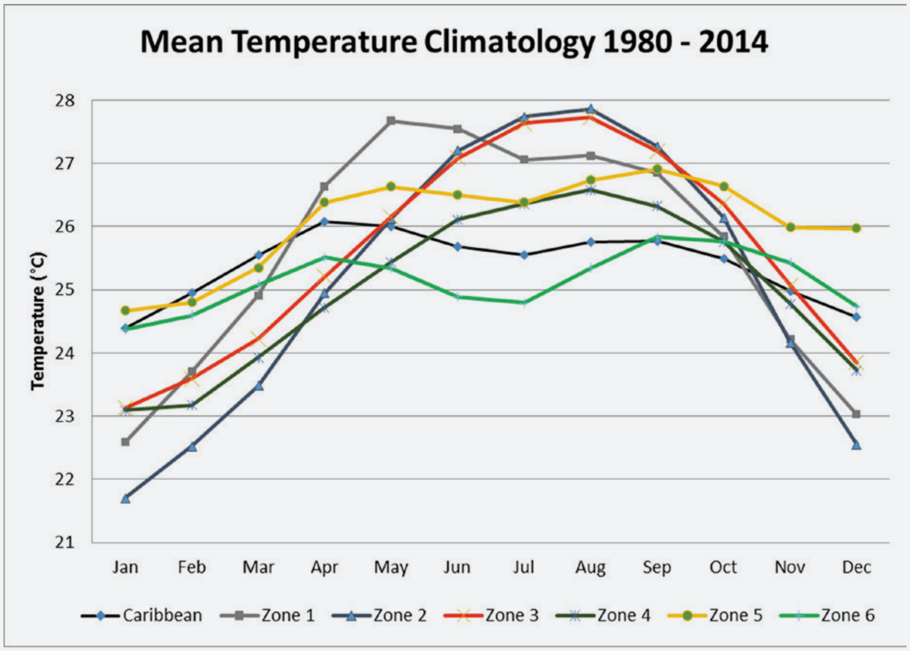


Figure 3.10: Climatological air temperature pattern (1980 to 2014) for the Caribbean as a whole and its six defined rainfall zones.

Table 3.5 presents air-temperature climatologies for individual countries. As noted for the rainfall, the temperature climatologies calculated using the station data mirror the patterns for the zones in which the stations fall.

Table 3.5: Temperature climatologies calculated from station data across selected Caribbean countries. Time periods used to calculate the means are indicated in column 3. Data source: CAROGEN.

		PRECIPITATION MONTHLY TOTAL CLIMATOLOGIES (MM)											
STATION	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ANGUILLA													
-	-	-	-	-	-	-	-	-	-	-	-	-	-
ANTIGUA AND BARBUDA													
VCB Airport	1971 to 2017	25.3	25.3	25.6	26.3	27.0	27.8	28.0	28.2	28.0	27.4	26.7	25.8
BARBADOS													
GA Airport	1979 to 2017	25.8	25.9	26.1	26.8	27.6	27.7	27.7	27.9	27.8	27.5	27.2	26.5
BELIZE													
Belmopan	1979 to 2017	23.6	24.1	25.1	27.0	28.3	28.1	27.5	27.6	27.6	26.5	24.8	23.8
BRITISH VIRGIN ISLANDS													
-	-	-	-	-	-	-	-	-	-	-	-	-	-
CAYMAN ISLANDS													
Metro	1971 to 2017	25.6	25.5	26.1	27.4	28.1	28.9	29.3	29.3	29.0	28.1	27.3	26.2
DOMINICA													
Douglas-Charles	1981 to 2017	25.4	25.1	25.2	26.1	26.9	27.7	27.7	27.8	27.6	27.2	26.5	25.8
GRENADA													

		PRECIPITATION MONTHLY TOTAL CLIMATOLOGIES (MM)											
STATION	PERIOD	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Maurice Bishop	1985 to 2017	26.4	26.5	26.9	27.6	28.1	27.8	27.6	27.9	28.2	27.9	27.5	27.0
GUYANA													
Georgetown	1971 to 2017	26.4	26.7	26.9	27.2	27.1	26.9	26.9	27.3	27.9	28.0	27.6	26.7
HAITI													
Port-au-Prince	2000 to 2017	26.7	27.0	27.4	28.3	28.8	30.6	30.8	30.6	29.6	29.2	28.2	27.5
JAMAICA													
Sangster Airport	1973 to 2017	25.7	25.5	26.3	27.1	27.5	28.2	28.7	28.8	28.3	27.9	27.1	26.1
MONTSERRAT													
-	-	-	-	-	-	-	-	-	-	-	-	-	-
ST KITTS AND NEVIS													
Nat-Agric-Station	1972 to 2015	25.6	25.4	25.9	26.6	27.3	28.1	28.3	28.5	28.3	27.9	27.1	26.2
ST LUCIA													
Hewanorra Airport	1979 to 2017	26.4	26.3	26.8	27.4	28.2	28.2	28.2	28.3	28.3	28.1	27.7	27.5
ST VINCENT AND THE GRENADINES													
ET Joshua Airport	1979 to 2017	25.6	25.6	25.9	26.8	27.4	27.4	27.4	27.5	27.7	27.4	27.0	26.4
SURINAME													
Cultuurtuin	1971 to 2017	26.7	26.7	27.1	27.3	27.1	27.2	27.4	28.0	28.4	28.4	27.8	26.9
THE BAHAMAS													
Lynden Pindling	1971 to 2017	20.4	20.9	21.1	23.6	25.3	26.9	27.5	27.6	27.4	25.9	23.3	21.3
TRINIDAD AND TOBAGO													
Piarco Airport	1971 to 2017	25.4	25.6	26.2	27.0	27.3	26.9	26.8	26.9	27.0	26.8	26.4	25.8
TURKS AND CAICOS ISLANDS													
-	-	-	-	-	-	-	-	-	-	-	-	-	-

3.3.3. AIR-TEMPERATURE TIME SCALE DECOMPOSITION AND TRENDS

Figure 3.11 gives a plot of the historical (1900 to 2014) air-temperature for the Caribbean region. It shows a strong linear trend of approximately 0.09oC/decade which is statistically significant. This is in contrast to the Caribbean rainfall record (see again Section 3.2). The strong linear trend in the Caribbean temperature record is consistent with other studies which have similarly noted a dominant linear trend in the temperature records of the region (see for example Jones et al. 2014; Stephenson et al. 2012). The increase is also consistent with the global warming trend recorded over the past century (IPCC 2018). Stephenson et al. (2014) also show an increase in the Caribbean average day time (nighttime) temperature of approximately 0.19 °C/decade (0.28°C/decade) over the period 1960-2010. The difference between the rates of increase of day versus nighttime temperatures further suggests a decrease in the diurnal temperature range. Figure 3.11 also illustrates the annual and decadal variability evident in the Caribbean historical temperature record.

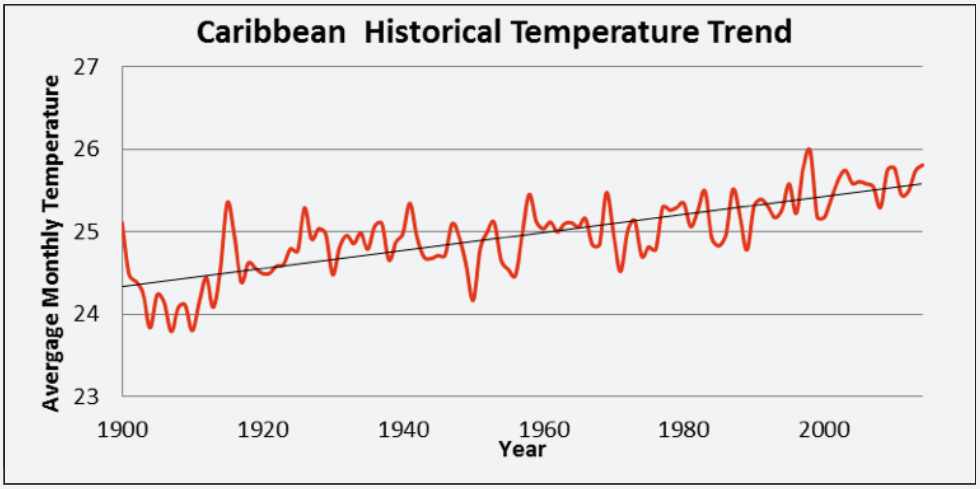
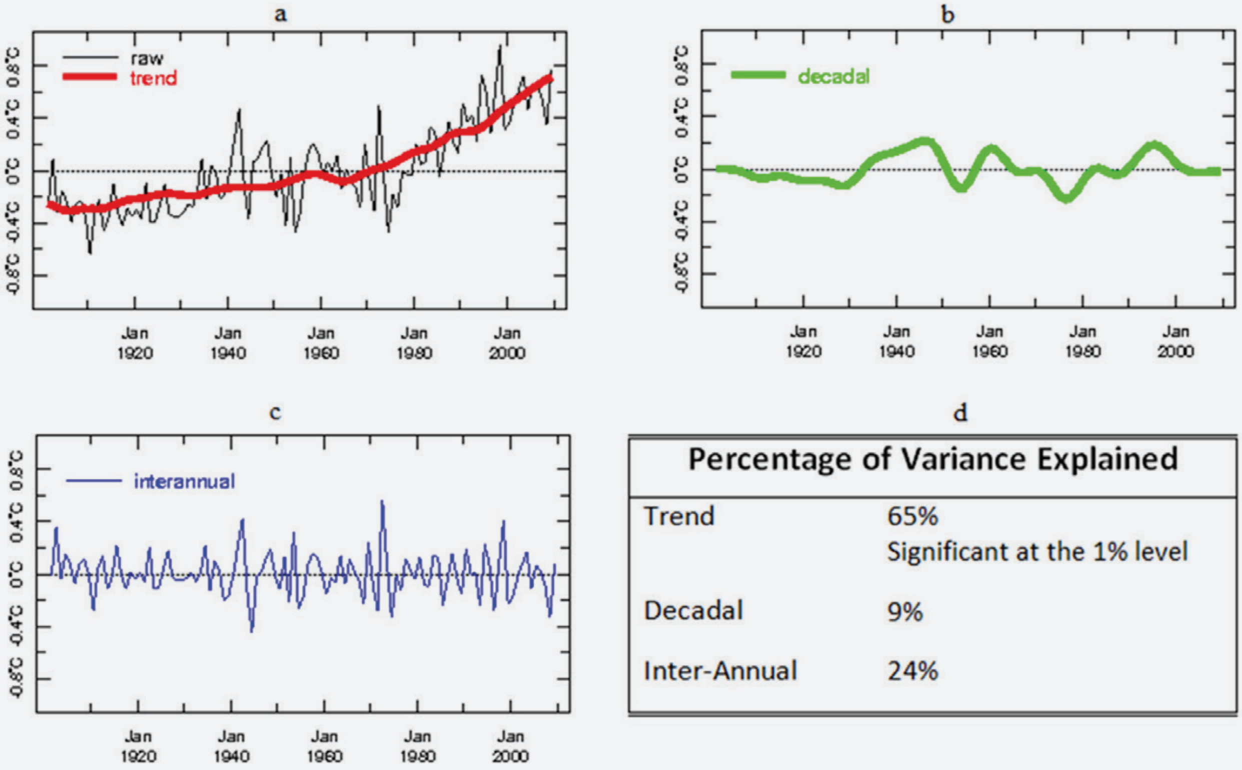


Figure 3.11: Historical Temperature (°C) Trends (1900 to 2014) for the Caribbean as a whole. Data Source: CRU.

Similar to Figure 3.4, Figure 3.12 shows a decomposition of the Caribbean region's air-temperature anomaly time series for the twentieth century. The linear trend accounts for 65% in the observed change in temperature and is significant at the 1% significance level. In comparison, the decadal signal accounts for 9%, while interannual variations account for 24% of the observed signal's pattern.



Percentage of Variance Explained	
Trend	65% Significant at the 1% level
Decadal	9%
Inter-Annual	24%

Figure 3.12: Historical Temperature Time Scales for the Caribbean. Images generated using IRI Maproom (https://iridl.ldeo.columbia.edu/maproom/Global/Time_Scales/). Data Source: CRU.

Figure 3.13 presents a similar plot to Figure 3.11, but for the historical air-temperature of the region's six defined rainfall zones. All except Zone 2 display a significant upward linear trend, along with annual and decadal variability. Table 3.6 presents the numerical values for the decomposed time series. The following things are noted:

- Linear trends accounts for 17% to 65% of the variability and are all significant at the 1% confidence
- Decadal signals account for 9% to 22% of the variability.
- 22% to 56% of the signals pattern is as a result of inter-annual variations.

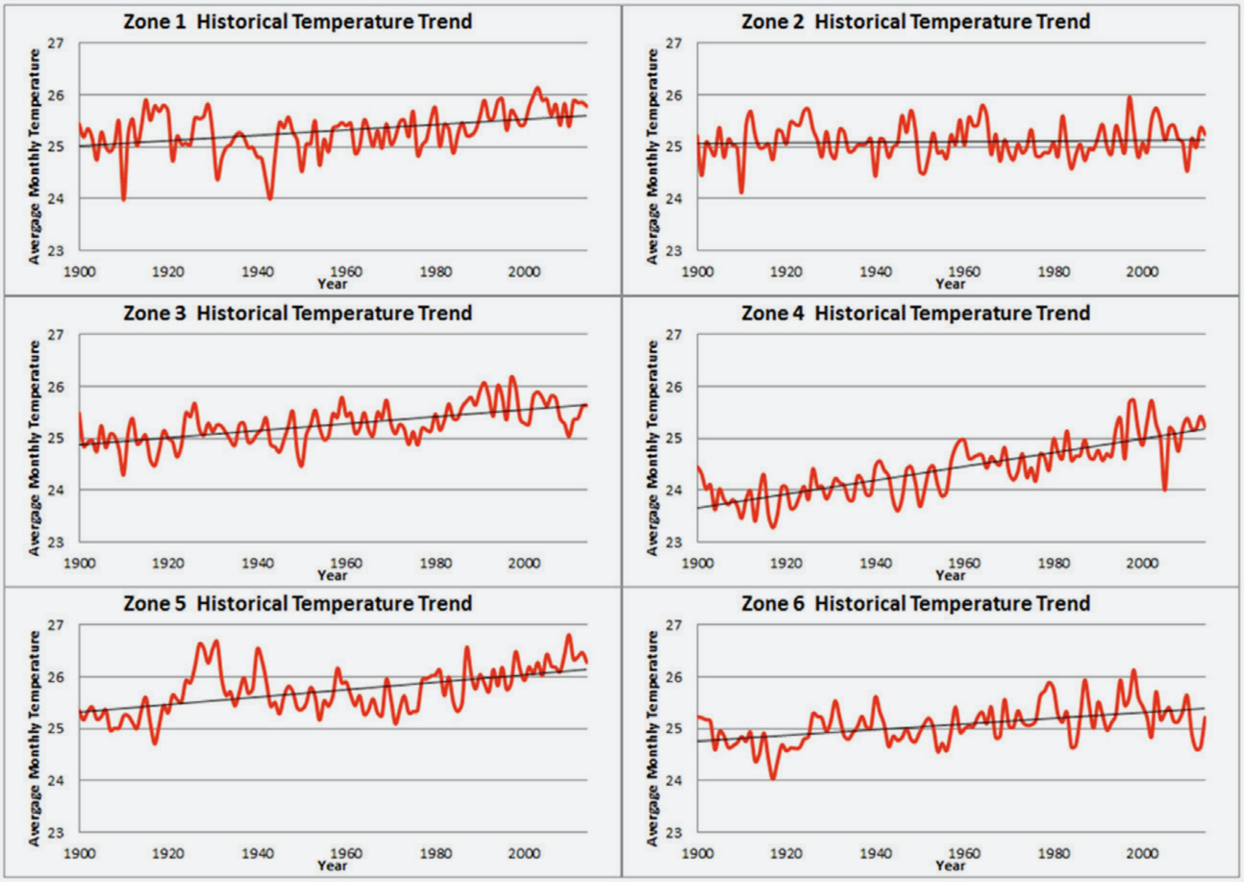


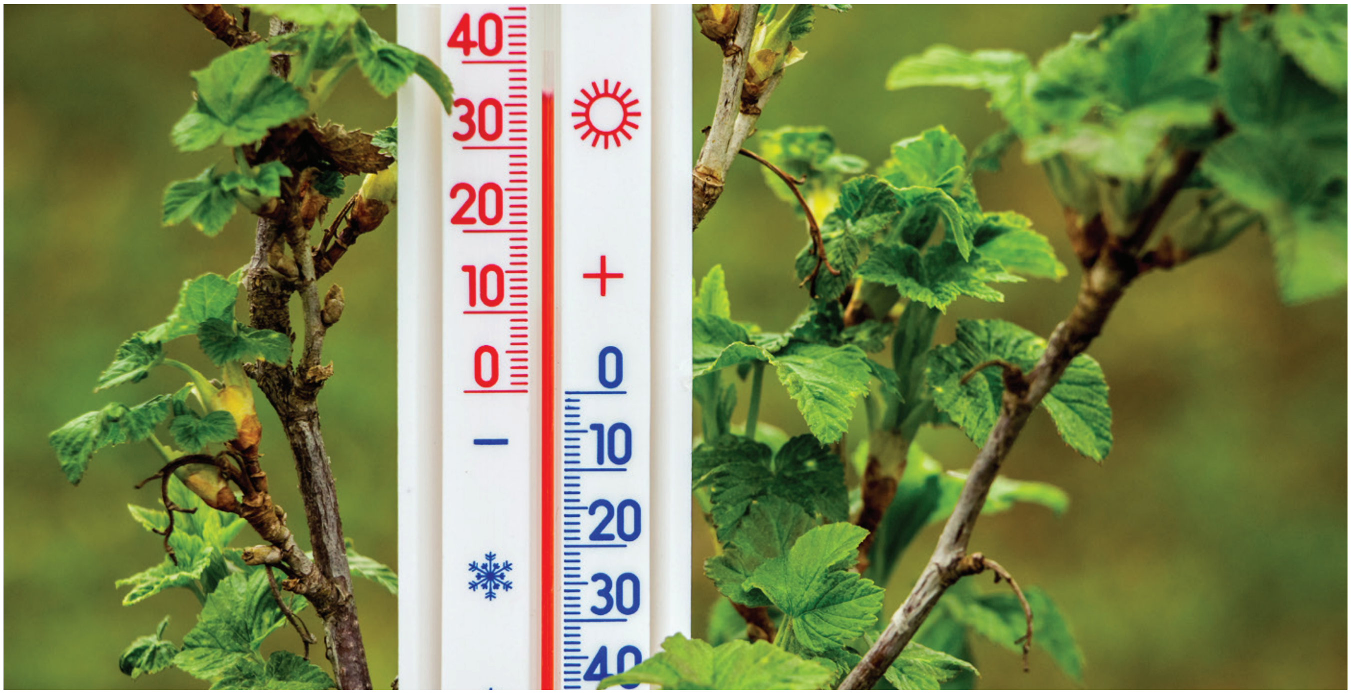
Figure 3.13: Historical Air-Temperature Trends (1900 to 2014) for the Caribbean six rainfall zones.

Table 3.6: Air-Temperature Time Series Decomposition Numbers

REGION	PERCENTAGE OF TEMPERATURE VARIANCE EXPLAINED		
	TREND	DECADAL	INTER-ANNUAL
CARIBBEAN	65% Significant at the 1% level	9%	24%
ZONE 1	38% Significant at the 1% level	18%	41%
ZONE 2	17% Significant at the 1% level	18%	56%
ZONE 3	45% Significant at the 1% level	12%	37%
ZONE 4	46% Significant at the 1% level	16%	33%
ZONE 5	62% Significant at the 1% level	12%	22%
ZONE 6	20% Significant at the 1% level	22%	48%

3.3.4. AIR TEMPERATURE EXTREMES AND TRENDS

Finally, Figure 3.14 depicts in the top row, the mean number of warm days and warm nights in a year, while the bottom row shows the mean number of cool days and cool nights. Averaging is done for the period 1980 to 2011. The average number of warm days (nights) across the region varies between 10 and 55 (22 and 53) days for the stations analysed. Cultuurtuin in Suriname showed the highest average number of warm days in a year while Grenada's Point Salines showed the least. Belmopan, Belize showed the highest number of warm nights while Lelydorp, Suriname has the least. With respect to the number of cool days (nights) the range is between 10 and 37 (18 and 36) days per year.



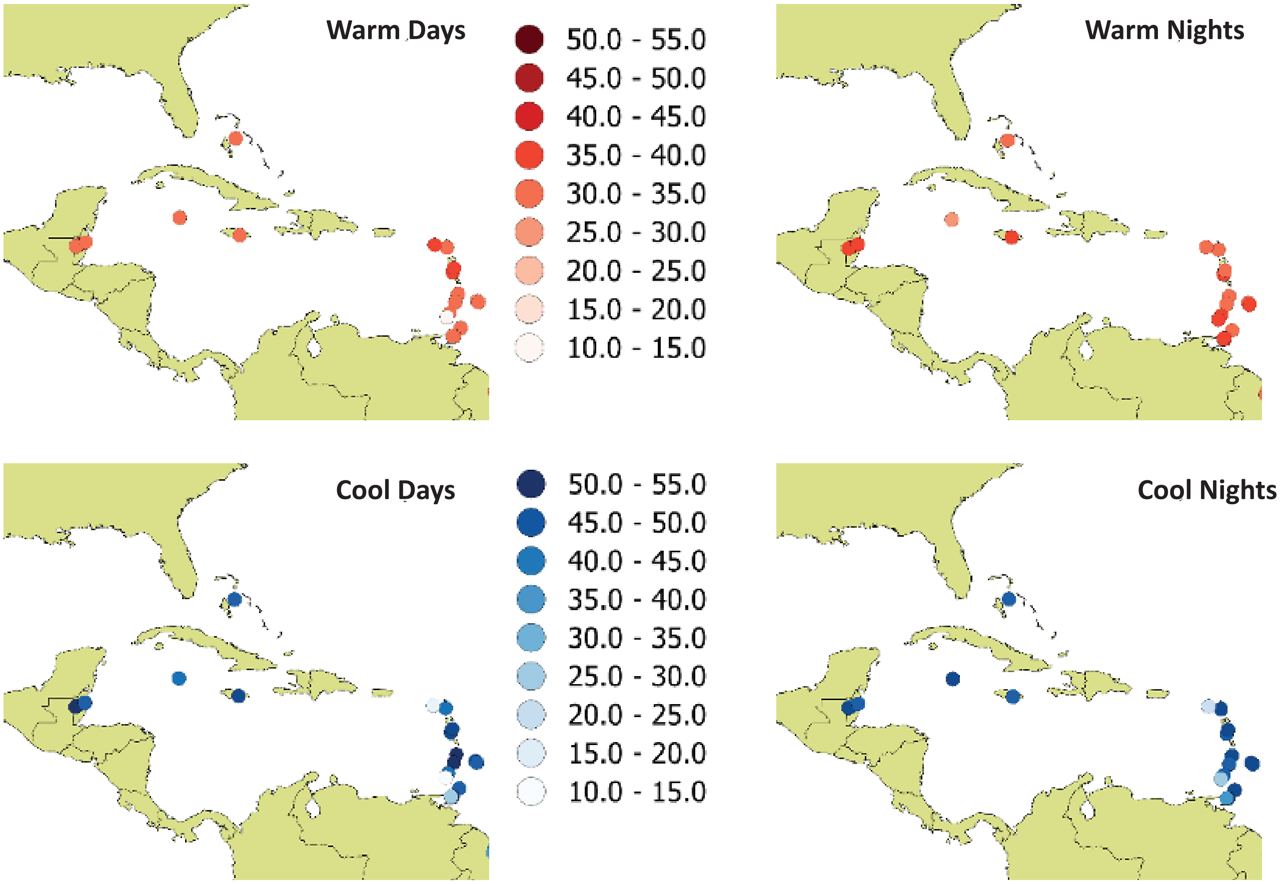


Figure 3.14: Top row: Warm Days and Warm Nights. Bottom row: Cool Days and Cool Nights for the Caribbean region over the period 1980 to 2011. Units are days. Data Source: CAROGEN.

Table 3.7 shows the linear trend for the extreme temperature indices. As for rainfall, data for stations in a zone are averaged. There is an increasing trend in very warm days and nights for the Caribbean as a whole (an increase of approximately 34 more days over the period) and across all zones. There is also a decreasing trend in cool days and nights for the Caribbean and across all zones except for Zone 1 which showed a negligible increase for cool days. These results are consistent with Stephenson et al. (2014). The greatest increase for warm days and warm nights was observed for Zone 5 and Zone 1 respectively. For cool days and cool nights, the greatest decrease over the period 1980 to 2011 was for Zone 5.

Table 3.7: Slope Estimates for Extreme Temperature Indices (1980 to 2011)

	WARM DAYS	WARM NIGHTS	COOL DAYS	COOL NIGHTS
CARIBBEAN	1.133	0.839	-0.357	-0.519
ZONE 1	0.520	1.357	0.006	-0.049
ZONE 2	-	-	-	-
ZONE 3	1.324	0.599	-0.436	-0.072
ZONE 4	-	-	-	-
ZONE 5	1.508	1.041	-0.727	-0.979
ZONE 6	0.896	0.624	-0.231	-0.941


DO NOT
ENTER

4. SEA LEVEL RISE, DROUGHTS & FLOODS, HURRICANES

4.1. INTRODUCTION

In this chapter, historical trends in sea level, as well as trends in the occurrence of floods, droughts and hurricanes are examined. In general, the climatology of each variable is examined first, followed by a summary of what is known about historical trends. For floods, use is made of the EM-DAT database (The Emergency Events Database) (Guha-Sapir et al. 2015). As opposed to examinations of trends and variability in Caribbean temperature and rainfall records, there is far less research done on sea level rise, droughts, floods and hurricanes for the Caribbean region as a whole.

4.2. SEA LEVEL RISE

4.2.1. HISTORICAL TRENDS

Globally, sea levels rose at a rate of 1.7 ± 0.2 mm/year through the 20th century according to tide gauge records (IPCC 2013). This rate of increase for the 20th century was the fastest increase in sea level for the previous 28 centuries (Robert E. Kopp et al. 2016). Table 4.1, however, shows that this sea level rise is modest in comparison to the 3.2 ± 0.4mm/year which was recorded by satellite altimeters during the end of the 20th century and the early 21st century. This suggests an acceleration in global sea level rise, which is projected to continue with increased global warming (Church & White 2006). More recently, Yi et al. (2015) have observed that this rate has increased to 4.5 ± 0.4 mm/year for regions during the period 2010-2014.

Table 4.1: Mean rate of global averaged sea level rise

PERIOD	RATE (MM/YEAR)		INFORMATION SOURCE
1901 AND 2010	1.7 ± 0.2	Tide gauge	IPCC (2013)
1993 AND 2010	3.2 ± 0.4	Satellite Altimeter	IPCC (2013)

Studies on historical Caribbean sea level trends are limited in comparison to similar studies showing trends in atmospheric variables. This is due in part to the absence of very long records. The existing studies however suggest that, in the mean, Caribbean sea level trends are very similar to the global trends.

Table 4.2 shows mean Caribbean sea level trends estimated from tide gauge records and satellite altimetry. Palanisamy et al. (2012) calculates the mean Caribbean sea level rise rate to be 1.8 ± 0.1 mm/year for the period 1950 – 2009. Torres and Tsimplis (2013) determine the rate to be 1.7 ± 1.3 mm/year over the period 1993-2010. These rates are similar to the global rate of 1.7 ± 0.2 mm/year which was shown in Table 4.1. When the mean Caribbean sea level trend measured by satellite altimetry is corrected for Global Isostatic Adjustment, it is estimated to be approximately 2.5 ± 0.4 mm/year (Torres and Tsimplis 2013).

Table 4.2: Mean rate of sea level rise averaged over the Caribbean basin.

PERIOD	RATE (MM/YEAR)	INFORMATION SOURCE
1950 - 2009	1.8 ± 0.1	Palanisamy et al. (2012)
1993 - 2010	1.7 ± 1.3	Torres and Tsimplis (2013)
1993 - 2010	2.5± 1.3	Torres and Tsimplis (2013), after correction for Global Isostatic Adjustment (GIA)

The examined historical records also indicate that there is regional variation in the rate of sea level rise i.e. it is not uniform across the Caribbean. Figure 4.1 and Table 4.3 illustrate this. Figure 4.3 shows sea level trends for different tide gauge stations around the Caribbean region. The inconsistencies in record lengths across the region are noted. Table 4.3 gives the calculated trend for each station. Both the figure and the table are adapted from Torres and Tsimplis (2013).

Notwithstanding the station examined, there is a general increasing trend in the sea level of the Caribbean region i.e. there are no negative trends. The sea level rise varies from 0.26 mm/year off the coast of Venezuela, to as high as 10.76 mm/year for the Port-au-Prince, Haiti station. Figure 4.2 shows a map of how these rates differ across the region. The map is constructed using the Mean Reconstruction sea level (MRESL) dataset. Tide gauge records are a major data component used to develop the MRESL. However other components such as post glacial rebound and tectonics are also taken into account. The variation in sea level rise rates across the region is evident in the plot with largest increasing trends found in the southern Caribbean close to the South American continent.

The mean sea level of the Caribbean region also varies on decadal and interannual time scales. The interannual variations are evident in the time series plots of Figure 4.1. Caribbean sea level is highly correlated with El Niño-Southern Oscillation (ENSO) especially since the mid-1980s, with larger increases in sea levels occurring during stronger El Niño events (Palanisamy et. al. 2012; Torres et al. 2013; Torres and Tsimplis 2014; Blunden et al. 2016). This may have led to sea levels reaching as high as 11.3 cm above mean sea level during the 2015 El Niño event. Recent studies also show a significant correlation between the interannual variability in sea level and hurricane activity (Torres and Tsimplis 2014). This is especially true for the post 2000 period, during which hurricane intensity and sea level interannual variability have both increased.

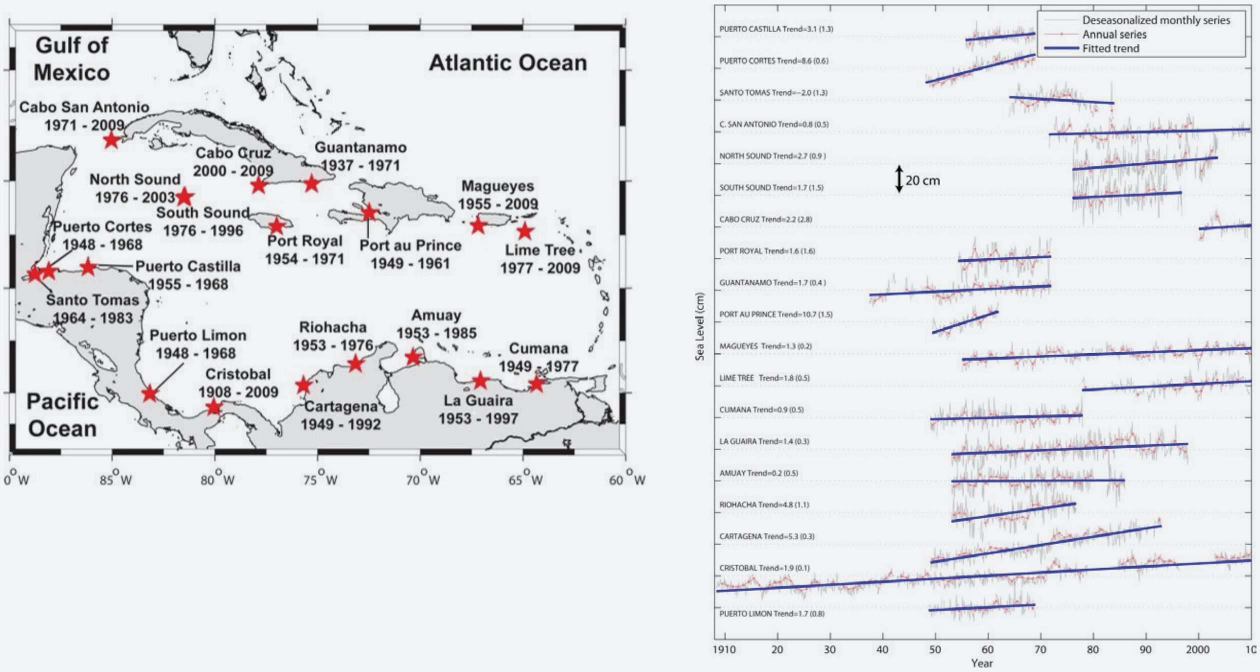


Figure 4.1: a) Location of tide gauge stations and time series start and end year. b) Tide gauge observed sea-level trends computed from all available data. Monthly time series after the removal of the seasonal cycle (gray), the linear trend (blue), and the annual series (red) are also shown. The trends (and 95% error) in mm/yr. From Torres and Tsimplis (2013).

Table 4.3: Tide gauge observed sea-level trends for Caribbean stations shown in Figure 4.1. Table adapted from Torres & Tsimplis (2013)

	Country	Lat (N)	Lon (W)	Span years	% of data	Trend (mm/ year)	Months	Gauge corrected
P. LIMON	Costa Rica	10	83	20.3	95.1	1.76±0.8	216	2.16±0.9
CRISTOBAL	Panama	9.35	79.9	101.7	86.9	1.96±0.1	566	2.86±0.2
CARTAGENA	Colombia	10.4	75.6	44	90	5.36±0.3	463	5.46±0.3
RIOHACHA	Colombia	11.6	72.9	23.8	95.8	4.86±1.1	273	4.86±1.1
AMUAY	Venezuela	11.8	70.2	33	93.4	0.26±0.5	370	0.26±0.5
LA GUAIRA	Venezuela	10.6	66.9	45	98.9	1.46±0.3	534	1.56±0.3
CUMANA	Venezuela	10.5	64.2	29	98.6	0.96±0.5	331	0.76±0.6
LIME TREE	US Virgin Islands	17.7	64.8	32.2	81.9	1.86±0.5	316	1.56±0.5
MAGUEYES	Puerto Rico	18	67.1	55	96.2	1.36±0.2	635	1.06±0.2
P. PRINCE	Haiti	18.6	72.3	12.7	100	10.76±1.5	144	12.26±1.5
GUANTANAMO	Cuba	19.9	75.2	34.6	89.9	1.76±0.4	258	2.56±0.6
PORT ROYAL	Jamaica	17.9	76.8	17.8	99.5	1.66±1.6	212	1.36±1.6
CABO CRUZ	Cuba	19.8	77.7	10	90	2.26±2.8	108	2.16±2.8
SOUTH SOUND	Cayman	19.3	81.4	20.8	87.6	1.76±1.5	219	1.26±1.5
NORTH SOUND	Cayman	19.3	81.3	27.7	89.2	2.76±0.9	296	2.26±0.9
C. SAN ANTONIO	Cuba	21.9	84.9	38.3	76.7	0.86±0.5	353	0.36±0.5
SANTO TOMAS	Mexico	15.7	88.6	20	85.4	2.06±1.3	205	1.76±1.3
P. CORTES	Honduras	15.8	87.9	20.9	98	8.66±0.6	224	8.86±0.7
P. CASTILLA	Honduras	16	86	13.3	100	3.16±1.3	160	3.26±1.3

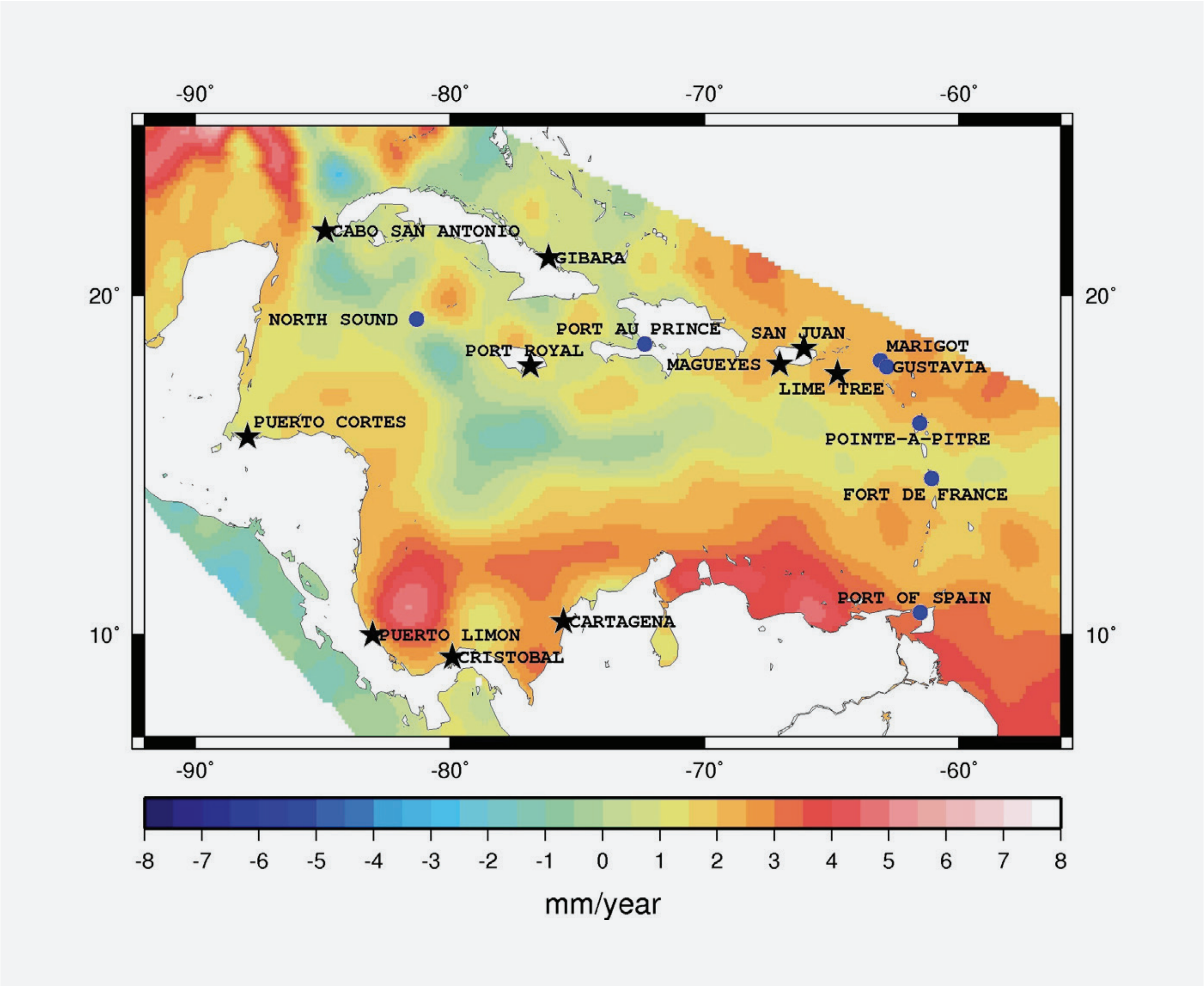


Figure 4.2: Mean Reconstruction Sea Level (MRESL) from 1950- 2009. Figure Source: Palanisamy et al. (2012).

4.3. HURRICANES

4.3.1. CLIMATOLOGY

The hurricane season in the North Atlantic spans June to November. This coincides with the period when the Gulf of Mexico, the Caribbean Sea, and the north tropical Atlantic are most conducive to convective activity. During this time of the year, the region is characterised by weak easterly trade winds, decreased vertical wind shear, and SSTs in excess of 26oC (see again Box 3.1). In tandem, these create ideal conditions for tropical cyclone (TC) activity.

The climatology of hurricanes and tropical storms in the tropical Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico is shown in Figure 4.3. It is to be noted that although storms and hurricanes generally occur between June 1 and November 30 (i.e. the official hurricane season), it does not preclude storm or hurricane activity in May or December. The peak of the North Atlantic season is from mid-August to late October, with a primary peak around September 10th. A secondary peak occurs around the middle of October, which is mainly for the Caribbean Sea and the Gulf of Mexico region, after which the number of storms drops off quickly through the end of the season.

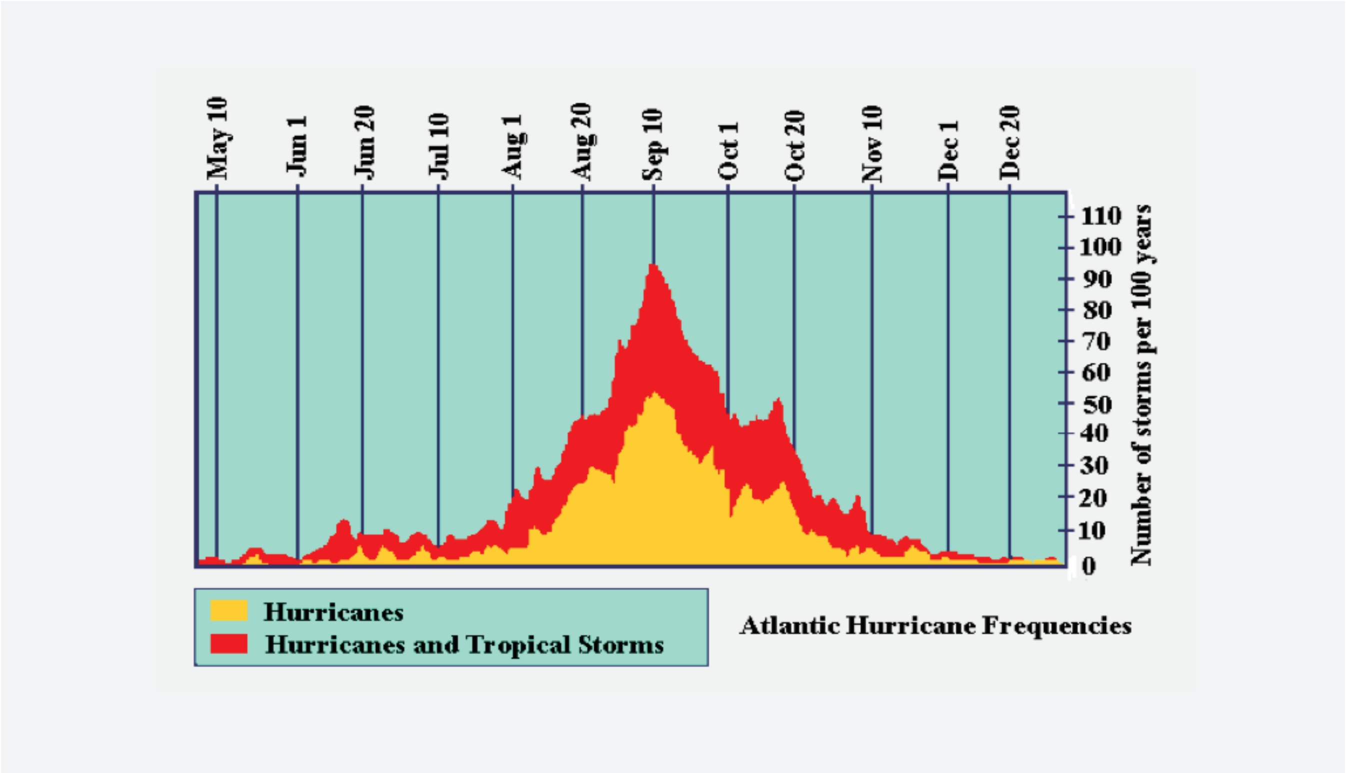


Figure 4.3: Storm frequency during the Atlantic Ocean hurricane season. Source: NOAA.

Figure 4.4 shows the mean areas of origin and prevailing tracks during selected months of the hurricane season. From June through August, the areas of origin shift from the western Caribbean Sea and Gulf of Mexico (June) into the Atlantic Ocean (August-September). This coincides with the eastward expansion of the Atlantic warm pool which results in water temperatures becoming warmer in the north tropical Atlantic (see Section 3.2.1) thereby allowing easterly waves coming off the African coast to develop into storms and hurricanes. By October, the water temperatures in the north tropical Atlantic east of the Caribbean basin start to cool and wind shear increases, and storm genesis and activity generally shifts back into the Caribbean Sea and Gulf of Mexico, where the water temperatures are still very warm.

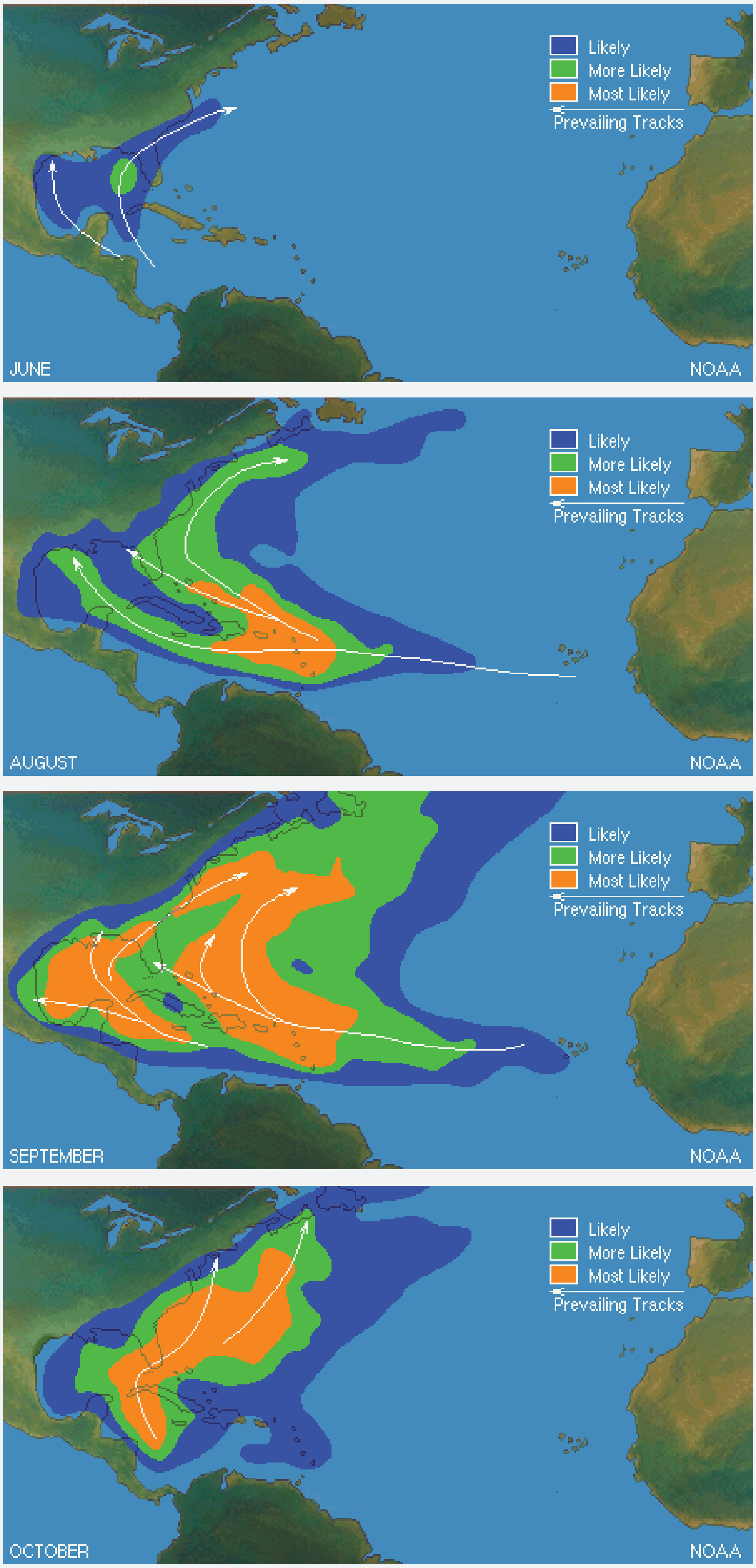


Figure 4.4: Zones of likely origin and track density of storms by month during the hurricane season from August-October. Source: NOAA.

4.3.2. TRENDS

Tropical cyclone activity can be measured with a variety of metrics for intensity, frequency, and duration. Though storm records for the North Atlantic region date as far back as the mid-1800s (see for example Figure 4.5), analysis of trends is generally restricted to the period after 1950 to coincide with the instrumental period beginning in the mid-1950s. This period signifies the start of the use of aircraft reconnaissance. Since the late 1970s satellite imagery has also been used to verify the state of tropical storms.

Most measures of Atlantic hurricane activity show a marked increase since the early 1980s when high-quality satellite data became available (Bell et al. 2012; Bender et al. 2010; Emanuel 2007; Landsea and Franklin 2013). These include measures of intensity, frequency, and duration as well as the number of strongest (category 4 and 5) storms. Figure 4.5 shows the total number of storms passing through the North Atlantic region over the period 1950-2019. The North Atlantic has seen a significant increase in tropical cyclone activity since 1995 with a distinct increase in the number of intense (category 4 and 5) storms (Webster et al. 2005). Though there is a significant increase in recent research suggesting a global warming link with recent changes in hurricane activity, in particular with increases in the number of intense hurricanes, there is still a lack of consensus on the extent of its contribution, since other long term modulators of SST in the north tropical Atlantic such as the Atlantic Multi-decadal Oscillation (AMO) are in a positive (enhancement) phase.

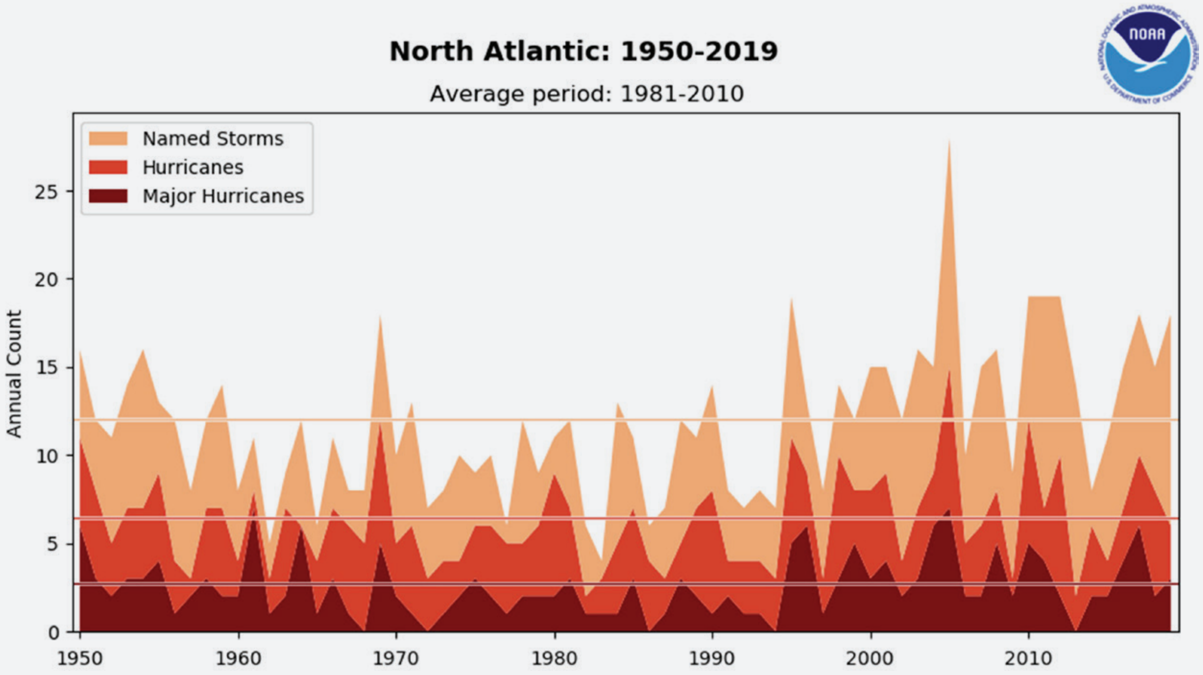


Figure 4.5: The number of named storms, hurricanes and major hurricanes per year passing through the North Atlantic and Gulf of Mexico from 1950-2019. Source: NOAA 2020.

The El Niño-Southern Oscillation phenomenon plays a significant role in modifying hurricane activity in the North Atlantic from year to year i.e. notwithstanding long term trends. El Niño contributes to fewer Atlantic hurricanes while La Niña contributes to more Atlantic hurricanes. El Niño produces upper level westerly wind anomalies and lower level easterly wind anomalies across the tropical Atlantic, which together result in higher vertical wind shear. El Niño and La Niña also influence where the Atlantic hurricanes form. During El Niño events, fewer hurricanes and major hurricanes develop in the deep Tropics from African easterly waves. During La Niña, more hurricanes form in the deep Tropics from African easterly waves, with these systems having a much greater likelihood of becoming major hurricanes and eventually threatening the U.S. and Caribbean.

Figure 4.6 shows all the named storms between 1980 and 2016 that have passed through each of the six rainfall zones previously defined in Chapter 3 and depicted in Figure 3.1. Table 4.4 gives the breakdown by category. All the zones have similar total activity except for Zones 1 and 6. Zone 2 had an even distribution of storms across all categories. Zone 4 had the largest number of category 1 storms while Zone 3 had the highest number of category 4 storms. Zones 4 and 5 have the highest frequency of storms being category 1 storms, with category 4 storms being second. Zone 3, however, has its highest frequency of storms being category 4 storms, with category 1 storms being second. Zone 3 has the most frequent storm tracks of category 4 among all the zones investigated. Zone 6 (Grenada, Guyana and Suriname) shows zero storm activity for the period.

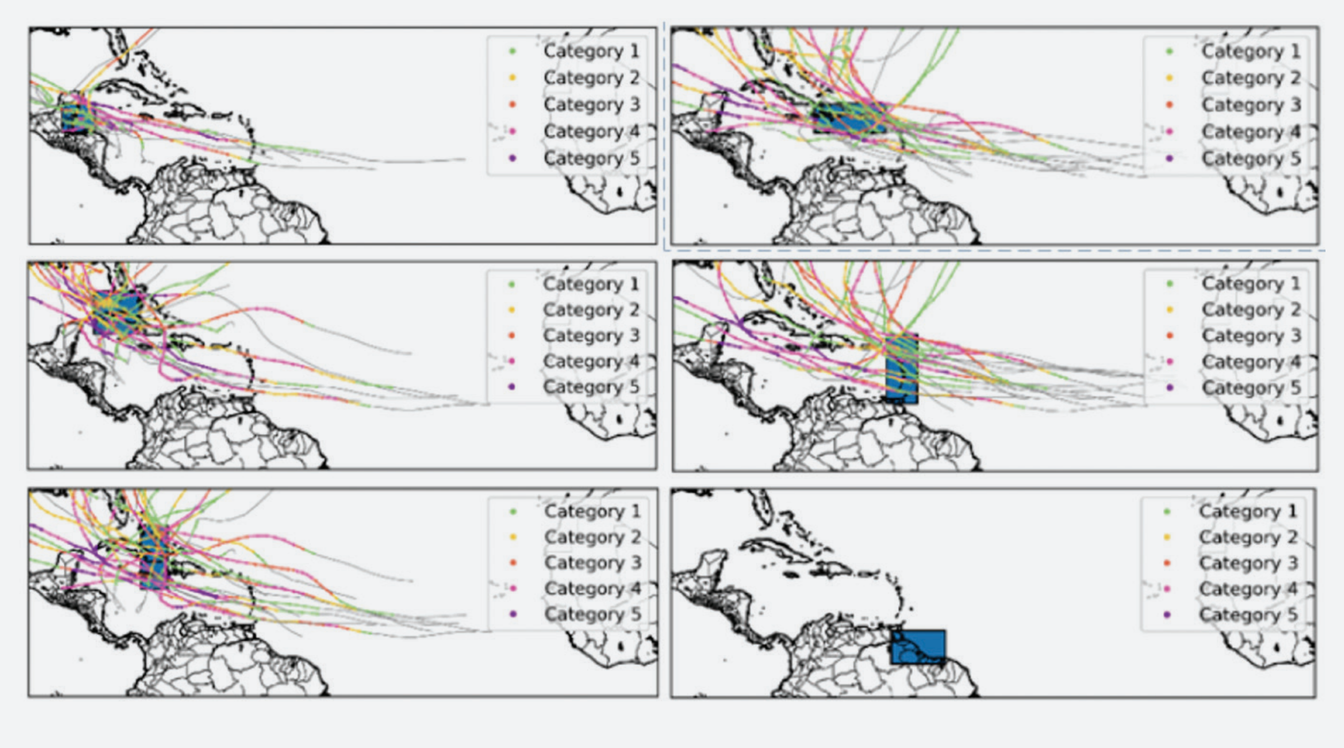


Figure 4.6: Storms and Hurricane tracks for zones 1-6 from 1980-2016. Left panels: Zones1, 2 and 3. Right panels: Zones 4,5 and 6.

Table 4.4: Named storms by decades that have passed within 200 km of the identified country representing each zone. The table also shows the category of the storm from 1980-2016.

ZONES	COUNTRIES IN ZONE	NUMBER OF HURRICANES IMPACTING THE ZONES BY CATEGORY					
		CATEGORY 1	CATEGORY 2	CATEGORY 3	CATEGORY 4	CATEGORY 5	TOTAL
1	Belize	2	3	2	4	3	14
2	-	6	5	4	5	3	23
3	Jamaica and Bahamas	9	2	3	11	0	25
4	Haiti	12	1	4	7	1	25
5	Anguilla, Antigua & Barbuda, Barbados, British Virgin Island, Dominica, Montserrat, St Kitts & Nevis, St Lucia and St Vincent, the Grenadines & Trinidad and Tobago	10	4	3	7	0	24
6	Grenada, Guyana, Suriname	0	0	0	0	0	0
TOTAL		**39**	**15**	**16**	**34**	**7**	**111**

4.4. DROUGHTS & FLOODS

4.4.1. FLOODS

The Caribbean region is prone to flooding given its susceptibility to storms and hurricanes. Burgess et al. (2018) using the EM-DAT disaster database (Guha-Sapir et al. 2015) show that there were at least 370 occurrences of meteorological related disasters between 1960 and 2013 in 22 Caribbean countries (Figure 4.7). Tropical cyclones (264 or 71.4%) and riverine flooding (59 or 15.9%) accounted for the majority of the occurrences. Tropical cyclones also accounted for 94.5% of the damages in the Caribbean countries from meteorological disasters since 1960 according to the EM-DAT database. In a similar study, Acevedo (2014) showed that at least 250 storm and flooding events impacted 12 Caribbean countries between 1970 and 2009, resulting in approximately USD20 billion in damages (2010 dollars).

Figure 4.8 shows a breakdown by country of flooding events listed in the EM-DAT database between 1900 and 2016. There is an uneven distribution across the Caribbean with the islands of the Greater Antilles experiencing the highest number of events. In particular, Haiti is shown to experience the highest number of flooding events among the countries examined.

Burgess et al. (2018) also examined how occurrences of Caribbean meteorological disasters have changed from 1960 to 2013. They find that occurrences have increased from an annual average of 1.7 events for the period prior to 1980 to 10.8 events after 1980 (Figure 4.9). They suggest there may be a link to warming in global surface air temperatures.

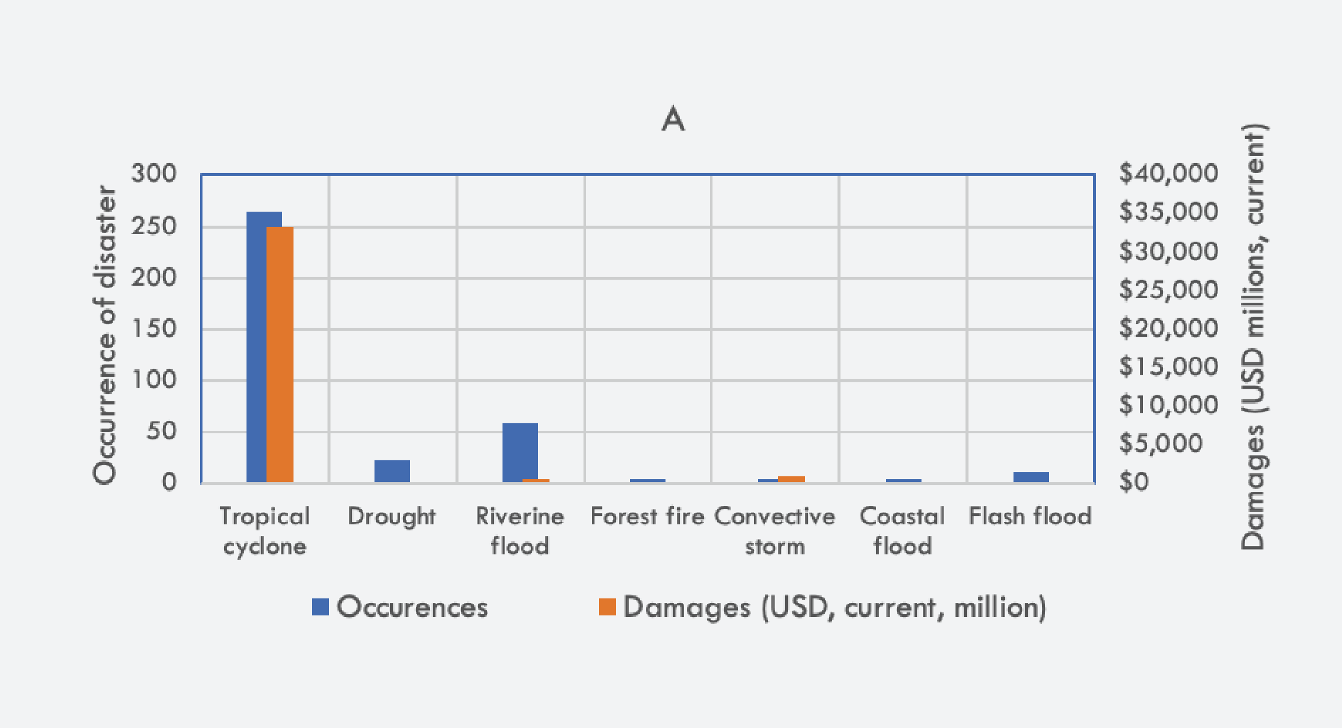


Figure 4.7: Occurrence and damages in the Caribbean (USD millions, current) categorized by disaster type for the period 1960 to 2013. Data Source: EM-DAT Database. Adapted from Burgess et al (2018).

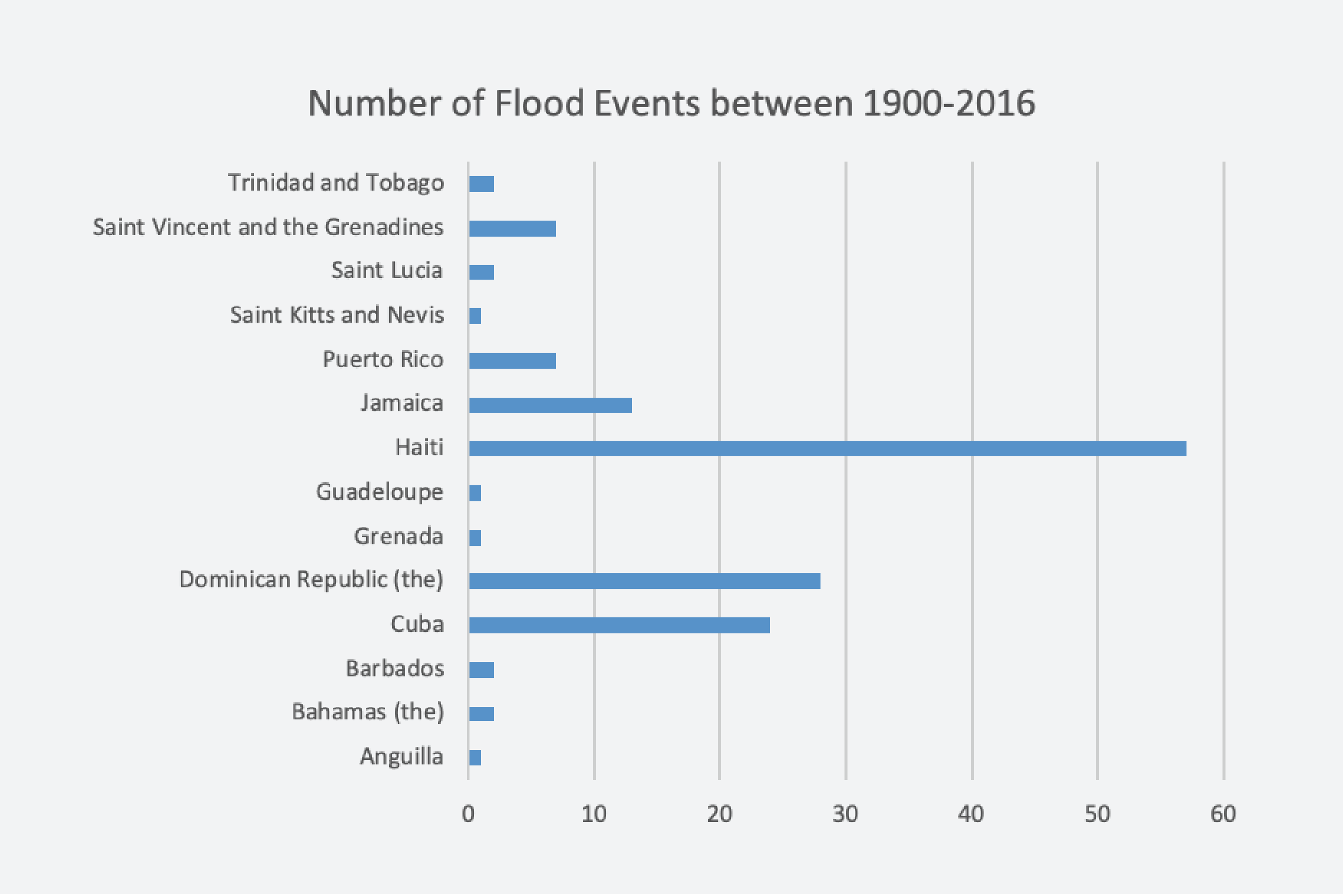


Figure 4.8: Number of flood events across selected Caribbean countries during 1900-2016. Data source: EM-DAT Database.

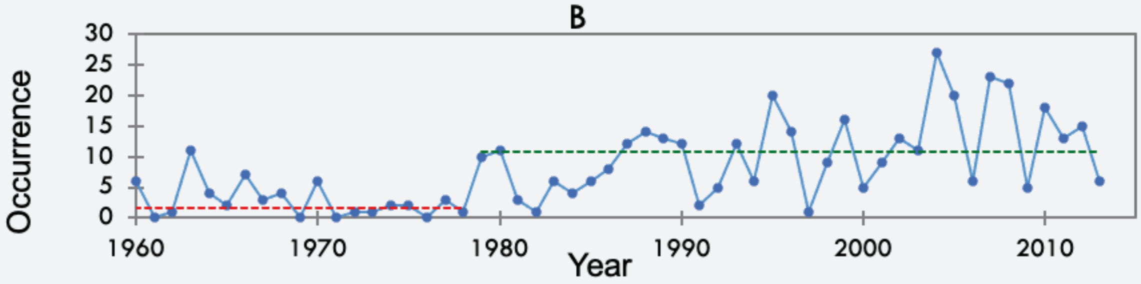


Figure 4.9: Occurrence of Caribbean meteorological disasters from 1960 to 2013. Source Data: EM-DAT database. Adapted from Burgess et al. (2018).

4.4.2. DROUGHT

The Caribbean region faces significant challenges due to drought. However, because of its slow-onset nature, it is often overlooked. During the past decades, the Caribbean has experienced several drought events, with many seemingly linked to years with El Nino events. These include events in 1957, 1968, 1976-77, 1986-1987, 1991, 1994, 1997-1998, 2009-2010, and again in 2013-2016. Numerous drought indices have been used to characterize the stage of drought or the severity of a drought episode. The following discussion draws on the conclusions of studies which use respectively the Standardized Precipitation Index (SPI) and the self-calibrating Palmer Drought Severity Index (scPDSI). In the first study (Walters 2018), SPIs are used to examine the spatial distribution of drought occurrence across the Caribbean between 1951 and 2000. In the second set of studies (Herrera and Ault 2017; and Herrera et al. 2018), scPDSI is used to focus on severe drought events between 1950 and 2016.

Walters (2018) uses the Standardized Precipitation Index (SPI) to characterize the rarity of extreme and moderate drought events in different parts of the Caribbean on a variety of time scales. SPIs were derived from time series of rainfall representing four zones in the Caribbean, which overlap with the six rainfall zones examined in Chapter 3. The four zones capture drought variation in the far north Caribbean (western Cuba and the Bahamas), a Jamaica region (eastern Cuba, Jamaica, Turks and Caicos and the western half of Hispaniola), the eastern Caribbean (Puerto Rico and the Lesser Antilles) and the southern Caribbean (Trinidad and Tobago and Guyana).

Major conclusions from the Walters (2018) study are:

- The far north Caribbean seems the least prone to extreme drought.
- There are likely different features modulating the occurrence of drought, depending on the region of the Caribbean being considered, as the SPIs across the four zones do not always behave in phase. Of the four regions, the eastern and southern Caribbean exhibit the highest degree of correlation.
- The Jamaica region experienced extreme droughts in the mid-1960s, mid-1970s, and again in the early 1990s. The far north Caribbean experienced extreme drought conditions in the 1950s, 1963 and 1972, and moderate drought after 1975. The eastern and south Caribbean experienced extreme drought conditions in the 1960s and 1970s, with the eastern Caribbean experiencing these conditions again in the mid-1990s.
- After 1983, the south Caribbean and the Jamaica region tend to have predominantly negative SPIs suggesting a shift toward drier conditions. This is also true for the eastern Caribbean after 1990.
- Though region wide droughts (i.e. when all SPIs for all zones are simultaneously negative) are not common over the period analysed (up to 2000), the mid to late 1970s stand out.

- Timescales of 2-3 years and 9-13 years characterise drought occurrence across most of the Caribbean zones. A 3-6 year timescale also occurs in the eastern Caribbean, and a 5-6 year signal occurs in the south Caribbean.
- All zones generally seem to exhibit correlations with tropical and equatorial Pacific SSTs, suggesting a potential link to El Nino events. However, whereas the El Nino event seems to bring dry conditions across most of the Caribbean, it seems to enhance wet conditions in the far north Caribbean. The Caribbean Sea is correlated with the Jamaica region, the far north Caribbean, and the eastern Caribbean, but not the south Caribbean.

In two other recent studies, Herrea and Ault (2017) and Herrera et al. (2018) use scPDSI to show that since 1950, the Caribbean has experienced a general drying trend (Figure 4.10). They however point out that the trend is not homogeneous across the region, with, in particular, the far north Caribbean seeing a tendency to be wetter. Like Walters (2018), they also confirm the tropical Pacific and tropical north Atlantic as significant modulators of drought variability in the region.

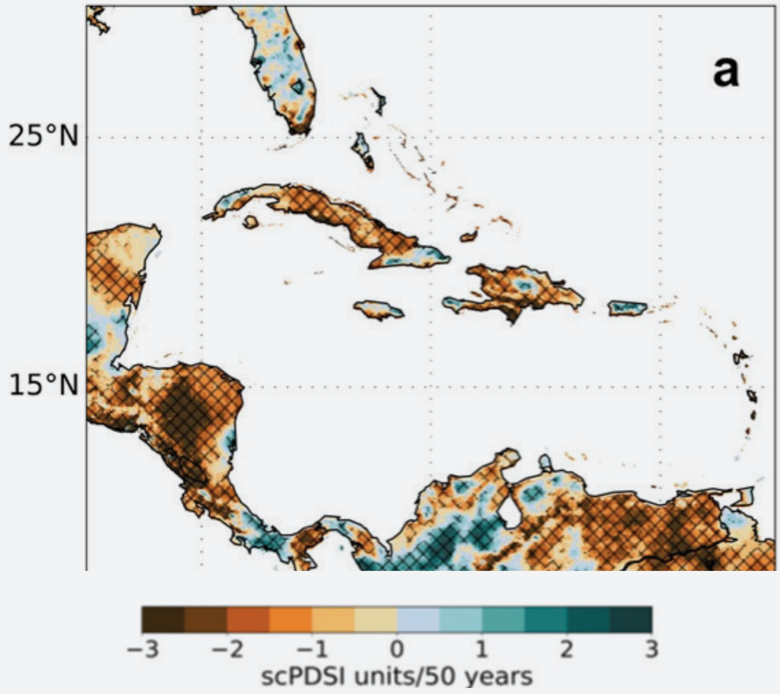


Figure 4.10: Linear trends showing the change of the scPDSI during the 1950–2016 interval Brown colours represent drying trend and cyan colours a wetting trend. In (a) and (b), the hatching means a significant trend ($p < 0.05$) at the 95% level. From Herrera and Ault (2017).

The studies also show that the region as a whole has experienced severe droughts in 1974–77, 1997/98, 2009/10, and 2013–16 (Figure 4.11). Of the four periods, the 2013-2016 drought was the most severe experienced by the Caribbean, as virtually the entire region experienced a Pan-Caribbean drought. During the three-year period, drought conditions in 2014 ranked as the most severe since 1950 due to the greater area covered. However, 2015 ranked as the driest year during the 2013–16 droughts and had the highest potential evapotranspiration (PET) and temperatures which may have added to the severity of the drought. Though the 2013-2016 Caribbean drought can be associated with the 2015/16 El Nino event, Herrera et al (2018) also suggest that global warming likely contributed to ~15–17% of drought severity for the 2013-2016 event, by increasing evapotranspiration rates and accounting for ~7% of land area under drought. That is, their results indicate that anthropogenic warming is likely already increasing drought risk in the Caribbean.

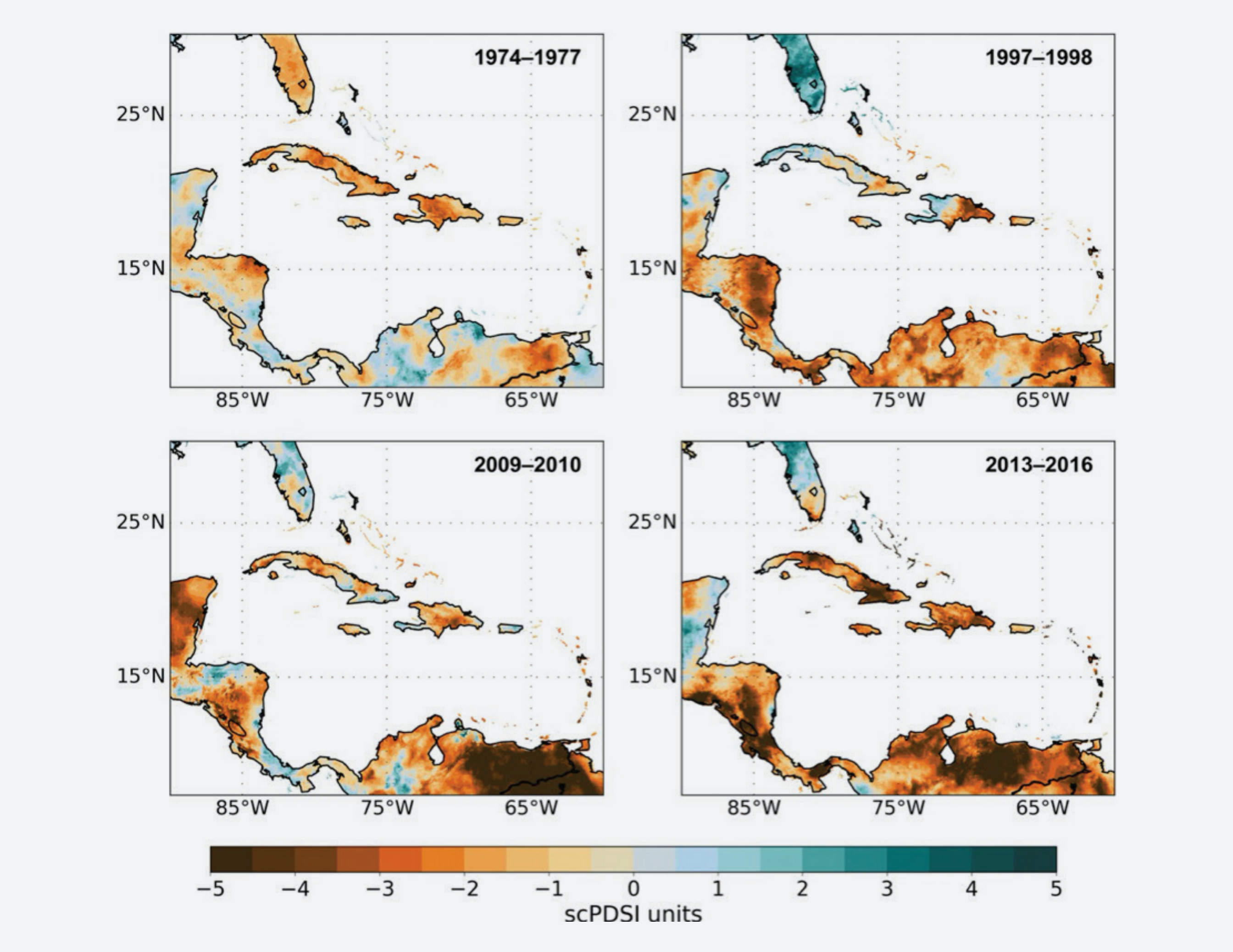


Figure 4.11: Major droughts in the Caribbean between 1950 and 2016 of at least one year in duration. From Herrera and Ault (2017).

5. CLIMATE SCENARIOS AND PROJECTIONS

5.1. INTRODUCTION

The literature on future climates in the Caribbean region has grown in the past two decades. As a result, a consensus picture of what the Caribbean may look like through to the end of the century has gradually emerged based on a variety of studies using different models (GCMs and RCMs), methodologies (statistical versus dynamical downscaling), and scenarios (SRES and RCPs).

A scan of the literature suggests that:

- The Caribbean as a whole will gradually warm through to the end of the current century. This is true across all the modelling studies and irrespective of model, methodology or scenario employed. The mean annual temperature of the Caribbean region will be warmer by between 1.0°C and close to 3.5°C compared to today. The entire region will experience the warming, including both ocean and land, with the largest warming occurring over the larger land masses (Taylor et al. 2018; Karmalkar et al. 2013; Campbell et al. 2011). Concomitant will be an increased frequency of temperature extremes, including very hot days and nights, a decrease in very cold days and nights, and an increase in consecutive hot days (or warm spells) (Taylor et al. 2018, Stennett-Brown et al. 2017, Mclean et al. 2015; McSweeney et al. 2010).
- The Caribbean in general will gradually dry going towards the end of the century. When taken as a whole, the Caribbean drying may be moderate as there is a gradient in drying with less in the far north Caribbean and more in the south and southeast. The GCMs, however, suggest for the central and southern Caribbean basin, drying up to 20% for annual rainfall, while RCM based projections suggest up to 25-30% less rainfall by the end of the century (Taylor et al. 2018; Karmalkar et al. 2013; Campbell et al. 2011). Projected drying is most pronounced in the early and late wet seasons between May and October. Most studies show that interannual variability will still be the dominant feature of the Caribbean rainfall record, but the linear downward trend in rainfall will be such that the variability will occur around a lower mean. The models also project changes in rainfall extremes but suggest these may have regional variations, for example, increases in the proportion of total rainfall that falls in heavy events toward the end of the century in the north and eastern Caribbean, and an increase in the number of consecutive hot and dry days particularly in the south and southeast (Taylor et al. 2018; Mclean et al. 2015, Hall et al. 2013).
- Whereas there is little consensus that there may be an increase in Atlantic storms and hurricanes, the literature is in agreement that the intensity of the storms and hurricanes will likely increase under global warming (IPCC 2012).
- Sea-levels will continue to rise in the Caribbean and may be close to the projected global mean rise. By mid-century, the global increase is between 0.24 and 0.30 m, while by the end of century, the change is between 0.40–0.63 m relative to 1986–2005 (IPCC 2013). A few studies suggest that the upper bound may be conservative and could be up to 1.4 m including for the Caribbean (Rahmstorf 2007; Rignot and Kanargaratnam 2006; Horton et al. 2008; IPCC 2013; Perrette et al. 2013).

It is to be noted, then, that the projections suggest that as the century progresses, the Caribbean under the worst scenarios will be a significantly different place (much warmer and drier, with higher sea levels and prone to more intense storms) than at present, with the magnitude of projected changes greater than the magnitude of change seen over the last century (Chapters 3 and 4).

The literature scan also suggests a number of deficiencies in the science of projections for the Caribbean region. These include, inadequate science on (i) projections using the RCPs (ii) future hurricane characteristics in the

Caribbean (intensity, frequency, genesis, etc.) (iii) future droughts at the regional or sub-regional scale, (iv) projections of other climatic parameters (e.g. wind speed, solar radiation, sea levels), and (v) projections on intermediary timescales i.e. near and medium term as opposed to end of century.

This chapter provides Caribbean climate projections based on GCMs, RCMs and statistical downscaling as described in Chapter 2. For both temperature and rainfall, the pattern of presentation is the same. First, data from the GCMs are used to provide region-wide projections under the four RCP scenarios. The RCMs are then used as the basis for providing projections over the six defined rainfall zones. Recall that a suite of GCMs are used for the CMIP5 project while the PRECIS 25 km simulations are used for the RCM projections (see again Chapter 2). In all cases projections are offered for three time slices: a near term or 2020s (averaged over 2020-2029), a medium term or 2050s (2050-2059) and end of century (2091-2100). Statistical downscaling is then utilised to determine projected changes in temperature and rainfall extremes, premised on the country station data (see Chapter 2). Projections for sea level rise and hurricanes are also presented and are largely gleaned from literature.

The data in the chapter are presented in the form of tables, maps, and graphs. A summary of the GCM, RCM and statistically downscaled results are provided in narrative form at the beginning of the sections for temperature and rainfall projections.

5.2. TEMPERATURE

All models and scenarios indicate a continuation of the historical warming trend across the Caribbean as a whole and its sub-regions. The following are noted about the projected changes in temperature and temperature extremes:

» GCMs suggest a warming trend across the Caribbean irrespective of scenario. The rate of warming is similar for mean, maximum, and minimum temperature under all scenarios.

» Considered as a whole, projected further warming of the mean temperature from the GCMs is up to 0.56oC (range of mean: 0.48 oC-0.56 oC) during the 2020s relative to a 1986-2005 baseline. (It is important to bear in mind that up to the baseline period the Caribbean will likely have already seen up to 0.5oC of warming.) However, by the 2050s, mean temperature is projected to rise by up to 1.50oC (0.86 oC to 1.50 oC) and 3.05oC (0.83 oC to 3.05 oC) by the end of the century.

» Projected changes in maximum and minimum temperatures are of similar magnitude to that for the mean temperature.

» The RCMs suggest that all zones will warm going toward the end of the century. The projected changes are summarized by time slice in Table 5.1 per zone. The warming shown is slightly greater than projected by the GCMs which is to be expected given the greater resolution of the RCMs and the fact that they capture the smaller land masses which are represented as ocean in the GCMs. The warming magnitudes are, however, comparable especially bearing in mind that the RCM baseline is 1961-1990. The warming will occur throughout the year in all zones for all future time slices.

Table 5.1: Range of annual temperature change across the six Caribbean zones from an RCM ensemble running the A1B scenario. Baseline is 1961-1990. See again Figure 2.3 for grid boxes in each zone.

		ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	ZONE 6
TMEAN	2020s	0.99 – 1.40	0.72 – 1.22	0.89 – 1.24	0.93 – 1.30	0.78 – 1.35	0.90 – 1.56
	2050s	1.84 – 2.49	1.57 – 2.40	1.71 – 2.30	1.64 – 2.37	1.34 – 2.28	1.56 – 2.56
	EOC	2.35 – 3.96	2.53 – 3.72	2.43 – 3.70	2.15 – 3.74	1.78 – 3.38	1.80 – 3.90
TMAX	2020s	0.98 – 1.48	0.70 – 1.21	0.87 – 1.25	0.93 – 1.27	0.79 – 1.33	0.95 – 1.61
	2050s	1.93 – 2.49	1.59 – 2.39	1.75 – 2.36	1.69 – 2.38	1.32 – 2.25	1.52 – 2.57
	EOC	2.46 – 4.02	2.74 – 3.74	2.49 – 3.75	2.20 – 3.75	1.76 – 3.38	1.65 – 4.02
TMIN	2020s	0.95 – 1.33	0.75 – 1.24	0.92 – 1.26	0.92 – 1.33	0.78 – 1.34	0.85 – 1.52
	2050s	1.79 – 2.50	1.59 – 2.43	1.73 – 2.29	1.62 – 2.39	1.36 – 2.28	1.63 – 2.57
	EOC	2.34 – 3.91	2.75 – 3.77	2.41 – 3.72	2.14 – 3.80	1.80 – 3.40	1.97 – 3.89

- There are regional variations in warming evident in the RCM results. The far western Caribbean (Zone 1) and the southern Caribbean (Zone 6) show slightly higher warming than the rest of the region. This likely reflects that these zones include continental Caribbean countries.

- From RCMs, the greatest seasonal warming will likely occur during SON in all zones in the 2020s except for Zones 4 and 5, in which the dry season shows the greatest warming. Of the six zones, the far south Caribbean (Zone 6) shows the greatest annual warming during the 2020s of 1.21oC.

- A similar trend persists in the 2050s, during which Zones 1, 2, and 6 show greatest warming during SON, and Zones 3, 4, and 5 during NDJ. Greatest annual warming occurs in the far western Caribbean (Zone 1) in the 2050s, reaching 2.12 oC warmer than baseline.

- By the end of the century, warming is projected to be highest in Zone 1, both seasonally and annually, where annual temperature may exceed baseline by a mean of 3.22oC. Range of mean annual temperature change for each zone by end of century is 2.35 – 3.96 oC in Zone 1, 2.53 – 3.72 oC in Zone 2, 2.43 – 3.70 oC in Zone 3, 2.15 – 3.74 oC in Zone 4, 1.78 – 3.38 oC in Zone 5, and 1.80 – 3.90 oC in Zone 6.

- End of century warming is projected to occur at a slightly faster rate in maximum temperature than in minimum temperature in Zones 1, 3, and 6, while the reverse is projected for Zones 2, 4, and 5. However, this difference is most prominent in Zone 1.

- SDSM projections show a projected increase for both warm days and warm nights for the end of century period. The number of warm nights was projected to increase more than the number of warm days. The projected increase in warm days ranged between 51 and 251 days and for warm nights between 24 and 360 days for RCP 8.5.

- The trend was for a decrease in both cool days and nights. The range for cool days was between 1 and 41 days and between 1 and 32 days for cool nights for the end of century under RCP 8.5.

5.2.1. GCMS

GCM projections of the Caribbean as a whole are provided below for future mean, minimum, and maximum temperature relative to a 1986 – 2005 baseline (Tables 5.2-5.4 and Figure 5.1).

Table 5.2: Mean annual temperature change for the Caribbean with respect to 1986-2005. Change shown for four RCP scenarios. Source: AR5 CMIP5 subset, KNMI Climate Explorer.

	TMEAN								
	2020s			2050s			END OF CENTURY		
AVERAGED OVER	2020-2029			2050-2059			2091-2100		
	min	mean	max	min	mean	max	min	mean	max
RCP 2.6	0.30	0.53	0.96	0.39	0.86	1.57	-0.04	0.83	1.74
RCP 4.5	0.23	0.52	0.89	0.56	1.09	1.83	0.68	1.53	2.50
RCP 6.0	0.20	0.48	0.79	0.69	1.00	1.66	1.00	1.85	2.92
RCP 8.5	0.31	0.56	0.87	0.94	1.50	1.23	2.10	3.05	4.22
RANGE OF MEAN:	0.48 – 0.56			0.86 – 1.50			0.83 – 3.05		

Table 5.3: Mean annual minimum temperature change for the Caribbean with respect to 1986-2005. Change shown for four RCP scenarios. Source: AR5 CMIP5 subset, KNMI Climate Explorer.

	TMIN								
	2020s			2050s			END OF CENTURY		
AVERAGED OVER	2020-2029			2050-2059			2091-2100		
	min	mean	max	min	mean	max	min	mean	max
RCP 2.6	0.30	0.53	0.97	0.39	0.87	1.58	-0.07	0.83	1.75
RCP 4.5	0.23	0.52	0.89	0.55	1.10	1.82	0.65	1.53	2.50
RCP 6.0	0.19	0.48	0.80	0.68	0.99	1.67	0.96	1.84	2.92
RCP 8.5	0.33	0.57	0.87	0.92	1.51	2.24	2.07	3.07	4.23
RANGE OF MEAN:	0.48 – 0.57			0.87 – 1.51			0.83 – 3.07		

Table 5.4: Mean annual maximum temperature change for the Caribbean with respect to 1986-2005. Change shown for four RCP scenarios. Source: AR5 CMIP5 subset, KNMI Climate Explorer.

	TMAX								
	2020s			2050s			END OF CENTURY		
AVERAGED OVER	2020-2029			2050-2059			2091-2100		
	min	mean	max	min	mean	max	min	mean	max
RCP 2.6	0.30	0.53	0.95	0.40	0.87	1.56	0.01	0.84	1.73
RCP 4.5	0.24	0.52	0.89	0.57	1.10	1.84	0.73	1.54	2.51
RCP 6.0	0.22	0.48	0.79	0.70	1.00	1.66	1.05	1.85	2.91
RCP 8.5	0.33	0.57	0.86	0.96	1.51	2.21	2.12	3.08	4.21
RANGE OF MEAN:	**0.48 – 0.57**			**0.87 – 1.51**			**0.84 – 3.08**		

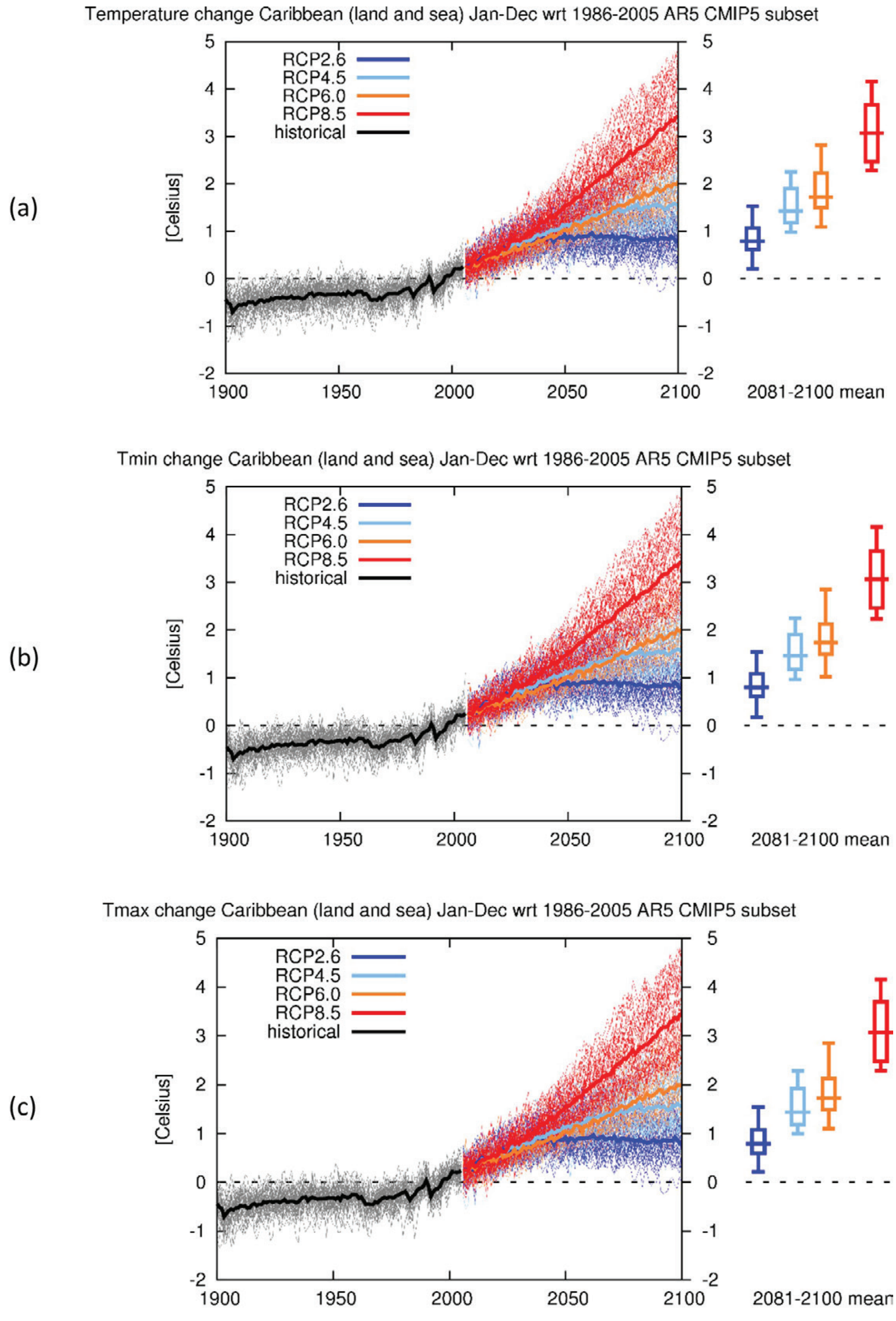


Figure 5.1: (a) Mean annual temperature change (°C) (b) Mean annual minimum temperature change (°C) (c) Mean annual maximum temperature change (°C) for the Caribbean with respect to 1986-2005 AR5 CMIP5 subset. On the left, for each scenario one line per model is shown plus the multi-model mean, on the right percentiles of the whole dataset: the box extends from 25% to 75%, the whiskers from 5% to 95% and the horizontal line denotes the median (50%).

5.2.2. RCMS

RCM projections are provided below for changes in mean, minimum, and maximum temperature in the six Caribbean climate zones (Tables 5.5 – 5.7 and Figure 5.2).

Table 5.5: Projected absolute changes in mean temperature by season and for annual average (°C) for the 2020s, 2050s and EOC (2081-2098) relative to the 1961-1990 baseline. Data presented for the mean value of a six-member ensemble. Range shown is over all the grid boxes in the zone (see Table 2). Source: PRECIS RCM perturbed physics ensemble run for A1B scenario.

ZONE 1

	2020S			2050S			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.92	1.08	1.26	1.55	2.07	2.50	2.25	3.09	3.81
FMA	0.79	1.09	1.45	1.68	1.93	2.15	2.31	3.10	3.93
MJJ	0.83	1.19	1.58	1.76	2.17	2.55	2.24	3.28	4.24
SON	0.99	1.24	1.50	1.92	2.29	2.78	2.62	3.42	4.03
ANN	**0.99**	**1.15**	**1.40**	**1.84**	**2.12**	**2.49**	**2.35**	**3.22**	**3.96**

ZONE 2

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.56	0.98	1.34	1.43	2.02	2.50	2.24	2.99	3.57
FMA	0.60	0.94	1.30	1.18	1.75	2.13	2.40	2.98	3.46
MJJ	0.81	1.11	1.43	1.76	2.12	2.58	2.70	3.38	4.18
SON	0.90	1.17	1.38	1.93	2.18	2.56	2.77	3.33	3.85
ANN	**0.72**	**1.05**	**1.22**	**1.57**	**2.02**	**2.40**	**2.53**	**3.17**	**3.72**

ZONE 3

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.81	1.05	1.17	1.74	2.06	2.37	2.42	3.04	3.62
FMA	0.78	1.02	1.38	1.57	1.85	2.03	2.49	2.98	3.62
MJJ	0.84	1.06	1.29	1.71	1.99	2.38	2.35	3.07	3.89
SON	0.88	1.14	1.38	1.84	2.04	2.43	2.45	3.03	3.65
ANN	**0.89**	**1.07**	**1.24**	**1.71**	**1.98**	**2.30**	**2.43**	**3.03**	**3.70**

ZONE 4

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	1.00	1.16	1.44	1.70	2.09	2.55	2.22	3.06	3.81
FMA	0.89	1.08	1.35	1.74	1.97	2.26	2.30	3.00	3.84
MJJ	0.79	1.03	1.22	1.57	1.88	2.30	2.03	2.79	3.67
SON	0.98	1.13	1.42	1.53	1.91	2.38	2.04	2.85	3.64
ANN	**0.93**	**1.10**	**1.30**	**1.64**	**1.96**	**2.37**	**2.15**	**2.93**	**3.74**

ZONE 5

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.82	1.13	1.55	1.49	1.93	2.51	2.03	2.84	3.57
FMA	0.73	0.98	1.25	1.43	1.81	2.20	1.87	2.63	3.40
MJJ	0.67	0.97	1.22	1.22	1.71	2.18	1.52	2.38	3.23
SON	0.90	1.09	1.39	1.21	1.72	2.24	1.71	2.60	3.38
ANN	**0.78**	**1.05**	**1.35**	**1.34**	**1.79**	**2.28**	**1.78**	**2.61**	**3.38**

ZONE 6

	2020s			2050s			EOC		
	Min	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
NDJ	0.86	1.24	1.74	1.73	2.11	2.79	2.02	3.16	4.00
FMA	0.74	1.08	1.43	1.46	1.93	2.41	1.63	2.75	3.64
MJJ	0.89	1.16	1.40	1.38	1.90	2.35	1.57	2.81	3.80
SON	1.09	1.36	1.66	1.67	2.20	2.68	2.00	3.24	4.21
ANN	**0.90**	**1.21**	**1.56**	**1.56**	**2.03**	**2.56**	**1.80**	**2.99**	**3.90**

Table 5.6: Projected absolute changes in maximum temperature by season and for annual average (°C) for the 2020s, 2050s and EOC (2081-2098) relative to the 1961-1990 baseline. Data presented for the mean value of a six-member ensemble. Range shown is over all the grid boxes in the zone (see Table 2). Source: PRECIS RCM perturbed physics ensemble run for A1B scenario

ZONE 1

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.90	1.09	1.27	1.62	2.12	2.37	2.28	3.28	3.74
FMA	0.83	1.12	1.49	1.78	1.97	2.18	2.28	3.21	4.00
MJJ	0.95	1.22	1.71	1.89	2.26	2.54	2.35	3.52	4.33
SON	0.94	1.30	1.58	2.11	2.45	2.95	2.92	3.71	4.19
ANN	**0.98**	**1.18**	**1.48**	**1.93**	**2.20**	**2.49**	**2.46**	**3.43**	**4.02**

ZONE 2

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.59	0.94	1.28	1.45	1.96	2.33	2.51	3.08	3.38
FMA	0.56	0.93	1.29	1.19	1.73	2.08	2.64	3.06	3.41
MJJ	0.74	1.12	1.45	1.79	2.14	2.62	2.79	3.62	4.27
SON	0.91	1.20	1.44	1.95	2.21	2.62	3.03	3.54	3.92
ANN	**0.70**	**1.05**	**1.21**	**1.59**	**2.01**	**2.39**	**2.74**	**3.33**	**3.74**

ZONE 3

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.80	1.02	1.16	1.75	2.04	2.29	2.40	3.14	3.61
FMA	0.78	1.00	1.35	1.59	1.87	2.13	2.48	3.09	3.63
MJJ	0.84	1.06	1.30	1.73	2.03	2.46	2.46	3.30	4.00
SON	0.87	1.15	1.41	1.92	2.12	2.55	2.62	3.26	3.75
ANN	**0.87**	**1.06**	**1.25**	**1.75**	**2.02**	**2.36**	**2.49**	**3.20**	**3.75**

ZONE 4

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.99	1.11	1.29	1.71	2.05	2.43	2.19	3.11	3.74
FMA	0.88	1.05	1.31	1.77	1.97	2.29	2.31	3.09	3.80
MJJ	0.80	1.02	1.22	1.65	1.91	2.34	2.14	2.98	3.73
SON	0.96	1.15	1.45	1.64	1.98	2.47	2.18	3.05	3.71
ANN	**0.93**	**1.08**	**1.27**	**1.69**	**1.98**	**2.38**	**2.20**	**3.06**	**3.75**

ZONE 5

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.83	1.12	1.44	1.47	1.90	2.40	1.99	2.91	3.54
FMA	0.74	0.99	1.26	1.40	1.80	2.20	1.83	2.71	3.38
MJJ	0.69	0.97	1.21	1.22	1.70	2.14	1.53	2.49	3.22
SON	0.91	1.10	1.41	1.19	1.72	2.25	1.67	2.71	3.38
ANN	**0.79**	**1.05**	**1.33**	**1.32**	**1.78**	**2.25**	**1.76**	**2.70**	**3.38**

ZONE 6

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.90	1.30	1.74	1.71	2.18	2.86	1.86	3.38	4.19
FMA	0.82	1.15	1.49	1.45	1.99	2.46	1.52	2.82	3.69
MJJ	0.91	1.18	1.40	1.25	1.81	2.15	1.42	2.88	3.74
SON	1.16	1.48	1.83	1.67	2.33	2.81	1.80	3.47	4.45
ANN	**0.95**	**1.28**	**1.61**	**1.52**	**2.08**	**2.57**	**1.65**	**3.14**	**4.02**

Table 5.7: Projected absolute changes in minimum temperature by season and for annual average (°C) for the 2020s, 2050s and EOC (2081-2098) relative to the 1961-1990 baseline. Data presented for mean value of a six-member ensemble. Range shown is over all the grid boxes in the zone (see Table 2). Source: PRECIS RCM perturbed physics ensemble run for A1B scenario.

ZONE 1

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.88	1.06	1.29	1.47	2.01	2.49	2.25	3.16	3.72
FMA	0.77	1.10	1.43	1.63	1.93	2.20	2.40	3.20	3.86
MJJ	0.76	1.16	1.45	1.74	2.13	2.58	2.21	3.33	4.18
SON	0.97	1.23	1.49	1.86	2.21	2.72	2.48	3.41	3.99
ANN	**0.95**	**1.14**	**1.33**	**1.79**	**2.07**	**2.50**	**2.34**	**3.28**	**3.91**

ZONE 2

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.59	0.99	1.39	1.42	2.04	2.47	2.65	3.23	3.59
FMA	0.57	0.99	1.33	1.20	1.82	2.19	2.78	3.24	3.55
MJJ	0.84	1.11	1.42	1.80	2.14	2.57	2.68	3.54	4.18
SON	0.95	1.18	1.42	1.94	2.20	2.61	2.87	3.46	3.85
ANN	**0.75**	**1.07**	**1.24**	**1.59**	**2.05**	**2.43**	**2.75**	**3.37**	**3.77**

ZONE 3

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.81	1.04	1.18	1.75	2.04	2.27	2.45	3.21	3.67
FMA	0.79	1.06	1.42	1.59	1.89	2.08	2.53	3.16	3.66
MJJ	0.86	1.09	1.31	1.74	1.99	2.37	2.31	3.19	3.89
SON	0.91	1.16	1.44	1.81	2.02	2.43	2.35	3.13	3.65
ANN	**0.92**	**1.08**	**1.26**	**1.73**	**1.98**	**2.29**	**2.41**	**3.17**	**3.72**

ZONE 4

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.98	1.17	1.40	1.71	2.09	2.50	2.29	3.22	3.92
FMA	0.91	1.12	1.40	1.74	2.01	2.34	2.32	3.17	3.92
MJJ	0.79	1.05	1.25	1.55	1.91	2.33	1.99	2.92	3.71
SON	1.01	1.15	1.47	1.48	1.89	2.39	1.98	2.96	3.64
ANN	**0.92**	**1.13**	**1.33**	**1.62**	**1.98**	**2.39**	**2.14**	**3.07**	**3.80**

ZONE 5

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.82	1.11	1.45	1.51	1.90	2.41	2.06	2.91	3.54
FMA	0.72	0.99	1.29	1.45	1.82	2.25	1.89	2.74	3.42
MJJ	0.66	0.97	1.24	1.23	1.72	2.20	1.50	2.48	3.24
SON	0.90	1.10	1.39	1.24	1.73	2.25	1.75	2.72	3.39
ANN	**0.78**	**1.04**	**1.34**	**1.36**	**1.79**	**2.28**	**1.80**	**2.71**	**3.40**

ZONE 6

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	0.82	1.18	1.59	1.79	2.05	2.59	2.20	3.17	3.84
FMA	0.65	1.05	1.41	1.49	1.90	2.41	1.75	2.84	3.63
MJJ	0.85	1.17	1.46	1.52	2.04	2.60	1.72	3.05	3.95
SON	1.06	1.32	1.62	1.71	2.16	2.70	2.23	3.36	4.14
ANN	**0.85**	**1.18**	**1.52**	**1.63**	**2.04**	**2.57**	**1.97**	**3.11**	**3.89**

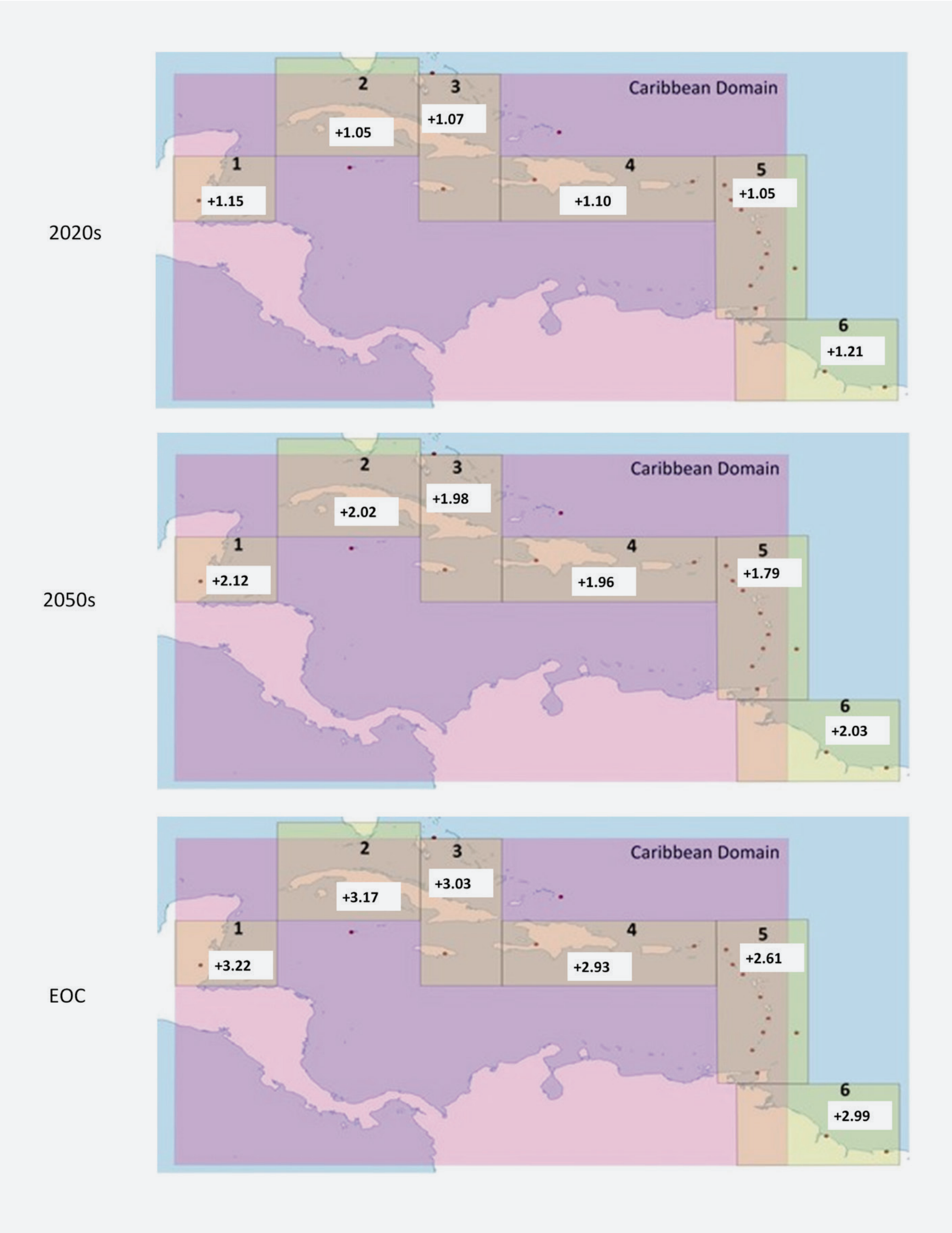


Figure 5.2: Summary map showing absolute maximum change per grid box of the ensemble mean of annual Mean Temperature (◦C) for the 2020's (top panel) and 2030s (bottom panel). Source: PRECIS RCM PPE.

5.2.3. STATISTICAL DOWNSCALING

The general trend was a projected increase for both warm days and warm nights for the period 2090 to 2100. Warm nights were projected to increase more than warm days. From Figure 5.3, the projected increase in warm days ranged between 51 and 251 days, and for warm nights between 24 and 360 days. St. Augustine, Trinidad had the greatest projected increase in the number of warm days and Belmopan, Belize had the least. Zorg en Hoop in Suriname had the greatest projected increase in the number of warm nights. However, the greatest percentage change in warm days and nights relative to the 2006 to 2016 period was Hewanorra, St. Lucia and Belmopan in Belize respectively. The model projected a decrease in warm days of 5 and 18 days for only two stations namely Nickerie, Suriname and Zanderij, Suriname respectively.

Figure 5.4 shows cool days and nights for the period 2090 to 2100 for RCP 8.5. The trend for the stations studied was a decrease in both cool days and nights. The range for cool days was between 1 and 41 days, and between 1 and 32 days for cool nights. The greatest decrease in the number of cool days and nights was for Barbados - Grantley Adams International Airport (GAIA) - and Cayman respectively. Two stations in Trinidad and Tobago projected an increase in the number of cool days (4 and 5 days), namely Crown Point and Piarco.

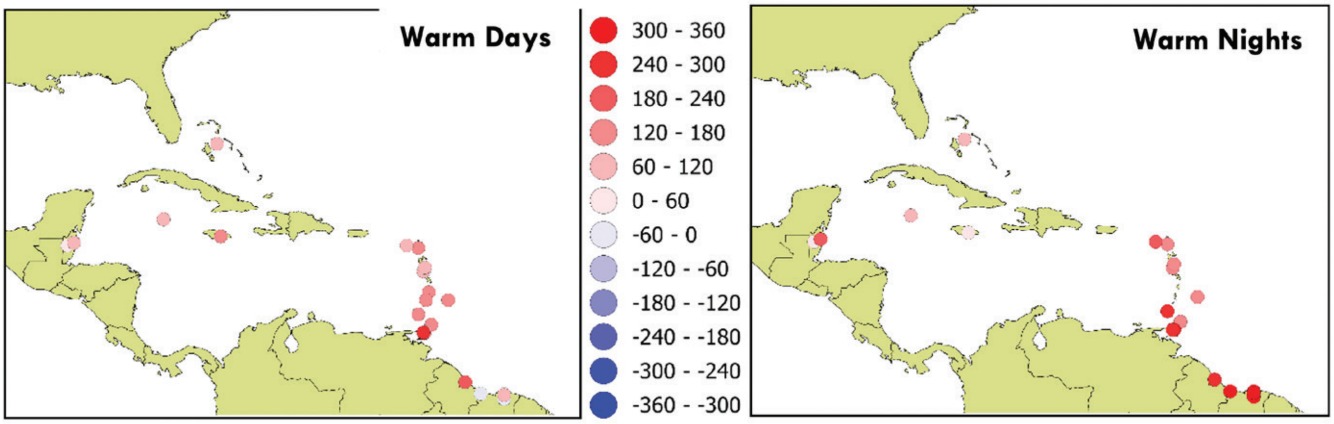


Figure 5.3: Projections of warm days and nights for the period 2090 to 2100 relative to 2006 to 2016 period for RCP 8.5. Units are in days.

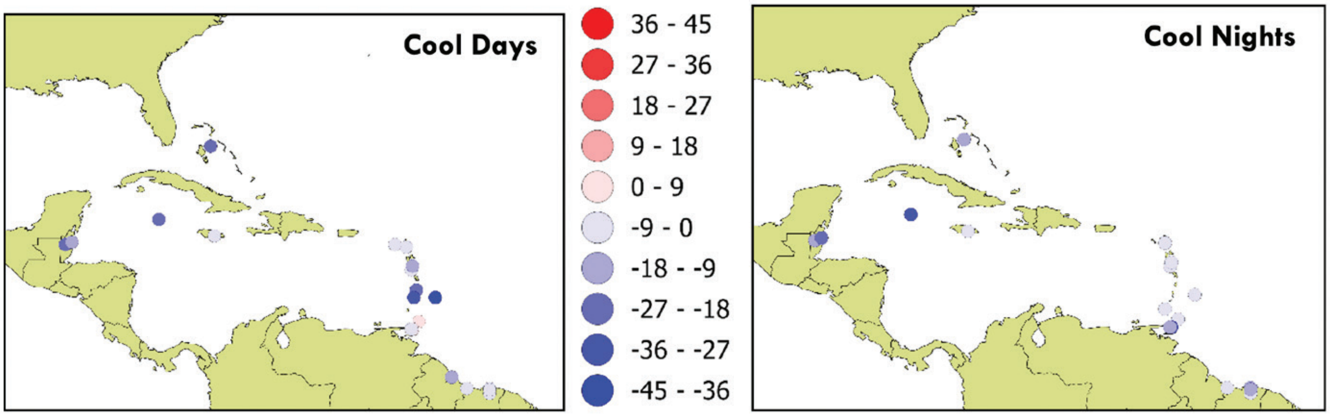


Figure 5.4: Projections of cool days and cool nights for the period 2090 to 2100 relative to 2006 to 2016 period for RCP 8.5. Units are in days.

5.3. RAINFALL

The following are noted about future changes in Caribbean rainfall from the GCM, RCM, and statistical downscaling projections.

- GCM projections suggest a drying trend in annual rainfall. Across all scenarios the drying is already established by the 2020s (up to 2% drier for the mean of all models). By the 2050s, the region is in the mean up to 6% drier, and by the end of century the region may be up to 17% drier (Figure 5.6).
- The Caribbean drying trend is likely driven by drying in the late wet season. It is slightly drier (up to ~ 1%) under all but a best-case scenario from as early as the 2020s. By the 2050s, it is up to 4% drier, while by the end of century, all scenarios result in drying, with up to 12% less rainfall projected for SON under RCP8.5.
- Drying in the Caribbean dry season (November through January) is projected to occur only under RCP8.5 in the 2050s and under RCP6 and RCP8.5 (up to 4%) by the end of the century. In general, the dry season may be slightly wetter or unaffected through to mid-century.
- The RCM projections suggest sub-regional variation in projections with some parts of the region being more significantly impacted by drier conditions than others (Table 5.8). A general pattern is for Belize in the far west Caribbean (Zone 1) and the Lesser Antilles and southern Caribbean (Zones 5 and 6) to be the most severely impacted once drying has onset, as well as the central Caribbean (Zone 4) to a lesser extent. Changes to mean annual rainfall in the far north and north Caribbean (Zones 2 and 3) suggest slightly wetter conditions through to mid-century which changes to drier conditions by the end of century. It is important to note however, that even for the far north Caribbean, the rainy seasons are projected to dry from as early as the 2020s.

Table 5.8: Range of percentage rainfall change across the six Caribbean zones from an RCM ensemble running the A1B scenario. Baseline is 1961-1990. See again Figure 2.3 for grid boxes in each zone.

		ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	ZONE 6
ANNUAL	**2020s**	-16.82 –11.03	-7.69 – 14.64	-9.16 – 16.16	-8.87 – 14.42	-20.15 – 4.09	-28.83 – -5.93
	2050s	-25.77 – 0.67	-4.4.3 – 9.90	-4.96 – 16.22	-28.16 – 21.66	-35.15 – 3.53	-37.82 – -13.92
	EOC	-38.32 – - 1.44	-6.82 – 9.39	-15.93 – -5.12	-41.09 – -11.40	-46.19 – -13.74	-54.32 – -0.69

- From as early as the 2020s, the wet seasons begin to show evidence of drying throughout the entire Caribbean. The RCMs project a mean decrease in rainfall during the May-July (MJJ) and September-November (SON) rainfall seasons in all six zones. Drying is also projected during the dry season (NDJ) in the far west and south Caribbean (Zones 1 and 6).
- The west (Zone 1), Lesser Antilles (Zone 5) and south (Zone 6) Caribbean seem most susceptible to drying. From as early as the 2020s, projections suggest drying in the far south Caribbean for all seasons of the year, while the west (Zone 1) and the Lesser Antilles (Zone 5) are projected to dry in three of four seasons. By the 2050s, RCMs project drying in all seasons for the Lesser Antilles and south Caribbean zones (Zones 5 and 6) and in three of four seasons in the west Caribbean (Zone 1). By the end of the century, RCMs project drying in all seasons for Zones 1, 4, 5, and 6.
- With respect to mean annual rainfall, the west Caribbean, Lesser Antilles and south Caribbean (Zones 1, 5, and 6) are projected to decrease in the mean by up to 3%, 6%, and 16% respectively from as early as the 2020s. In contrast the far north, north and central Caribbean (Zones 2, 3, and 4) show a slight increase of up to 3%, 2%, and 1%, respectively. By the 2050s, projections show a mean annual decrease in Zones 1, 4, 5, and 6 of 10%, 5%, 12%, and 22%, respectively. However, Zones 2 and 3 show an increase of up to 4% and 2%, respectively. By the end of the century, drying is projected across all zones, with the least drying occurring in Zone 2 and the greatest in Zone 6.

- SDSM projections show a likely increase in heavy rainfall as suggested by projected increases in the following extreme rainfall indices: number of days with rainfall above 10 mm, maximum 1-day rainfall, and maximum 5-day rainfall across most of the region.

5.3.1. GCMS

GCM projections are provided below for annual, late wet season, and dry season rainfall across the Caribbean relative to a 1985 – 2005 baseline (Tables 5.9-5.11 and Figure 5.5).

Table 5.9: Mean percentage change in rainfall for the Caribbean with respect to 1986-2005. Changes are shown for the four RCP scenarios. Source: AR5 CMIP5 subset, KNMI Climate Change Atlas.

	ANNUAL RAINFALL								
	2020s			2050s			END OF CENTURY		
Averaged over	2020-2029			2050-2059			2091-2100		
	min	mean	max	min	mean	max	min	mean	max
rcp26	-6.44	-0.22	10.06	-8.55	-0.09	14.75	-27.75	-0.46	10.73
rcp45	-12.09	-1.77	8.76	-20.50	-4.30	16.96	-32.45	-5.26	17.44
rcp60	-12.47	-0.86	11.75	-12.26	-2.42	10.62	-34.97	-6.91	10.74
rcp85	-11.33	-0.99	16.36	-20.06	-6.27	15.48	-51.13	-16.95	15.48
Range of mean:	**-1.77 – -0.22**			**-6.27 – -0.09**			**-16.95 – -0.46**		

Table 5.10: Mean percentage change in late season (September-November) rainfall for the Caribbean with respect to 1986-2005. Changes are shown for the four RCP scenarios. Source: AR5 CMIP5 subset, KNMI Climate Change Atlas.

	LATE RAINFALL SEASON								
	2020s			2050s			END OF CENTURY		
Averaged over	2020-2029			2050-2059			2091-2100		
	Min	mean	max	min	mean	max	min	mean	max
rcp26	-8.35	0.43	17.61	-9.82	0.53	13.34	-23.72	-0.26	15.28
rcp45	-15.89	-0.49	14.88	-23.31	-2.62	25.45	-30.41	-3.63	22.75
rcp60	-9.38	-0.64	10.99	-15.78	-2.28	11.61	-33.88	-4.91	16.09
rcp85	-9.48	0.37	16.28	-21.23	-4.30	18.56	-51.52	-12.27	36.64
Range of mean:	**-0.64 – 0.43**			**-4.30 – 0.53**			**-12.27 – -0.26**		

Table 5.11: Mean percentage change in dry season (November-January) rainfall for the Caribbean with respect to 1986-2005. Changes are shown for four RCP scenarios. Source: AR5 CMIP5 subset, KNMI Climate Change Atlas.

	DRY SEASON RAINFALL								
	2020s			2050s			END OF CENTURY		
Averaged over	2020-2029			2050-2059			2091-2100		
	min	mean	max	min	mean	max	min	mean	max
rcp26	-16.25	1.02	16.27	-11.68	1.86	14.22	-24.60	1.55	18.25
rcp45	-9.83	0.59	14.04	-13.21	0.68	18.52	-29.30	0.32	20.15
rcp60	-11.21	-1.23	11.12	-11.04	0.71	15.13	-30.28	-1.40	18.85
rcp85	-11.42	2.11	17.45	-16.25	-0.19	17.28	-43.76	-4.06	36.02
Range of mean:	**-1.23 – 2.11**			**-0.19 – 1.86**			**-4.06 – 1.55**		

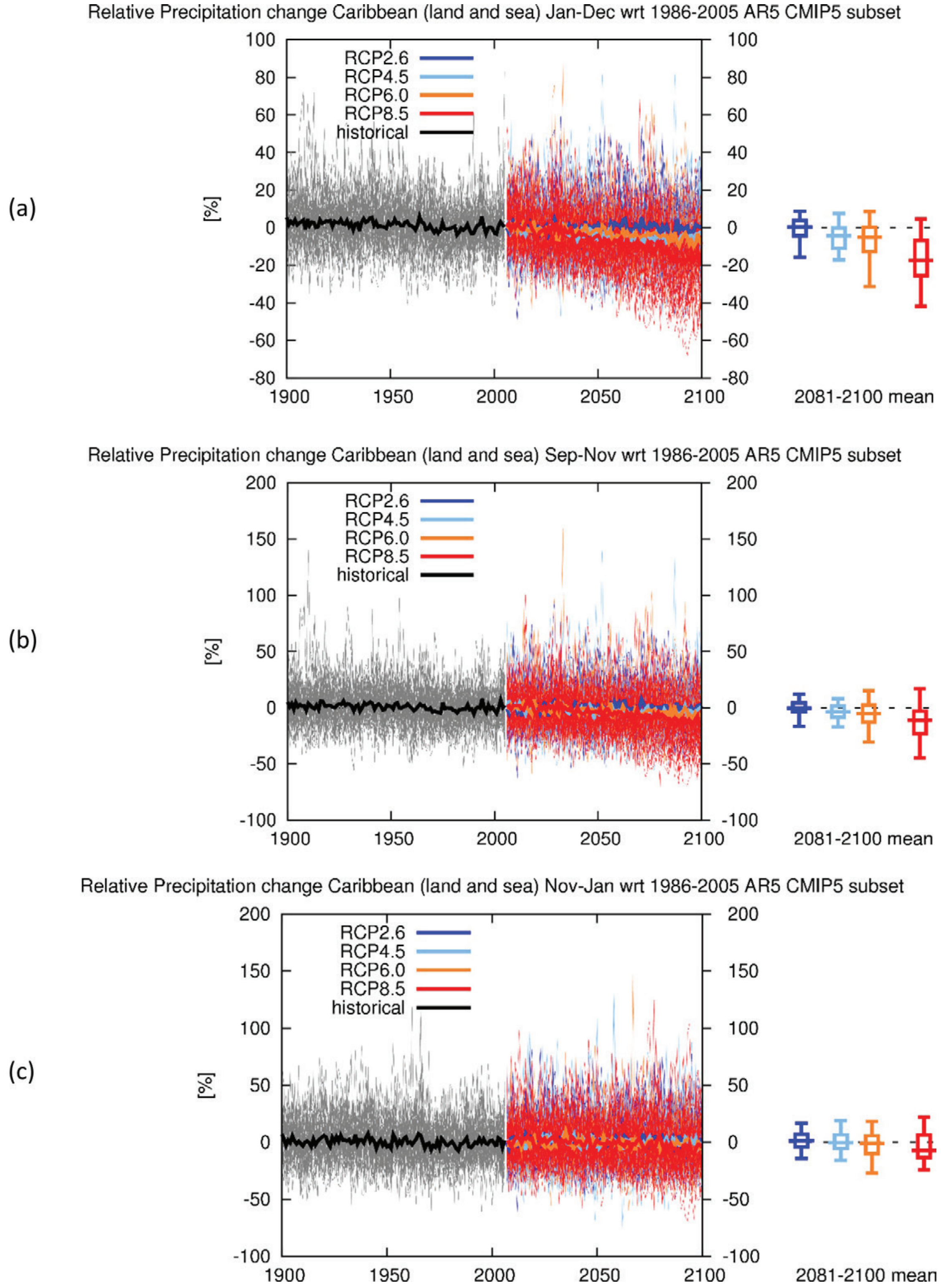


Figure 5.5: (a) Relative Annual Precipitation change (%) (b) Relative September-November Precipitation change (%) (c) Relative November-January Precipitation change (%) for the Caribbean with respect to 1986-2005 AR5 CMIP5 subset. On the left, for each scenario one line per model is shown plus the multi-model mean, on the right percentiles of the whole dataset: the box extends from 25% to 75%, the whiskers from 5% to 95% and the horizontal line denotes the median (50%).

5.3.2. RCMS

Rainfall Projections for the region from the PRECIS RCM have been provided in Table 5.12 below. A summary map showing percentage change per grid box of annual rainfall is given in Figure 5.6

Table 5.12: Percentage change in precipitation (%) for (a) the 2020s (2020-2029), (b) 2050s (2050-2059), and (c) end of century, EOC (2081-2098) relative to the 1962-1989 baseline. Values are representative of the 6 zones shown in Figure 2.3.

ZONE 1

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	-16.77	-5.03	8.56	-9.84	-2.49	5.55	-18.33	-5.55	32.31
FMA	-10.81	6.52	23.62	-4.56	3.63	11.64	-35.31	-10.07	26.75
MJJ	-29.01	-5.92	20.56	-48.76	-15.77	6.09	-65.52	-38.38	-17.54
SON	-21.47	-8.32	2.33	-39.93	-23.60	-11.24	-55.75	-38.66	-26.14
ANN	**-16.82**	**-3.19**	**11.03**	**-25.77**	**-9.56**	**0.67**	**-38.32**	**-23.16**	**-1.44**

ZONE 2

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	-11.61	1.31	19.61	-5.16	8.16	15.43	0.89	13.78	24.11
FMA	-4.88	15.03	42.19	-4.97	6.25	16.04	0.59	6.84	18.99
MJJ	-20.09	-5.66	18.65	-5.28	0.44	11.96	-23.72	-7.71	9.48
SON	-10.96	-0.26	8.21	-15.99	-0.44	6.62	-22.37	-14.78	-3.19
ANN	**-7.69**	**2.61**	**14.64**	**-4.43**	**3.60**	**9.90**	**-6.82**	**-0.47**	**9.39**

ZONE 3

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	-8.62	2.24	15.41	-1.44	7.90	19.49	1.76	11.22	30.52
FMA	-4.24	13.86	32.72	10.13	19.01	32.49	-8.53	9.10	18.09
MJJ	-13.00	-2.41	20.15	-20.41	-4.83	22.80	-47.38	-31.35	-19.83
SON	-14.79	-4.47	1.55	-18.22	-15.34	-9.90	-37.95	-32.25	-22.24
ANN	**-9.16**	**2.31**	**16.16**	**-4.96**	**1.69**	**16.22**	**-15.93**	**-10.82**	**-5.12**

ZONE 4

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	-0.49	7.99	16.57	-30.88	1.65	26.87	-27.36	-0.39	25.29
FMA	-9.50	6.75	33.04	-15.09	12.75	42.40	-25.28	-1.31	23.74
MJJ	-13.69	-4.76	7.51	-38.82	-7.75	43.46	-66.85	-48.03	-36.20
SON	-22.65	-5.22	10.11	-27.84	-25.32	-22.33	-44.88	-39.13	-29.55
ANN	**-8.87**	**1.19**	**14.42**	**-28.16**	**-4.67**	**21.66**	**-41.09**	**-22.22**	**-11.40**

ZONE 5

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	-9.40	1.54	18.43	-39.01	-10.26	3.48	-38.42	-15.73	19.60
FMA	-25.98	-6.18	11.38	-31.28	-8.73	10.91	-39.41	-21.56	1.55
MJJ	-30.45	-12.18	6.47	-43.15	-10.47	29.71	-66.27	-49.49	-32.14
SON	-14.76	-6.24	3.45	-27.16	-18.07	-12.48	-42.29	-30.83	-13.66
ANN	**-20.15**	**-5.76**	**4.09**	**-35.15**	**-11.88**	**3.53**	**-46.19**	**-29.40**	**-13.74**

ZONE 6

	2020s			2050s			EOC		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
NDJ	-22.80	-13.66	-2.64	-41.36	-19.84	-4.93	-56.48	-28.01	35.40
FMA	-40.88	-18.00	-1.73	-48.23	-30.34	-13.74	-60.07	-46.96	-22.06
MJJ	-30.30	-11.98	4.20	-28.16	-8.84	14.55	-61.18	-33.53	-8.09
SON	-24.56	-19.10	-11.21	-37.28	-27.57	-7.11	-54.72	-27.49	22.40
ANN	**-28.83**	**-15.68**	**-5.93**	**-37.82**	**-21.65**	**-13.92**	**-54.32**	**-34.00**	**-0.69**

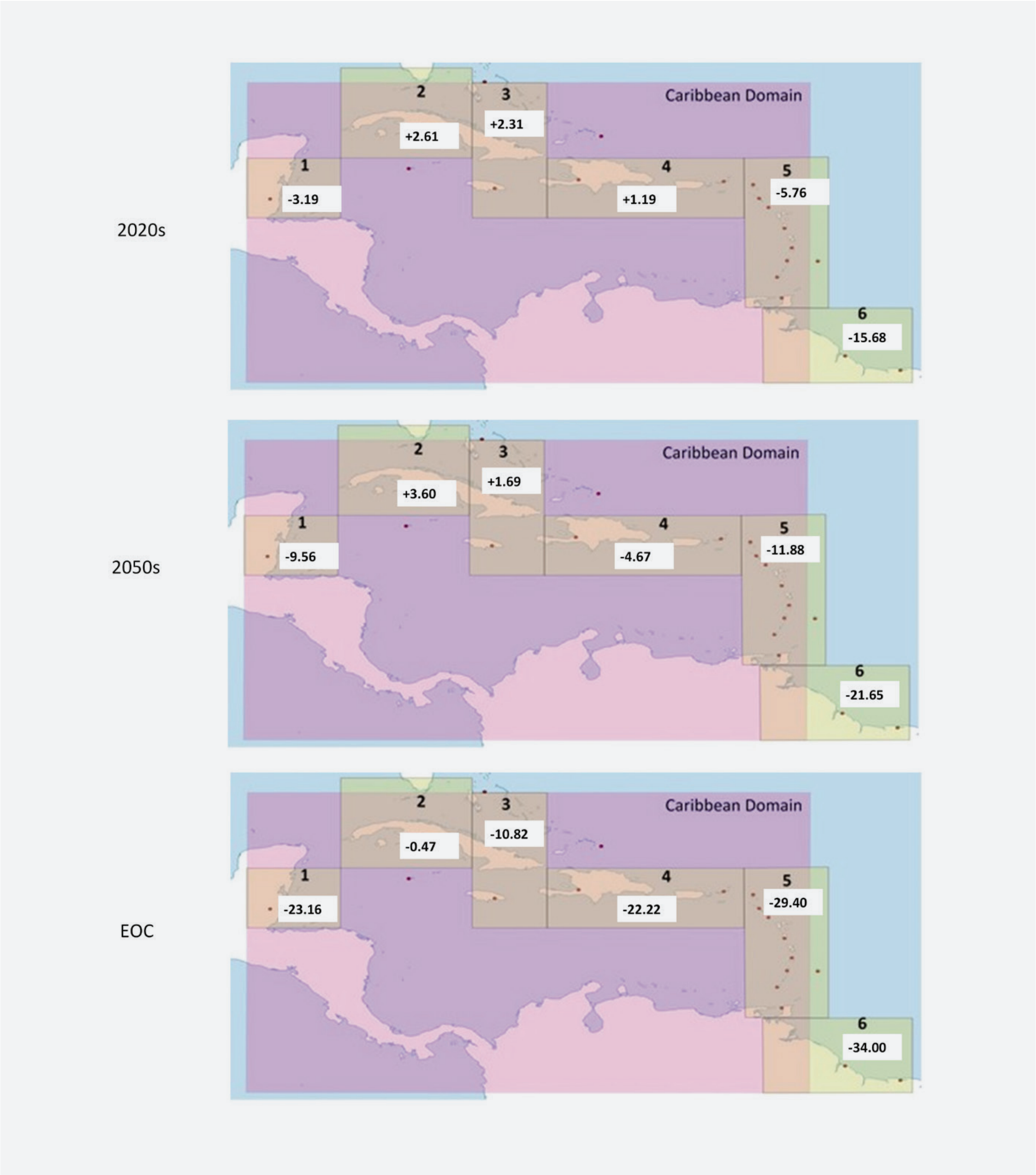


Figure 5.6: Summary map showing percentage change per zone of annual rainfall for the 2020s (top panel), 2030s (middle panel) and 2030s (bottom panel). Source: PRECIS RCM PPE.

5.3.3. RAINFALL EXTREMES

Figure 5.7 shows spatial results for consecutive dry days (CDD) and days with rainfall amounts greater than 10 mm (R10) for the end of century period (2090 to 2100) for RCP 8.5. Generally, the Statistical Downscaling Model (SDSM) projected an increase in R10. Greatest projected percentage change in R10 was observed for Point Salines in Grenada (an increase of 305%). Smallest change was projected for Hewanorra in St. Lucia (6%). Some stations projected a small decline in CDD while others projected major increases. GAIA in Barbados had a projected increase in CDD of 398% whereas Lelydorp in Suriname had a projected decrease of 63%.

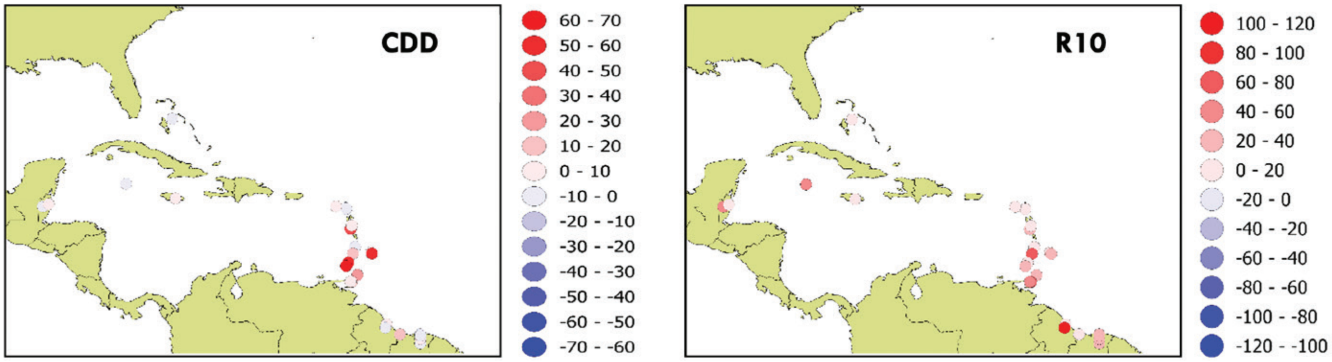


Figure 5.7: Projections of CDD and R10 for the period 2090 to 2100 relative to 2006 to 2016 period for RCP 8.5. Units are in days for CDD and mm for R10

Figure 5.8 shows projected changes in other heavy rainfall indices, namely maximum one-day rainfall (RX1) and maximum five-day rainfall (RX5) for 2090 to 2100 for RCP 8.5. The general trend is for an increase in both RX1 and RX5. Greatest percentage change is projected for St. Augustine, Trinidad of 185% and 195% for RX1 and RX5 respectively. Smallest percentage change was observed for Maurice Bishop International Airport (MBIA), Grenada (1%) for RX1 and St. Kitts (5%) for RX5. Georgetown, Guyana was the only station that had a projected decrease in both RX1 (8%) and RX5 (3%). CIMH, Barbados (3%) and Melville Hall, Dominica (2%) had a projected decrease for RX5.

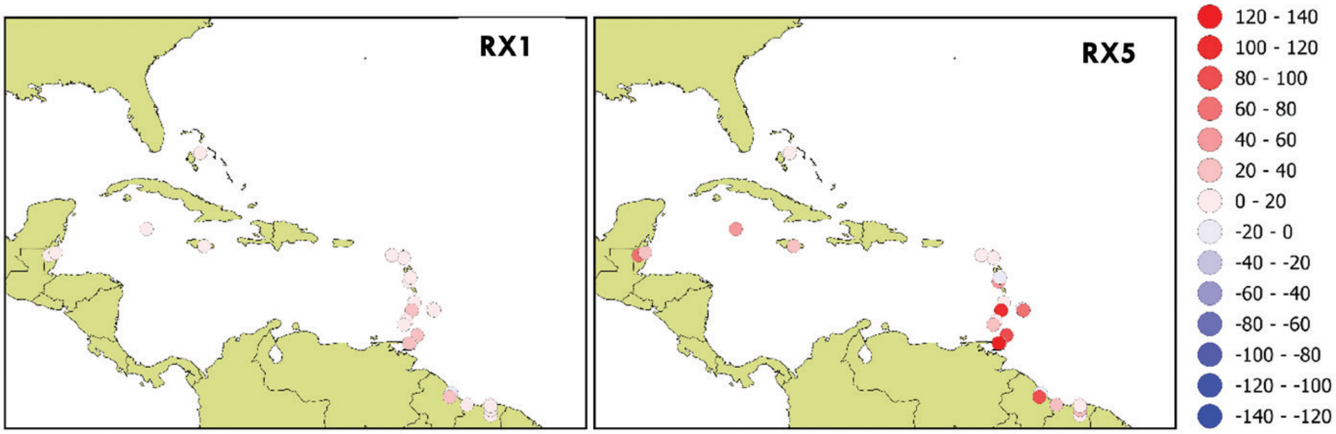


Figure 5.8: RX1 and RX5 for the period 2090 to 2100 relative to 2006 to 2016 period for RCP 8.5. Units are in mm.

5.4. HURRICANES

The IPCC Special Report on Extremes (IPCC 2012) offers five summary statements with respect to projections of future hurricane under global warming which are of relevance to the region. They are reiterated below as major conclusions, and supported with additional information (where available) specific for the Atlantic basin.

CONCLUSION 1: THERE IS LOW CONFIDENCE IN PROJECTIONS OF CHANGES IN TROPICAL CYCLONE GENESIS, LOCATION, TRACKS, DURATION, OR AREAS OF IMPACT.

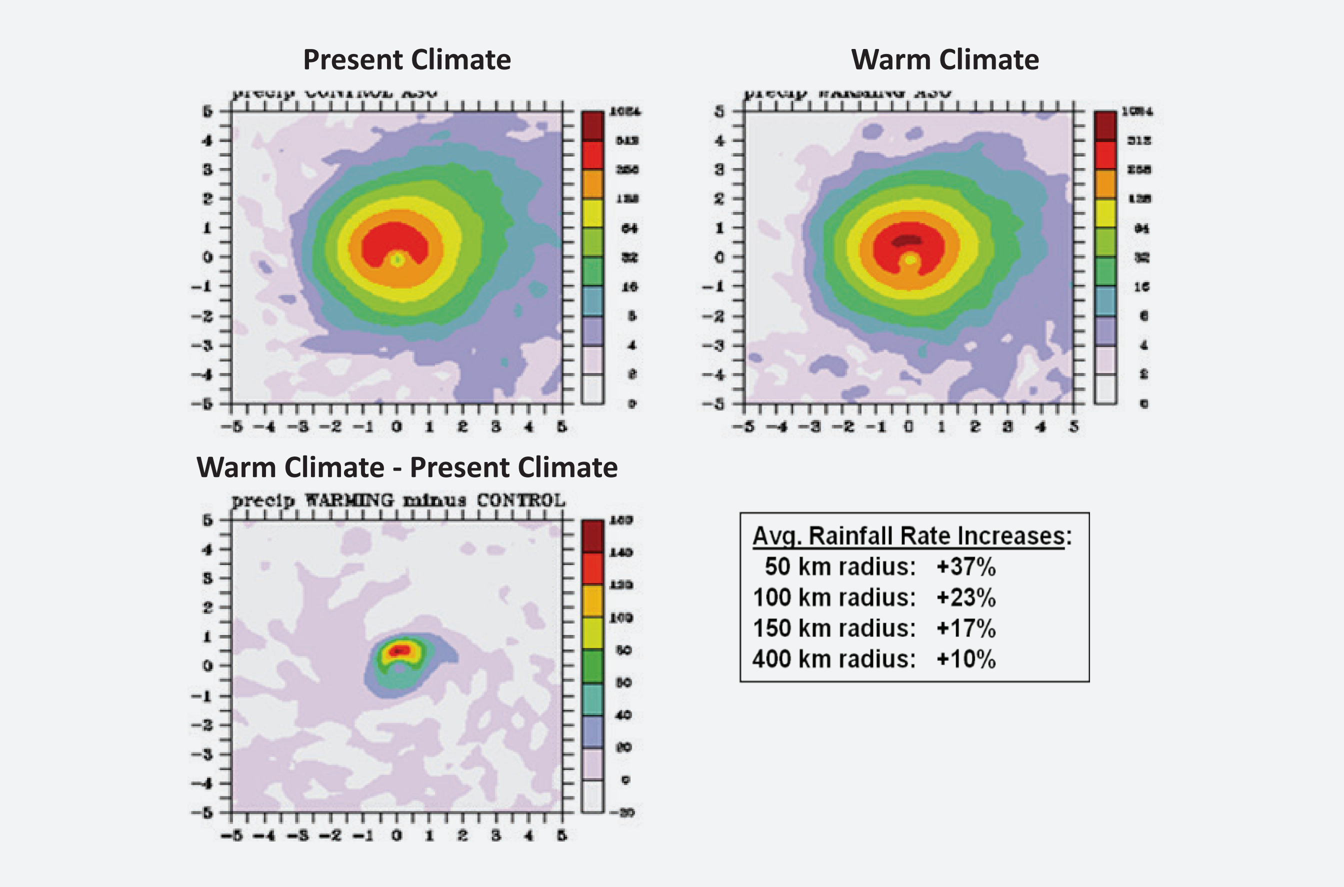
Tropical cyclone genesis and track variability is modulated in most regions by known modes of atmosphere-ocean variability. The details of the relationships vary by region (for example, El Niño events tend to suppress Atlantic storm genesis and development). The accurate modelling, then, of tropical cyclone activity fundamentally depends on the model's ability to reproduce these modes of variability to produce reliable projections of the behaviour of these modes of variability (for example, ENSO) under global warming, as well as on a good understanding of their physical links with tropical cyclones. At present, there is still uncertainty in the model's ability to project these behaviours.

CONCLUSION 2: BASED ON THE LEVEL OF CONSISTENCY AMONG MODELS, AND PHYSICAL REASONING, IT IS LIKELY THAT TROPICAL CYCLONE RELATED RAINFALL RATES WILL INCREASE WITH GREENHOUSE WARMING.

Observed changes in rainfall associated with tropical cyclones have not been clearly established. However, as water vapor in the tropics increases, there is an expectation for increased heavy rainfall associated with tropical cyclones. Models in which tropical cyclone precipitation rates have been examined are highly consistent in projecting increased rainfall within the area near the tropical cyclone centre under 21st-century warming, with increases of 3 to 37% (Knutson et al. 2010). Typical projected increases are near 20% within 100 km of storm centres (see Figure 5.9). More recent work premised on RCP 4.5 suggest that rainfall rates increase robustly for the CMIP3 and CMIP5 scenarios (Knutson et al. 2013). For the late twenty-first century, the increase amounts to +20% to +30% in the model hurricane's inner core, with a smaller increase (~10%) at radii of 200 km or larger.

CONCLUSION 3: IT IS LIKELY THAT THE GLOBAL FREQUENCY OF TROPICAL CYCLONES WILL EITHER DECREASE OR REMAIN ESSENTIALLY UNCHANGED.

Hurricane research done at NOAA's GFDL laboratory using regional models projects that Atlantic hurricane and tropical storms are **substantially reduced in number,** for the average 21st-century climate change projected by current models, but will have **higher rainfall rates**, particularly near the storm centre. http://www.gfdl.noaa.gov/global-warming-and-hurricaneshttp://www.gfdl.noaa.gov/global-warming-and-hurricanes



Avg. Rainfall Rate Increases:

50 km radius:	+37%
100 km radius:	+23%
150 km radius:	+17%
400 km radius:	+10%

Figure 5.9: Rainfall rates (mm/day) associated with simulated tropical storms in a) a present climate b) warm climate c) warm minus present climate. Average warming is 1.72 °C. From Knutson et al. (2010).

CONCLUSION 4: AN INCREASE IN MEAN TROPICAL CYCLONE MAXIMUM WIND SPEED IS LIKELY, ALTHOUGH INCREASES MAY NOT OCCUR IN ALL TROPICAL REGIONS.

Assessments of projections by Knutson et al. (2010), Bender et al., (2010) and statistical-dynamical models (Emanuel, 2007) are consistent that that greenhouse warming causes tropical cyclone intensity to shift toward stronger storms by the end of the 21st century as measured by maximum wind speed increases by +2 to +11%.

CONCLUSION 5: WHILE IT IS LIKELY THAT OVERALL GLOBAL FREQUENCY WILL EITHER DECREASE OR REMAIN ESSENTIALLY UNCHANGED, IT IS MORE LIKELY THAN NOT THAT THE FREQUENCY OF THE MOST INTENSE STORMS WILL INCREASE SUBSTANTIALLY IN SOME OCEAN BASINS.

The downscaling experiments of Bender et al. (2010) project a 28% reduction in the overall frequency of Atlantic storms and an 80% increase in the frequency of Saffir-Simpson category 4 and 5 Atlantic hurricanes over the next 80 years using the A1B scenario. Downscaled projections using CMIP5 multi-model scenarios (RCP4.5) as input (Knutson et al. 2013) still show increases in category 4 and 5 storm frequency, but these are only marginally significant for the early 21st century (+45%) or the late 21st century (+40%) using CMIP5 scenarios.

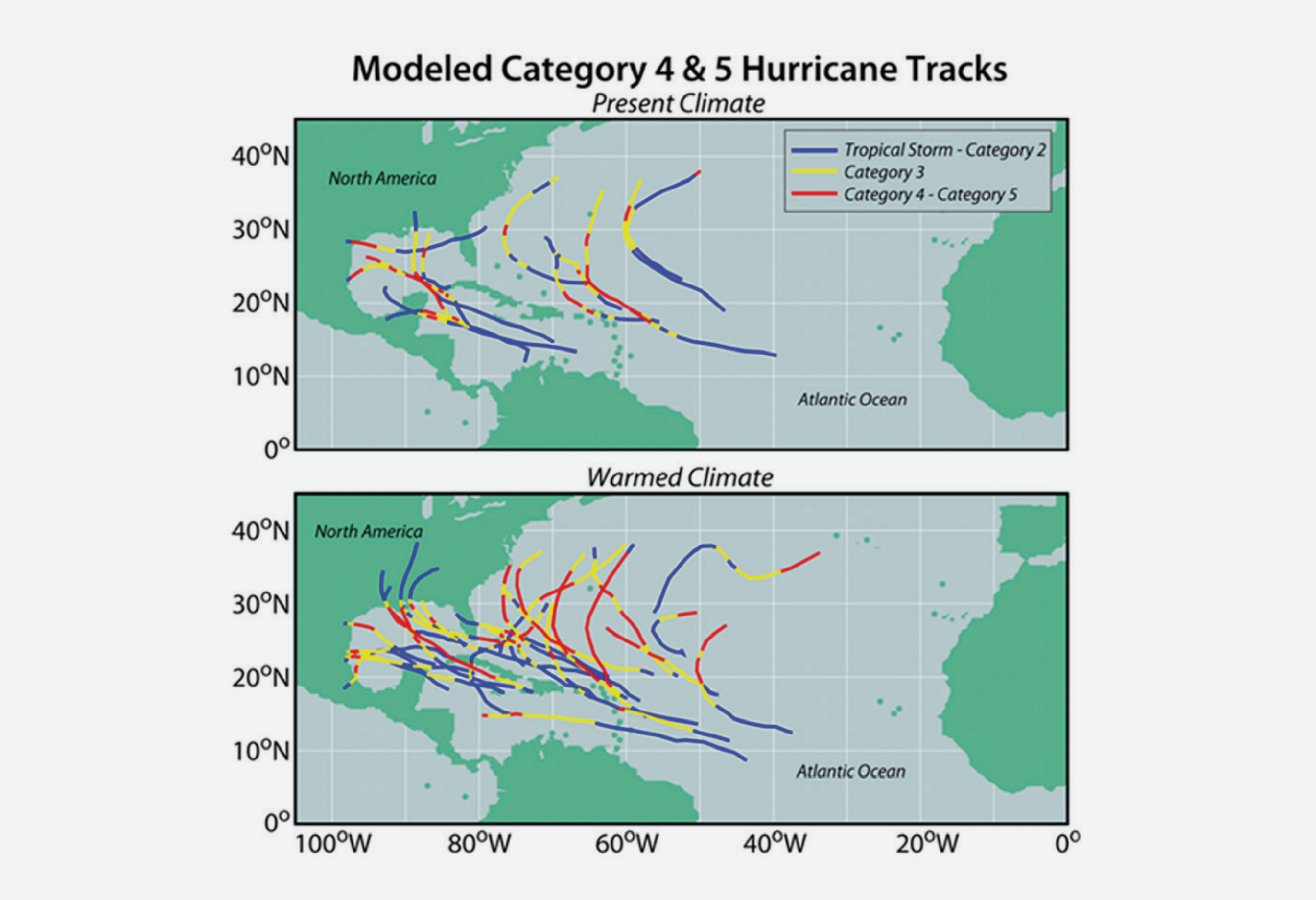
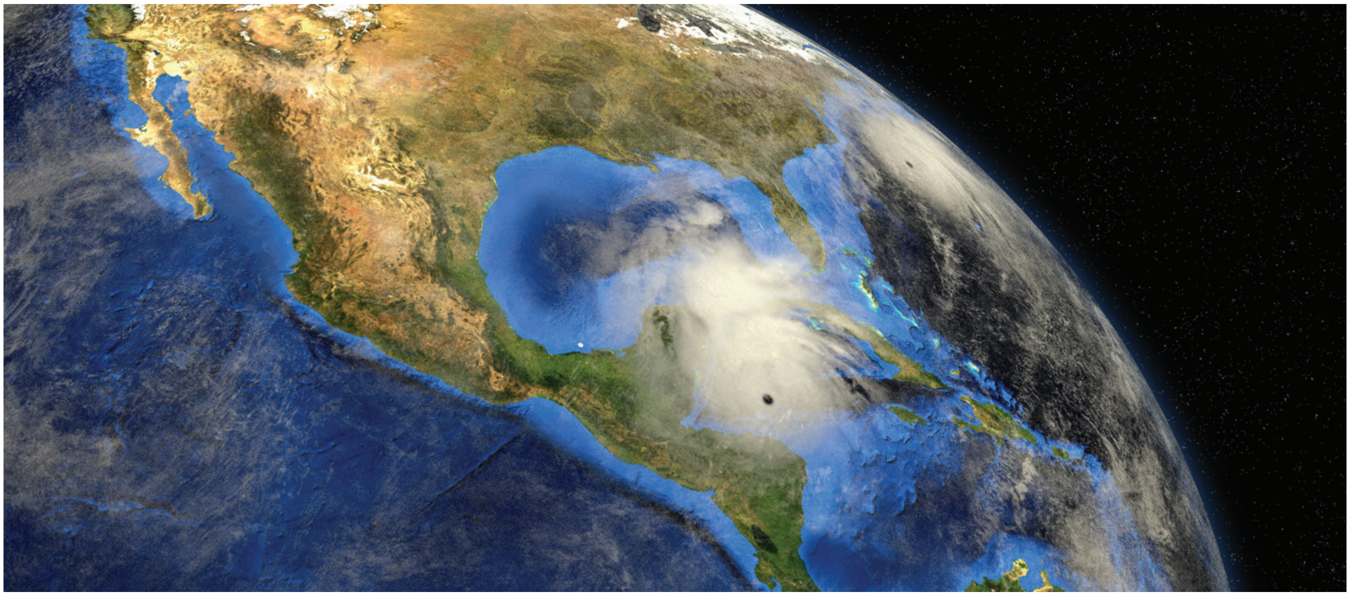
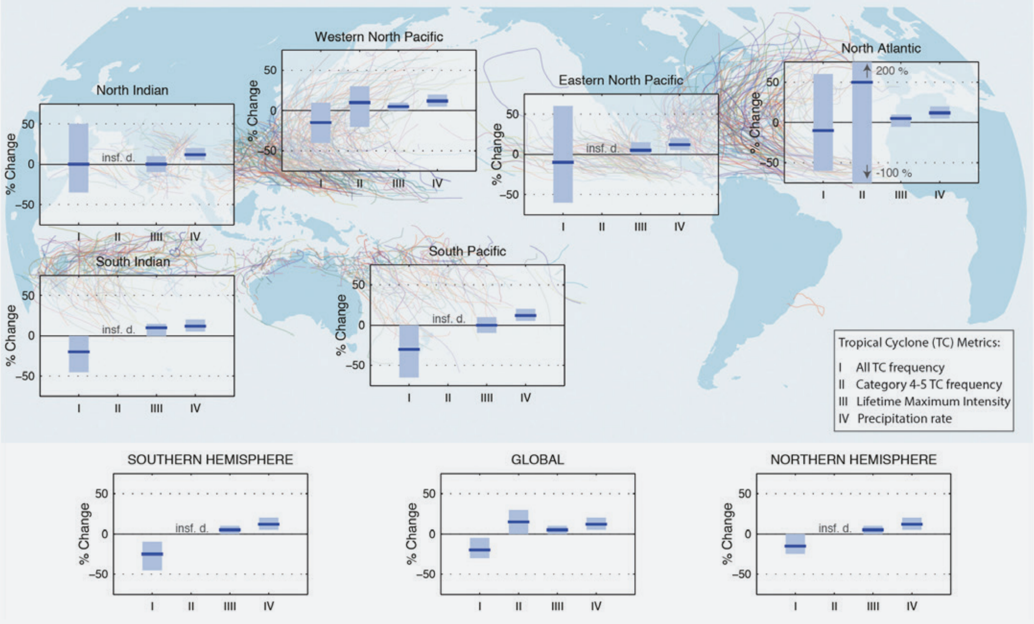


Figure 5.10: Late 21st century warming projections of category 4 and 5 hurricanes in the Atlantic. Average of 18 CMIP3 models. From Bender et al. (2010).

The uncertainty evident in the five conclusions suggests that at the very least the Caribbean should contemplate a future where tropical storm/hurricane genesis, frequency and tracks are similar to what has been experienced in the very recent past (last two decades), but intensities (rainfall rates and wind speeds) are increased.





27 Simulated Hurricane Seasons

Figure 5.11: IPCC AR5 Summary Diagram
General consensus assessment of the numerical experiments described in IPCC (2013) Supplementary Material Tables 14.SM.1 to 14.SM.4. All values represent expected percent change in the average over period 2081–2100 relative to 2000–2019, under an A1B-like scenario, based on expert judgement after subjective normalization of the model projections. Four metrics were considered: the percent change in (I) the total annual frequency of tropical storms, (II) the annual frequency of Category 4 and 5 storms, (III) the mean Lifetime Maximum Intensity (LMI; the maximum intensity achieved during a storm's lifetime) and (IV) the precipitation rate within 200 km of storm centre at the time of LMI. For each metric plotted, the solid blue line is the best guess of the expected percent change, and the coloured bar provides the 67% (likely) confidence interval for this value (note that this interval ranges across –100% to +200% for the annual frequency of Category 4 and 5 storms in the North Atlantic). Where a metric is not plotted, there are insufficient data (denoted 'insf. d.') available to complete an assessment. A randomly drawn (and coloured) selection of historical storm tracks are underlain to identify regions of tropical cyclone activity.

5.5. SEA LEVELS

5.5.1. GLOBE AND CARIBBEAN

Projections of sea level rise for the globe and for the Caribbean region from the IPCC's Fourth assessment report are given in Table 5.13. There is not a significant difference between the global SLR projections and projections of Caribbean SLR.

Table 5.13: Projected changes in sea level by 2090s from a regional climate model.

SCENARIO	GLOBAL MEAN SEA LEVEL RISE BY 2100 RELATIVE TO 1980 – 1999	CARIBBEAN MEAN SEA LEVEL RISE BY 2100 RELATIVE TO 1980 – 1999 (± 0.05M RELATIVE TO GLOBAL MEAN)
IPCC B1	0.18 – 0.38	0.13 – 0.43
IPCC A1B	0.21 – 0.48	0.16 – 0.53
IPCC A2	0.23 – 0.51	0.18 – 0.56

The Fifth Assessment Report of the IPCC does not provide projections for the Caribbean separate from that for the global mean. Using the assumption that Caribbean SLR is similar to that for the globe, Figure 5.12 depicts the rate of change in global sea level for RCP 2.6 and RCP8.5. Table 5.14 also summarizes global sea level rise for a mid-century and an end of century period for the four RCPs. Sea level rise projections are similar through to mid-century irrespective of RCP. Toward the end of the century the projections diverge with the higher RCPs associated with higher sea levels.

A number of studies, (e.g. Rahmstorf [2007]; Rignot and Kanargaratnam [2006]; Horton et al. [2008]) including some assessed in the IPCC's Fifth Assessment Report, suggest that the upper bound for the global estimates given in Table 5.13 are conservative and could be much higher, with a rate of 8 to 16 mm/year by the end of century (2081–2100). Diagrams from Perrette et al. (2013) suggest the same for estimates for the Caribbean Sea i.e. a higher upper bound of up to 1.5 m of seal level rise by the end of the century.

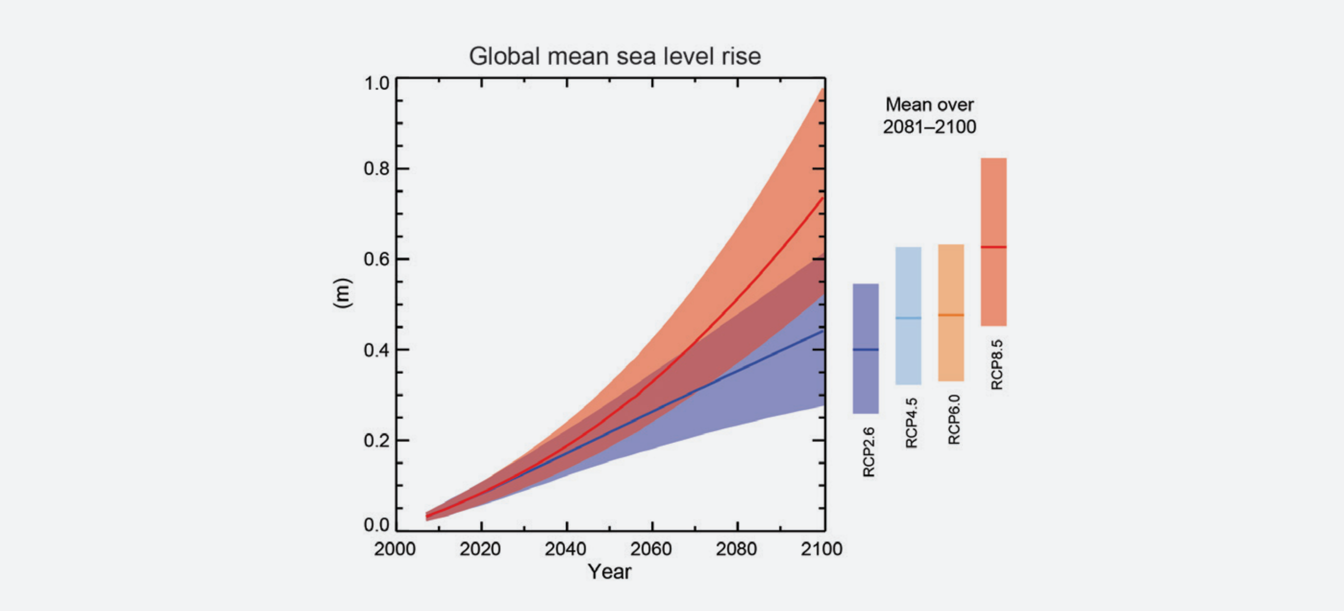


Figure 5.12: Projections of global mean sea level rise over the 21st century relative to 1986–2005 from the combination of the CMIP5 ensemble with process-based models, for RCP2.6 and RCP8.5.The assessed likely range is shown as a shaded band. The assessed likely ranges for the mean over the period 2081–2100 for all RCP scenarios are given as coloured vertical bars, with the corresponding median value given as a horizontal line. From IPCC (2013)

Table 5.14: Projected increases in global mean sea level (m) - Projections are taken from IPCC (2013) and are relative to 1986-2005 baseline levels.

TIME PERIOD		2046 – 2065		2081– 2100	
VARIABLE	SCENARIO	MEAN	LIKELY RANGE	MEAN	LIKELY RANGE
GLOBAL MEAN SEA LEVEL RISE (m)	RCP2.6	0.24	0.17 – 0.32	0.40	0.26 – 0.55
	RCP4.5	0.26	0.19 – 0.33	0.47	0.32 – 0.63
	RCP6.0	0.25	0.18 – 0.32	0.48	0.33 – 0.63
	RCP8.5	0.30	0.22 – 0.38	0.63	0.45 – 0.82

5.5.2. ZONES

Estimates for projected sea level rise across the six zones into which the Caribbean has been divided are provided in Table 5.15. Projections are shown for two RCPs. Regional variation is small with the north Caribbean tending to have slightly higher projected values than the southern Caribbean. By the end of the century, sea level rise is projected to reach or exceed 1 m across the Caribbean.

Table 5.15: Sea level rise projections for six Caribbean zones from the AR5 ensemble of 21 CMIP5 models. Projections are for the ensemble mean and the likely range represented by the 5% and 95% uncertainty bounds (See Chapter13 Sea Level Rise Supplementary Material[8]). Maximum projections for the listed decades are provided for two RCPs. Projections are relative to 1986-2005. Data source: Integrated Climate Data Center.

ZONE 1	4.5			8.5		
	5%	MEAN	95%	5%	MEAN	95%
2020	0.08	0.13	0.18	0.10	0.14	0.19
2050	0.18	0.28	0.40	0.21	0.33	0.46
2090	0.31	0.52	0.74	0.46	0.71	1.01

ZONE 2	4.5			8.5		
	5%	MEAN	95%	5%	MEAN	95%
2020	0.07	0.12	0.17	0.07	0.13	0.19
2050	0.18	0.29	0.41	0.21	0.32	0.44
2090	0.33	0.55	0.78	0.43	0.72	1.04

ZONE 3	4.5			8.5		
	5%	MEAN	95%	5%	MEAN	95%
2020	0.07	0.13	0.18	0.07	0.13	0.19
2050	0.18	0.30	0.41	0.21	0.33	0.45
2090	0.34	0.55	0.78	0.44	0.71	1.02

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[8] AR5 Sea Level Change Supplementary Material, Chapter 13:
Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, 2013: Sea Level Change Supplementary Material. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)].

ZONE 4	4.5			8.5		
	5%	MEAN	95%	5%	MEAN	95%
2020	0.05	0.11	0.17	0.05	0.11	0.17
2050	0.16	0.26	0.37	0.18	0.29	0.41
2090	0.30	0.51	0.73	0.38	0.66	0.98

ZONE 5	4.5			8.5		
	5%	MEAN	95%	5%	MEAN	95%
2020	0.06	0.11	0.17	0.07	0.11	0.16
2050	0.16	0.27	0.38	0.20	0.30	0.41
2090	0.31	0.52	0.74	0.42	0.69	0.99

ZONE 6	4.5			8.5		
	5%	MEAN	95%	5%	MEAN	95%
2020	0.07	0.11	0.15	0.07	0.11	0.15
2050	0.18	0.26	0.35	0.21	0.30	0.39
2090	0.31	0.49	0.70	0.44	0.68	0.95

5.5.3. SEA LEVEL EXTREMES

ADAPTED FROM IPCC (2013)

Higher mean sea levels can significantly decrease the return period for exceeding given threshold levels. Hunter (2012) determined the factor by which the frequency of sea levels exceeding a given height would be increased for a mean sea level rise of 0.5 m for a network of 198 tide gauges covering much of the globe (Figure 5.13). The AR5 repeats the calculations using regional sea level projections and their uncertainty under the RCP4.5 scenario. The multiplication factor depends exponentially on the inverse of the Gumbel scale parameter (a factor which describes the statistics of sea level extremes caused by the combination of tides and storm surges) (Coles and Tawn 1990). The scale parameter is generally large where tides and/or storm surges are large, leading to a small multiplication factor, and vice versa. Figure 5.13 shows that 0.5 m mean sea level rise would likely result in the frequency of sea level extremes increasing by an order of magnitude or more in some regions. The multiplication factors are found to be slightly higher, in general, when accounting for regional mean sea level projections. In regions having higher regional projections of mean sea level the multiplication factor is higher, whereas in regions having lower regional projections of mean sea level the multiplication factor is lower.

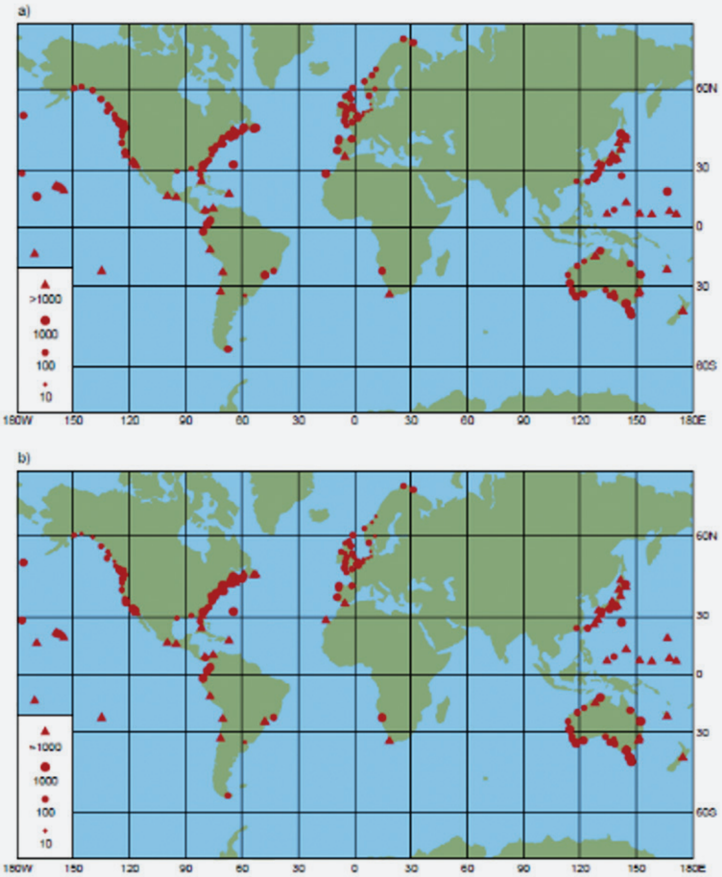

Figure 5.13: The estimated multiplication factor (shown at tide gauge locations by red circles and triangles), by which the frequency of flooding events of a given height increase for (a) a mean sea level rise of 0.5 m (b) using regional projections of mean sea level. The Gumbel scale parameters are generally large in regions of large tides and/or surges resulting in a small multiplication factor and vice versa. IPCC (2013)

5.6. SEA SURFACE TEMPERATURES

Not a lot of studies have examined projections of SSTs for the Caribbean. Antuna et al. (2015) determine future Caribbean SSTs for the period 2000-2099 for both a business-as-usual and a low CO2 emission scenario using a coupled ocean-atmosphere model. Their results are summarized in Table 5.16. The results show a continuation of the recent warming trend in SST (see again Chapter 4).

Table 5.16: Projected north tropical Atlantic SST trends (°C per century) for two future scenarios. Bracketed numbers indicate standard errors. Adapted from Antuna et al. (2015).

SST INCREASE (°C PER CENTURY)		
	BUSINESS-AS-USUAL SCENARIO	LOW CO2 SCENARIO
ANTILLES	1.80 (0.41)	0.77 (0.38)
WIDER CARIBBEAN	1.76 (0.39)	0.86 (0.43)
TROPICAL ATLANTIC	1.72 (0.42)	0.70 (0.42)

Nurse and Charlery (2014) also produced SST projections for two future SRES scenarios using data from a regional climate model. They examined three future time slices and deduced that SSTs will increase across the region throughout the twenty-first century irrespective of scenario examined. They note, however, that the mean decadal rate of warming increases from 0.13°C for the 30 year period 2000-2029 to 0.31°C for 2030-2059, and eventually reaches 0.41°C for 2070-2099 i.e., the warming intensifies.

Nurse and Charlery (2014) also suggest the following about the future warming of Caribbean SSTs:

- By mid-century, the expanding and contracting of the Atlantic Warm Pool (AWP) is replaced by a “blanket” of uniformly warm temperatures across the Caribbean Sea throughout the entire year. The projected SSTs therefore exceed 28°C across the entire Caribbean Sea year-round.
- The mean annual SST range of approximately 3.3°C currently observed in the Caribbean Sea is projected to contract to 2.9°C in the 2030s and to 2.3°C in the 2090s. By the end of the century, years of coolest projected SSTs fall within the range of the warmest years in the present.

This projected increase in Caribbean SST trends will likely support the generation of more intense future hurricanes and have increasingly negative impacts on coral health and general marine ecology (Taylor and Stephenson 2017).

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.

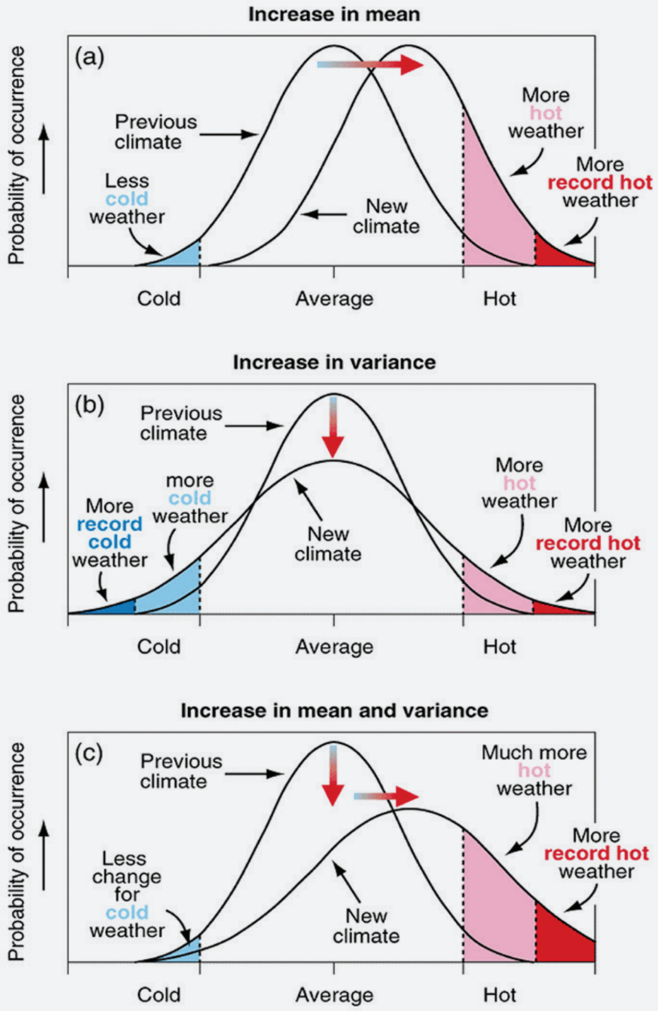

Figure 6.1: Schematic showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature. Source: IPCC (2001).

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).

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[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).

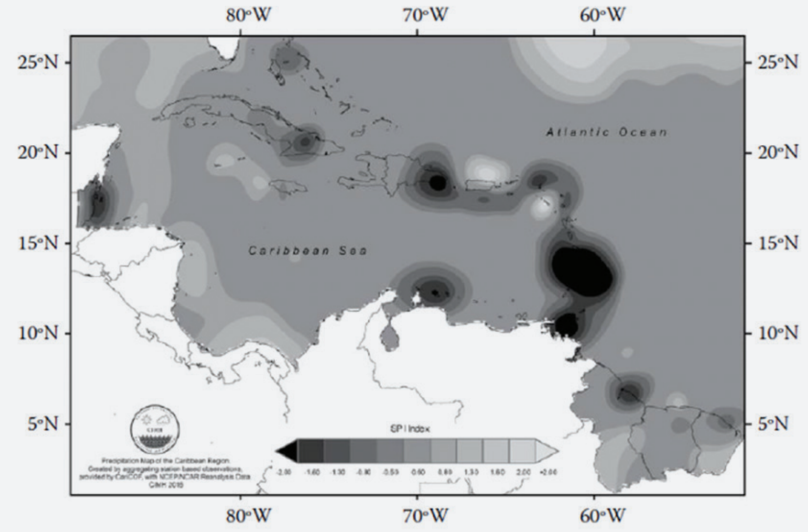

Figure 6.2: A 6-month SPI map (October 2009 to March 2010), where negative values point to increasingly severe dryness. Source: CDPMN

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

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[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.

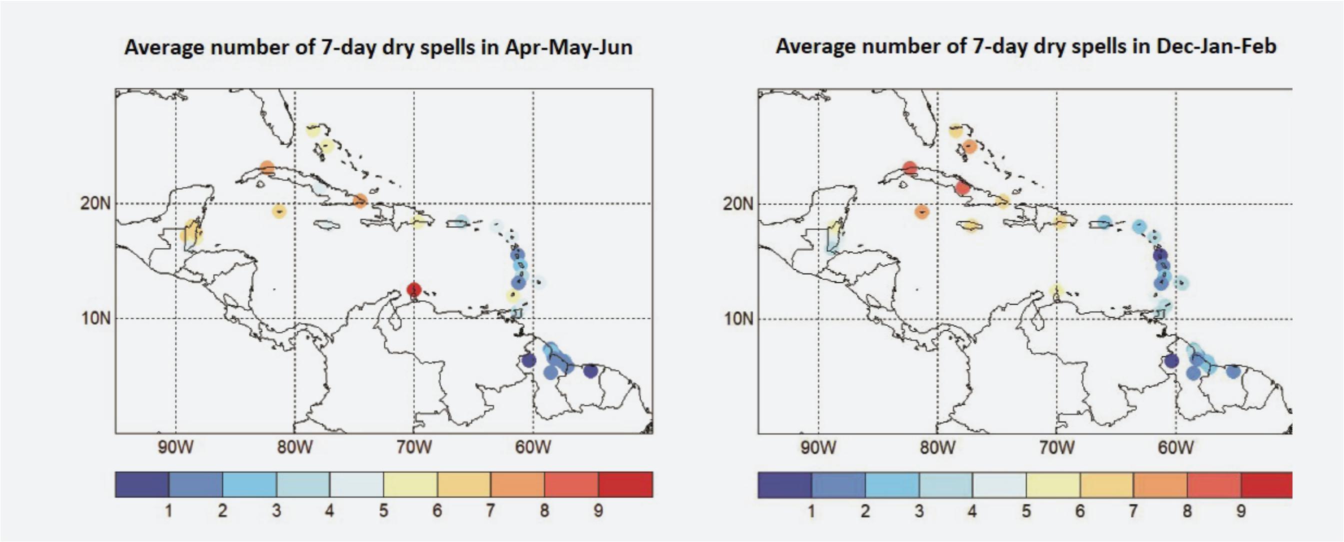

Figure 6.3: Map shows the average number of 7-day dry spell that occur during April May June (left) and December Jan February (right). The climatological period spans 1985 to 2014. Source: CIMH

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.

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[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

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[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).

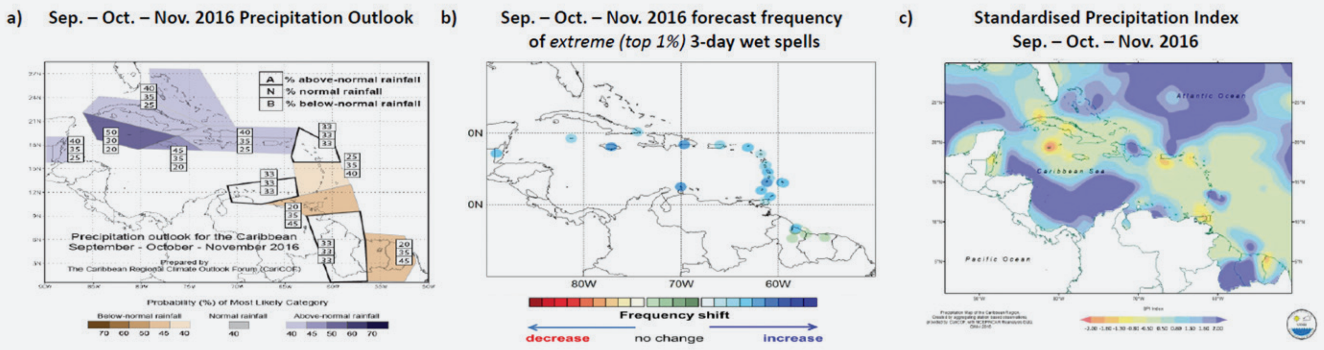
[14] The climatological reference period used to define the historical norm is 1981-2010, as mandated by the WMO. However, there is an insufficient amount of manned weather station based records of daily rainfall dating back to at least 1981 to allow a good geographic of the calculation of wet days and 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


a) Sep. – Oct. – Nov. 2016 Precipitation Outlook

b) Sep. – Oct. – Nov. 2016 forecast frequency of *extreme (top 1%)* 3-day wet spells

c) Standardised Precipitation Index Sep. – Oct. – Nov. 2016

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).

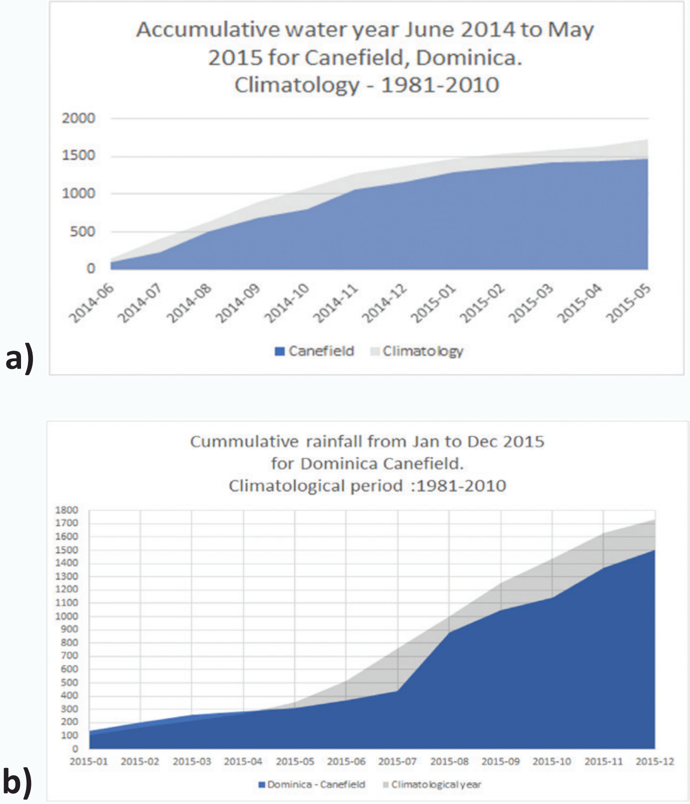


Figure B6.1: Charts shows the cumulative rainfall totals for (a) the water year June 2014 to May 2015 and (b) January to December 2015 in relation to the historical norm (i.e. climatology) for Canefield, Dominica. The climatological period spans 1982 to 2010. Source: CIMH

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.

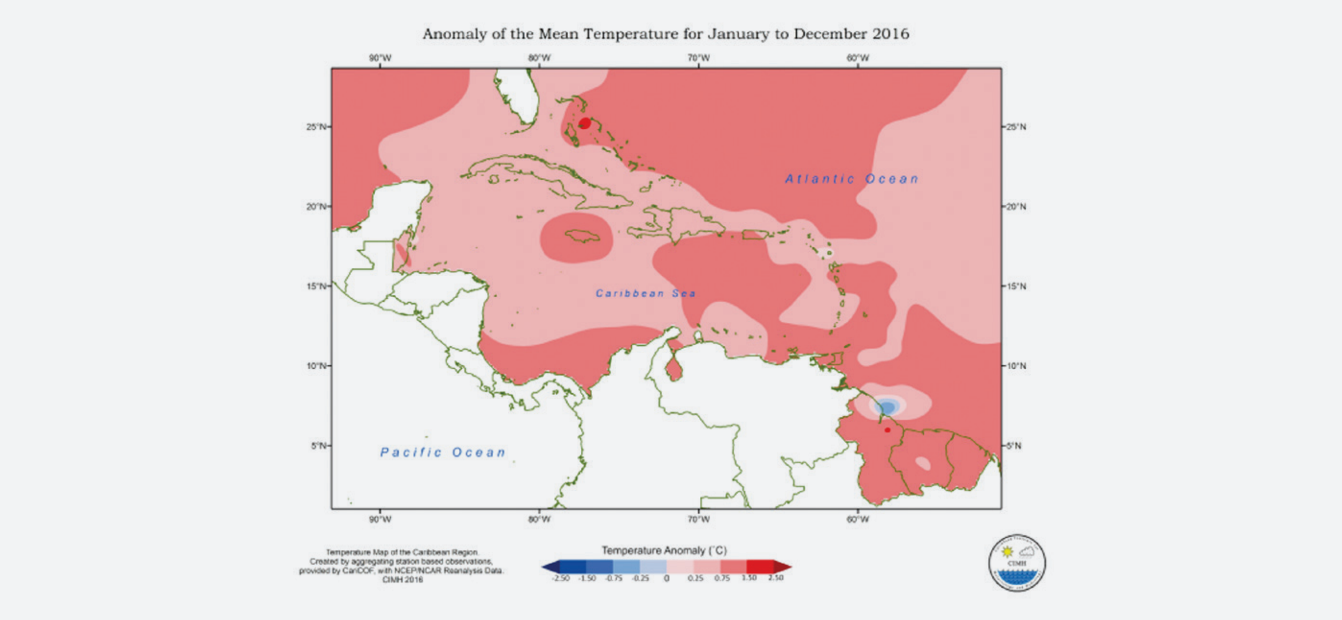


Figure 6.5: A 12-month mean near-surface air temperature anomaly map for 2016. Source: CIMH

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:

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[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.

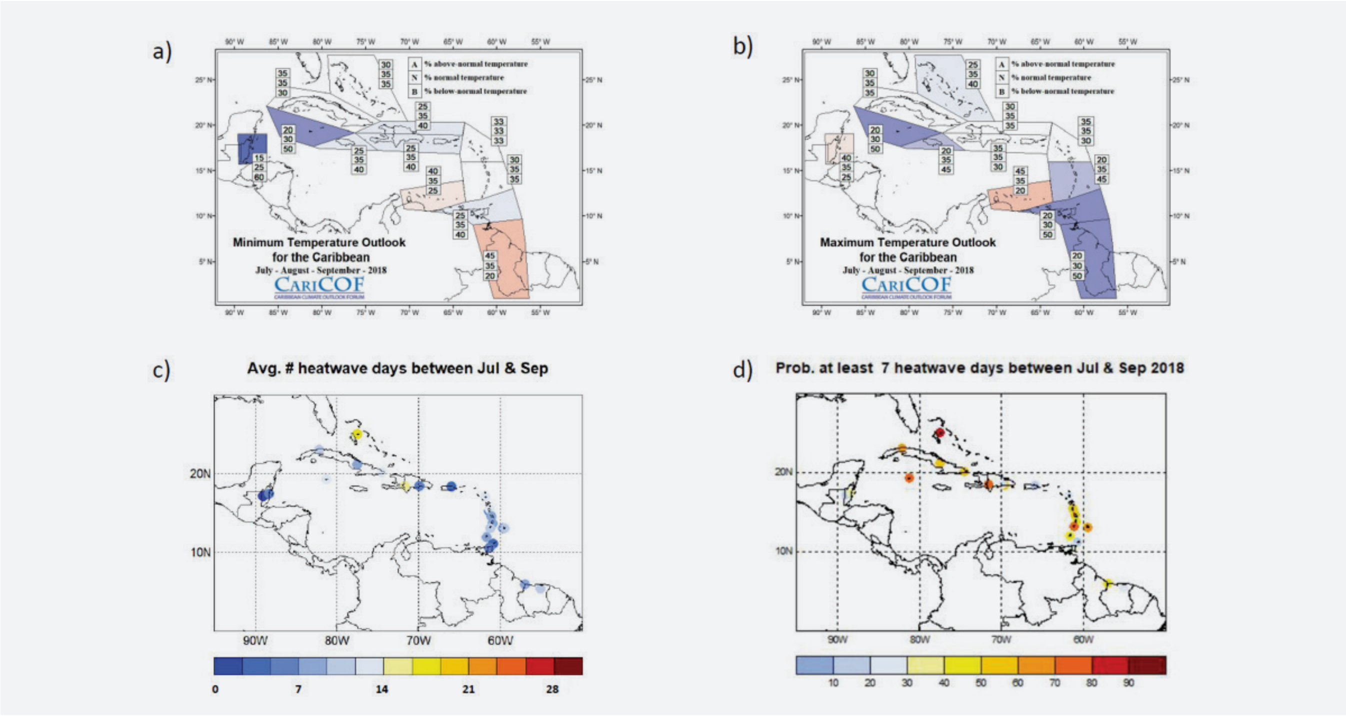

Figure 6.6: Excerpts from the CariCOF July to December 2018 Experimental Heat Outlook. Panels (a) and (b) depict the July to September minimum (nighttime) and maximum (daytime) temperature outlook maps in terms of the forecast probability of warmer than usual (above-normal), usual (normal) or cooler 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

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[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,

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[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).

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


Revenue Structure
Interest Bearing Debt (IBD) Ratio and Total Cash on Hand
Cost trends
Jan
Feb
Mar
Apr
May
Jul
Aug
Sep
Oct
Nov
Dec
Cost 3
Cost 4
Cost 5
Sum

7. REVIEW OF HISTORICAL & PROJECTED IMPACTS OF CLIMATE CHANGE IN THE CARIBBEAN

The impacts of shifts in climatic variables are far reaching and are particularly threatening to small island developing states because of the magnitude of the climatic events and increasingly recurrent nature of these threats. The Caribbean region which is home to 40 million people is extremely susceptible to climate impacts. This susceptibility is driven by several factors including-but not limited to- the following: the proximity of dense populations to flood prone coastal zones, the location of many islands within the path traversed by hurricanes and other tropical cyclones, and their small physical size with little reserve land capacity. Further, the region is also heavily dependent on climate sensitive sectors such as, Tourism, Agriculture and Fisheries and Freshwater Resources.

Although not exhaustive, this chapter explores the sensitivities of multiple sectors, vulnerable groups and resources to climate variability and extreme events in the Caribbean. The information is presented in tabular format based on review of the recent historical (from 2003) and projected impacts of climate change. It also provides social dimensions of these climate impacts on island people as it relates to climate sensitive sectors including-but not limited to- Agriculture, Tourism, Water, Health, and Education. Additionally, details are provided on Development, Poverty, and Security among other cross cutting themes.

Sections 7.1 and 7.2 present summaries of the major points presented within the impacts tables in Sections 7.3 (Sectors) and 7.4 (Crosscutting themes).

7.1. TABLE SUMMARIES: SECTORS

AGRICULTURE: CROP PRODUCTION, LIVESTOCK AND FISHERIES

The Caribbean has experienced marked increases in temperature in the few decades (1986-2010), with heavier daily rainfall and an increase in frequency and intensity of hurricanes (Stephenson et al. 2014; CSGM 2017). Droughts have also been very costly to the agriculture sector, especially given the over reliance on rain fed agriculture (Beckford and Barker 2007; Gamble et al. 2010; Farrell et al. 2010). Sea level rise also poses a threat to the availability of fresh water, which is a vital resource for the sector. The effects of these changes on this climate sensitive sector are examined in the tables below. For ease of reference, separate tables are used.

TOURISM

Tourism is one of the major economic sectors within the Caribbean region and due to its proximity to the coast, its most vulnerable (UNDP 2010). Tourism depends on the climatic features and attractiveness of a destination to attract or deter visitors (ECLAC 2011). In the Caribbean, climate change is already threatening touristic offerings and reducing tourist arrivals. Among impacts already experienced are increased beach erosion; increased incidence of vector borne diseases and recurrent damage to properties from hurricanes and other tropical cyclones. In 2016, tourism contributed US$56.4 billion to the Caribbean region and employed 2,319,500 of its people (WTTC 2017). The hurricane season in 2016 was particularly severe on the sector as several properties across the region were significantly damaged and there were marked disruptions to operations and loss of livelihoods. Projections for more intense hurricane in the future (CSGM 2017) therefore suggest that climate change will have adverse impacts on: (i) natural assets on which tourism depends (ii) man-made structures that support the activities of the sector, and (iii) the livelihoods on which so many of the region's people depend. Refer to the corresponding table for further information on the impacts of climate change on this important sector.

FRESHWATER RESOURCES

For the past 100 years (1900-2000), rainfall records have shown that there has been a slight reduction in Caribbean rainfall (See Section 3.2.2). Projections are that drier conditions (annual mean of 17%) are expected, as end of century is approached (See Section 5.3). However, increases are also projected in heavy rainfall events (see Section 5.3.3) which could cause flooding. Taken collectively, the following impacts could result from projected changes: increased temperatures could enhance surface water evaporation, floods could increase sediment load and increase turbidity in water systems, and sea level rise would likely contaminate freshwater sources. This table therefore highlights the degree to which increasing temperatures, droughts, floods sea level rise and flooding will affect the quality and availability of freshwater throughout the region. Refer to the corresponding tables for further information.

ENERGY

The Caribbean as a region derives up to 90% of its energy from imported crude oil (Bueno et al. 2008). Climate change presents increasing challenges for energy production and transmission, especially given the region's reliance on imported fuel and the concentration of critical energy infrastructure in the (flood-prone and exposed) coastal zone (Bueno et al. 2008; CMEP 2017). Further, as temperatures increase so too will the need for cooling thereby leading to an increase in energy demand and fuel importation. Severe weather systems (hurricanes and other tropical cyclones) could affect fuel transportation at times when energy demands have peaked. The sector table provides insight into how climate change could affect energy production and distribution, specifically focusing on increasing temperatures, hurricanes, inadequate rainfall and sea level rise.

BIODIVERSITY

The Caribbean region supports a wealth of marine and terrestrial biodiversity with a high proportion of species that are unique to the area (CEPF, 2011). These species live in special habitats and thrive best in a narrow range of environmental conditions (Miloslavich et al. 2010; Webber 2012). Climate change will alter these ideal conditions and will threaten both marine and terrestrial biodiversity (CANARI 2008; Webber 2012). For marine biodiversity, the table illustrates the degree to which climatic extremes like temperatures, sea level rise and hurricanes impact on coral reefs, Caribbean grazers like the parrotfish, sea turtle reproductive patterns and migratory patterns of some bird species. Refer to the corresponding tables for further information. Terrestrial biodiversity impacts examined include both direct (e.g. damage to forest trees) and indirect (loss of habitat and feeding ground) (CANARI 2008).

EDUCATION

The Caribbean's education sector is among the most critical sectors for consideration for present and projected impacts of climate change given, its impact on future generations. Extreme events (including hurricanes, droughts and floods) across the region, which have increased in the recent past, have been reported to adversely affect the formal education sectors at all levels. Among notable impacts have been damage to school infrastructure, lower teacher and student attendance, reduced productivity, as well as reduced student academic achievement for some subject areas. The following table summarizes key impacts of extreme events on the education system in the recent past; with reference to how the future could also be impacted.

HEALTH

Severe weather events have the potential to adversely impact the health of the people of the Caribbean (Bailey et al. 2009). This is particularly so in cases where health infrastructure is damaged or where conditions favour the life cycle of vectors or vector-borne diseases. The corresponding table includes the impacts of extreme temperatures on heat related illnesses and the emergence of vector borne diseases. Other impacts highlighted include drought and floods conditions and malnutrition and public health consequences associated with hurricanes/tropical storm passage. While the table is not exhaustive is provides useful reference information and should spur interest in further research.

FINANCE AND INSURANCE

Climate hazards have direct impacts on the financial and insurance sectors. Recurrent losses suffered in the region from hurricanes (2004, 2017) have emphasized the need for expansion of risk insurance and the type of hazards covered (CCRIF 2015; OECS 2004). It is more likely than not that the frequency of intense storms will increase in the Caribbean Region (see Section 5.4). This implies that insurance may have to be reconfigured to cover events with higher return periods. Furthermore, more frequent droughts and flood events have negatively impacted the economies of many islands (Farrell et al. 2010; CCRIF 2015). The table below demonstrates how impending changes in temperature, rainfall, droughts, and hurricanes could further impact this key sector.

INFRASTRUCTURE AND HUMAN SETTLEMENTS

Sea level rise poses one of the most widely recognized climate change threats to low-lying coastal areas, particularly in small islands where the majority of human communities and infrastructure is located in coastal zones (CDKN 2014) In the Caribbean, more than 50% of the population live less than 1.5 km from the shoreline (UNECLA, 2011). Hurricanes and other tropical cyclones have also significantly damaged residential settlements and public infrastructure, especially roads and bridges. Climate change considerations need to be factored into designs to prevent recurrent damage. The impacts experienced to date are captured in the corresponding table for further information.

7.2. TABLE SUMMARIES: CROSS-CUTTING THEMES

POVERTY

Poverty is a critical factor in determining vulnerability to climate change and extreme events (CDKN 2014). Across the Caribbean, the rural and urban poor will be disproportionately affected by climate change because of their socioeconomic circumstances, living conditions and lack of capacity to adapt to climate extremities. Of particular note, this cohort of society comprises persons living in very vulnerable areas (flood prone, highly exposed), with limited alternative options for employment and limited financial resources and with little or no assets that would be easily insured. This table highlights the extent to which the poor will be affected by climate variables and extremes like temperatures, droughts, flooding and hurricanes. Refer to the corresponding table for further information.

SOCIETY

The vulnerability of the Caribbean society is well documented (Simpson et al. 2010; ECLAC 2011; CDKN 2014; CSGM 2017). Among adverse impacts that could be experienced are reduced access to freshwater (a key resource for socioeconomic development as identified in the UN Sustainable Development Goals), increased incidence of diseases and other adverse health impacts. This table details the vulnerabilities of climate sensitive livelihoods and groups including the elderly, women, children and indigenous people to the impacts of climate change. Social impacts from extremes like droughts, hurricanes and extreme temperatures are highlighted. Refer to the corresponding table for further information.

GENDER

Gender can be defined as the socially learned differences between men and women and the different societal roles they play. Across the Caribbean, women remain mostly in low skilled service-oriented positions while male counterparts enjoy higher skilled, better paying jobs. This, coupled with their roles as caregivers and mothers for the family, affect their ability to respond and recover from disasters. Further, children and the elderly are groups often unable to tend to themselves in adverse environmental conditions and especially in the aftermath of a severe weather event. This table illustrates how extreme events affect men and women differently and emphasizes how women, children and the elderly are disproportionately impacted.

DEVELOPMENT

Climate change will directly and indirectly impact socioeconomic development. Small island developing states are extremely vulnerable to climate change because much of their socioeconomic development is based on climate sensitive sectors like tourism and agriculture. In the Caribbean the vulnerability is further exacerbated by the limited reserve capacity (due to the prevalence of mountainous areas or flood plains) so that much investment has been made in areas inherently vulnerable to the adverse impacts of extreme events. This in turn affects the resilience of Caribbean development and the nature of adaptation options that can be explored. Recurrent damage from severe weather events are particularly costly and divert funds from development initiatives to recovery and rehabilitation projects. This table examines these challenges and also includes the smaller scale impacts such as the effects of increasing temperatures on worker productivity and the potential displacement of vulnerable groups (mountainous and flood prone communities) after a severe weather event. Refer to the tables for further information.

SECURITY

Climate change presents major security challenges for the region. This is attributed to the heavy dependence of life, livelihood and economy on the coast, which is magnified by a relatively weak emergency response to the severe and frequent disasters impacting the region. Additionally, the disruption that could result from climate hazards and attendant loss of livelihoods could result in in an upsurge in robberies, theft of goods and services and illicit activities. This table illustrates the impacts of sea level rise, hurricanes, increasing temperatures and heavy rainfall on counterdrug trafficking efforts, military readiness for search and rescue efforts and threats to livelihood and food security across the region. Refer to the corresponding table for further information.

7.3. IMPACT TABLES: CLIMATE CHANGE AND KEY SECTORS

Table 7.1: Impacts of Climate Change on Agriculture (Livestock, Crop Production and Fisheries)

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
LIVESTOCK	
INCREASING TEMPERATURE	**Higher temperatures will negatively impact livestock and animal protein production. Higher temperatures will result in increased incidence of heat stress.** Heat stress affects these animals' ability to control their own body temperatures (DeShazer et al. 2009) and that will cause decreases in voluntary intake of food, weight, fertility and milk production and could result in death in extreme cases (Amundson et al. 2006; Ben Salem and Bouraoui 2009; Hernández et al. 2011; Gantner et al. 2012). Other heat stress related impacts include decreases in poultry egg production and quality (Mashaly et al. 2004; Ajakaiye et al. 2011). Lallo et al (2018) reported that Caribbean livestock (chickens, goats and pigs) are under considerable heat stress even in normal conditions and especially during the summer period. Future temperature increases of 1.5°C above pre-industrial levels (since 1860), will result in heat stress every month at dangerous or severe levels (Lallo et al. 2018). Increased temperature may speed up the life cycle of some pathogens and parasites living outside their hosts (Kimaro and Chibinga 2013; Karl et al. 2009; Harvell et al. 2002).
INADEQUATE RAINFALL AND DROUGHTS	**Inadequate rainfall and longer drought conditions will affect the production of forage and quality of hay.** This will adversely affect the nutritional value of feed for animals, which will compromise the nutritional quality of the meat produced from these animals (Chapman et al. 2012). **Water requirements will increase and could lead to dehydration and death in extreme cases. Variations in rainfall will also increase pathogen and parasite population and the emergence of new pests** (Henry et al. 2012; Thornton et al. 2009; Rojas-Downing et al. 2017).
CROP PRODUCTION	
INCREASING TEMPERATURE	**Higher temperatures increase water loss and reduce production, affecting crop yields.** Heat stress due to high temperatures causes a reduction in the absorption of nutrients which will retard crop growth and reduce yield. Warmer conditions may also lead to premature low quality crops (Mohammed & Tarpley 2009a; Seddigh & Jollif 1984). **High temperatures could also be more favourable to certain diseases and pests** which will compete with the plants for light and nutrients and could further reduce crop yields (Agrios 2005; Das 2016).
DROUGHTS	**Droughts will reduce crop yield and threaten food security.** The high reliance on open-field rainfed crop production in the Caribbean, makes the sector particularly vulnerable to droughts (Beckford and Barker 2007; Gamble et al. 2010). A number of studies have projected climate change induced decreases in yields of crops grown in developing countries like the Caribbean, especially in rural areas ((Parry et al. 2004; IPCC 2007, 2014; ECLAC 2011; Müller et al. 2010). The 2009/2010 drought in the Caribbean cost the government of Guyana US$1.3 Million to provide relief to farmers. Furthermore, production was 43% lower in Dominica in 2010 compared to the previous year, while production was 20% lower (on average) in St. Vincent and the Grenadines (Farrell et al. 2010).

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
HEAVY RAINFALL/FLOODING	**More heavy rainfall and flooding will increase crop losses.** Heavy rainfall events and flooding often causes soil erosion and in other cases waterlogged fields. Stephenson et al. (2014) showed that there has been an increase in daily rainfall intensity as reflected in records from 1986-2010, which meant that when rainfall occurred in the Caribbean, it tended to be heavier.
STORMS/ HURRICANES/ TROPICAL CYCLONES	**More frequent and severe hurricanes/storms will cause significant crop loss.** The region has experienced an increase in the frequency of hurricanes since 1985 and especially of intense magnitude (category 4 and 5 hurricanes). Recent studies suggest the region could be impacted by more intense hurricanes, by the end of the century (CSGM 2017). The impacts of recent storms [Ivan (2004); Irma and Maria (2017)] have demonstrated that most crops in the Caribbean cannot withstand the associated strong winds and rainfall. Some crops could be totally destroyed, while others will have longer recovery periods (OECS 2004; CTA 2017)
SEA LEVEL RISE	**Sea level rise will affect crop production and availability of arable lands.** Saline intrusion from sea level rise will reduce freshwater availability and most crops are not tolerant to saline conditions. Crop water loss is accelerated in saline conditions leading to crop dehydration and ultimately crop failure (FAO 2005).
FISHERIES	
INCREASING TEMPERATURE	**Extreme temperatures will increase coral bleaching and affect fish habitats and populations.**Higher temperatures will increase incidents of coral bleaching, which will lead to ultimate destruction of spawning and feeding areas for many fish species. As a result, both fish populations and marine biodiversity will be adversely impacted (CDKN 2014; Simpson 2010). **Warmer seas will affect coral reefs and marine ecosystems.** Warmer temperatures will make the seas more acidic, and this acidification which is due to carbon dioxide, will impact the functioning, behaviour and dynamics of organisms. Reef building corals are highly susceptible to this acidification and when coupled with larger scale changes including lower oxygen levels, impacts are amplified. (IPCC 2014).
STORMS/ HURRICANES/ TROPICAL CYCLONES	**More frequent and severe storms will increase damage to fish habitats and natural barriers.** Higher intensity storms which are projected for the Caribbean could result in greater damage to coral reefs, mangroves and seagrass beds. This could reduce habitats and in turn increase exposure of fisheries to harmful winds (CMEP 2017).

Table 7.2: Impacts of Climate Change on Tourism

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
SEA LEVEL RISE	**Sea level rise likely to damage many resort properties across the region.** In the Caribbean, sea level rise has been combined with elevation maps to estimate that 49-60% of tourist resort properties would be damaged (CDKN 2014). **Beaches retreat inland at 100 times the rate of sea level rise (CSGM 2012).** Another estimate suggests that a 1 metre rise in sea level will lead to the loss of at least 16 multimillion dollar tourism resorts across the Caribbean, with a replacement cost of over US$1.6 billion and the livelihoods of thousands of employees and communities affected (Simpson 2010).
DROUGHTS	**Declining water quality and availability affecting tourism operations.** More frequent drought events limiting availability and quality of freshwater will have adverse impacts on tourism operations (CDKN 2014).
INCREASING TEMPERATURE	**Extreme temperatures can lead to heat stress and other heat related illnesses.** Heat stress remains a concern with higher temperatures affecting tourists and outdoor workers. Heat storage of built structures will lead to the heat island effect. This will lead to additional costs for cooling aids (CSGM 2012). **Coral bleaching will compromise tourism product offerings.** A 1 degree increase in sea surface temperature will lead to coral reef bleaching (CSGM 2012) This will compromise the quality of tourism based activities like diving and snorkelling of which reefs form the bases (CDKN 2014). **Climate induced vector borne diseases led to a decline in tourist arrivals.** Extreme temperatures are associated with vector borne diseases such as the chikungunya virus. In 2014, the tourism industry in the region incurred significant economic losses with cancellation or reduction in tourism arrivals because of the Chikungunya Virus (Ramrattan 2015). **Destination attractiveness compromised by Sargasso blooms.** Warmer seas have led to the massive influx of Atlantic Sargasso in the Caribbean Sea, affecting countries like Barbados and Jamaica, covering white sandy beaches, emitting a pungent odour; and discolouring nearshore waters (Oxenford et. al. 2015; Doyle and Franks 2015).
HEAVY RAINFALL	**Heavy rainfall may lead to the displacement of visitors or cancellations of outdoor events which would incur revenue loss for the industry** (CARIBSAVE 2009).
HURRICANES/TROPICAL STORMS	**More frequent and severe hurricanes may continue to destroy hotels and affect arrivals across the region.**

Table 7.3: Impacts of Climate Change on Freshwater Resources

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
INCREASING TEMPERATURE	**Higher temperatures increase evaporation.** This will decrease water availability from rivers and streams. **Increasing temperatures also leads to increase in pathogens, nutrients and algal bloom in water storage facilities which could lead to reduction or lack of potable water** (CSGM 2012, 2017).
INADEQUATE RAINFALL / DROUGHTS	**Inadequate rainfall and longer drought conditions will affect water availability:** Increased variability in rainfall patterns will increase water demand across the region and adversely affect stability of water supplies (CDKN 2014).
HEAVY RAINFALL/STORMS	**Heavy rainfall and storm events could cause damage to water infrastructure by increasing the volume of water and decreasing water quality, as a result of excessive runoff.** Higher than normal sediment load and turbidity could also affect water treatment costs and water supply lines**.**
SEA LEVEL RISE	**Rising sea level increase the salinity of both surface water and ground water through salt water intrusion, especially in coastal basins.** This will affect the availability of freshwater which is already in short supply in islands of the Caribbean, especially in the Eastern Caribbean (Bueno 2008; Simpson 2010; CDKN 2014). Saline intrusion reduces the amount of available groundwater and may require costly treatment options.

Table 7.4: Impacts of Climate Change on Energy Resources

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
INCREASING TEMPERATURE	**Higher temperatures will reduce efficiency of electricity production and further increase demand for cooling systems.** Extreme temperatures will likely increase energy demand for air conditioning (in both cars and buildings), as well as change our ability to supply adequate fuel, produce electricity, and deliver it reliably (WEC 2014). As temperatures increase the efficiency of power production for many existing fossil fuel and nuclear power plants will decrease, because these plants use water for cooling. The colder the water the more efficient the generator; so warmer (air and water temperatures) will reduce the efficiency with which these plants convert fuel into electricity (WEC 2014; EPA 2017). **Higher temperatures are less favourable for harnessing of solar energy; photovoltaic solar voltage and power decrease with increased temperature** (Arjyadhara et al. 2013). **Increased sea surface temperatures will increase the efficiency of Ocean Thermal Energy Conversion (OTEC) systems** (CSGM 2012).
INADEQUATE RAINFALL	**Inadequate rainfall and drought conditions will affect reliability of energy supplies.** This includes decreases in river flow, and ultimately, power output for hydropower plants (CSGM 2012). Increased evaporation, and drought may increase the need for employing energy-intensive methods (e.g. desalinization) to meet critical needs (e.g., drinking and irrigation water) (CSGM 2012). Irrigation water may also have to be pumped over longer distances, further increasing energy demand.
HURRICANES/ TROPICAL STORMS	**More intense hurricanes and storm events may damage energy infrastructure.** This includes both onshore and offshore (distribution) equipment, wind turbines and power lines. These events may also delay repair and maintenance work (WEC 2014).
SEA LEVEL RISE	**Sea level rise may impact coastal power plants.** Many power plants in the Caribbean are located within the coastal zone (Bueno et al. 2008, CMEP 2017). Sea level rise in the Caribbean is projected to be between 1-2m by end of century (Chen 2011). Critical infrastructure including oil and gas pipelines could be adversely affected by damage from increased storm surge, which will be exacerbated by more intense storm events (United States Senate Committee on Energy and Natural Resources 2015; CSGM 2012).

Table 7.5: Impacts of Climate Change on Marine and Terrestrial Biodiversity

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
SEA LEVEL RISE	**Mangroves migrate landward in response to sea level rise.** Mangrove vegetation may migrate landward in response to changing ecological conditions brought on by an inland movement of the sea and saltwater intrusion into coastal waterways (ECLAC 2011) In Caribbean island nations like Belize ,Guyana and Suriname with extensive mangrove vegetation, a 1 metre rise in sea level would lead to deterioration from accelerated coastal erosion (UNDP 2010). **Sea level rise threatens sea turtle nesting areas**. The impacts of coastal erosion due to a 1 metre rise in sea level would lead to degradation or loss of 146 known sea turtle nesting areas across the Caribbean region (UNDP 2010).
INCREASING TEMPERATURES	Seagrasses can only accept temperatures 2-3 degrees above summer temperatures (CARIBSAVE 2009). **Warmer seas may lead to further coral bleaching events across the region.** Severe mass coral bleaching may occur in the Caribbean by 2074. Already, coral species have declined by 80% on Caribbean reefs due to ocean acidification and warmer sea surface temperatures (CDKN 2014). In 2005, extremely high sea surface temperatures in the Eastern Caribbean and North Atlantic led to a widespread coral bleaching event resulting in 90% of coral being affected in British Virgin Islands (Taylor 2015). **Blooms of sargassum on shorelines, affecting marine life.** Increasing sea surface temperatures and low winds has led to the presence of the Atlantic Sargasso seaweed on Caribbean shorelines. This seaweed smothers sea grass beds and coral reefs and tangles many marine animals including fish and sea turtles (Oxenford et. al. 2015). **Increasing temperatures will affect sea turtle population.** Increasing sand temperatures can lead to changes in sex ratios (declining male turtle population) since sex is determined by temperature (Webber n.d.). **Warmer seas promoting northern migration of Caribbean grazers and coral reefs.** Rising sea surface temperatures are leading to the migration of Caribbean grazers like parrotfish to more temperate seas. These fish species can now be found in areas such as the Mediterranean Seas, Japan and Australia feeding on sea grasses and kelp forests. Caribbean coral reefs have also followed these fish populations and are replacing the sea grasses and kelp forests (Struck 2014).
FLOODS/STORMS	**Flooding degrades wetlands.** Extreme events such as flooding degrades wetlands and reduce their ability to function as natural filters and buffering systems for shorelines and coral reefs (CARIBSAVE 2009). **Intense Caribbean storms affecting migratory bird patterns.** More severe storms in the Caribbean appear to be reducing the number of some migratory bird species from reaching their breeding grounds (ECLAC 2011). **Hurricanes could damage forest stands making them more exposed and therefore less resistant to wind damage.** This could also lead to habitat loss for many animal and plant species (CANARI 2008) and ultimately loss of the species themselves.
RAINFALL	Adequate shading and soil moisture are necessary for positive seedling development of plants in tropical dry forests. This was found to be the case in the Hellshire Hills, Jamaica, where water prolongs the survival of all plants regardless of shading (McLaren and McDonald 2003a). Soil moisture availability is highly dependent on rainfall which is highly seasonal in tropical dry forest ecosystems. This seasonality affects patterns of seed production, germination, survival and seed development (McLaren and McDonald 2003a). Inadequate rainfall will therefore lead to high seedling mortality in these dry forests. Coppicing is generally the primary regeneration mechanism in cut dry forest sites where stem and roots remain in place. In the Hellshire Dry Forest (Jamaica), there is a high incidence of shoot regrowth or coppicing among and within the tree species after it was cut. This means that it has considerable resilience to disturbance in tropical dry forests where successful seed regeneration is highly susceptible to rainfall seasonality. If long term clearance continues it could affect species diversity (McLaren and McDonald 2003b).

Table 7.6: Impact of Climate Change on Health

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
INCREASING TEMPERATURE	**Warmer seas may contribute to seafood poisoning.** Warmer seas may contribute to toxic algal bloom and increased cases of shellfish and reef fish poisoning (GOJ 2011). Ocean warming would increase temperature sensitive toxins produced by phytoplankton which would cause contamination in seafood (Moreno 2006) Ciguatera Fish Poisoning which is the most common non-bacterial food-borne illness associated with fish consumption, is expected to rise in the Lesser Antilles where warmer waters are associated with high incidence (IPCC 2014). **Hotter temperatures may lead to more vector borne diseases**. High temperatures speed up the life cycle of the Aedes aegypti mosquito and the disease organisms they harbour and make adult mosquitoes bite more often (Bailey et. al. 2009). **Increasing temperatures may cause reproductive problems in both men and women**. High temperatures may lead to reproductive problems in men due to the relationship of repeatedly raising testicular temperature by 3-5 degrees and decreased sperm count (Silva 2016). Exposure of pregnant women to increasing temperatures may lead to hyperthermia which may result in a high incidence of embryo deaths and malformation of the head and the central nervous system (Silva 2016).
INCREASING TEMPERATURES AND PRECIPITATION (MOISTURE)	**Extreme temperatures may lead to more incidence of dengue fever**. Higher temperatures and moisture availability provide favourable conditions for high dengue transmission rates and mosquito breeding (Amarakoon et. al. 2008).
INCREASING TEMPERATURE, HUMIDITY, CIRCULATION OF WIND PATTERNS AND CONCENTRATION OF DUST FROM THE SAHARA	**Climate factors will increase respiratory problems across the region.** Higher temperatures, humidity and Saharan dust (air pollution) will increase the incidence of asthma, bronchitis and respiratory allergies across the region (Bailey et. al. 2009). Inhalation of air pollutants from fossil fuel and waste incineration will lead to more respiratory illnesses (Bailey et. al. 2009). There has been an established link between the concentration of dust and the outbreak of asthma affecting children, which could lead to an overall increase of asthmatic cases in the Caribbean.
INCREASING TEMPERATURE AND HUMIDITY	**High temperatures and humidity stress the body's ability to cool itself. Heat stress can lead to heat related illnesses such as heat strokes and cramps** (Bailey et. al. 2009). In extreme cases, it can become fatal. The heat island effect will exacerbate the impact of increasing temperatures (CSGM 2012).
STORMS/ FLOODS/ HURRICANES/TROPICAL CYCLONES	**More frequent and severe extreme events may lead to disastrous public health consequences across the region.** Extremes such as hurricanes, tropical storms and floods can cause adverse effects in food production (Moreno 2006); deaths by drowning; more mental cases; increases in infectious diseases (water, food and vector borne); and population displacement (Bailey et. al. 2009). In 2010, Hurricane Sandy caused many deaths across the Caribbean region, 60 in Haiti, 2 in Bahamas and 1 in Jamaica (Taylor 2015).
DROUGHTS	**Water storage during droughts may lead to more vector borne diseases.** Storage of water during droughts in drums provides suitable habitats for mosquitoes, augmenting the transmission of vector borne diseases like dengue fever and malaria which are likely to increase with higher temperatures (GOJ 2011). **Malnutrition from disturbances in food production may occur(CARIBSAVE,2009).** Drought conditions lead to food shortages. Food imports may lead to obesity due to the importation of calorie laden, high sodium foods (Silva 2016). **Drought affects sanitation due to the lack of water affecting the transmission of disease** (CARIBSAVE 2009).

Table 7.7: Impact of Climate Change on Infrastructure and Human Settlements in the Caribbean

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
INCREASING TEMPERATURE	It is projected that there will be a 1-4 degree Celsius increase in temperature across the Caribbean (CDKN 2014). Warmer temperatures however are already affecting the region with greater impact in urban than rural areas. Bailey et al (2009) attributes this to a heat island effect which is a phenomena defined as heat absorption and storage in built structures allowing for radiant energy to thereby reduce night time cooling and relief.
EXCESS RAINFALL	Landslides are hazards that occur with extreme rainfall and flooding in some mountainous Caribbean islands such as Saint Lucia (GFDRR 2014). This subsidence of land has led to the degradation of foundation on which many houses were built across the Caribbean. The Christmas Eve Trough of 2013 is one such flood event in Saint Lucia which resulted in damages to 743 homes. Total damage and loss was estimated at EC$11.28 million and 3.81% in the housing sector (GFDRR 2014).
HURRICANES/ TROPICAL STORMS	**More intense hurricanes and storm events will cause damage to Caribbean infrastructure and settlements:** Hurricanes Irma and Maria's 2017 example confirms this fact with their landfall causing significant infrastructural damage in Caribbean islands such as Anguilla (EC$150.1 million), Bahamas (US$27 million) and British Virgin Islands (US$455 million) (ECLAC 2018). 6944 residential properties and several public buildings were damaged by Hurricanes Irma and Maria in 2017 in the British Virgin Islands which resulted in losses valued at US$680.2 million (ECLAC 2018). 81.5% of total losses in British Virgin Islands from Hurricanes Irma and Maria was attributed to the tourism sector with infrastructural damage so severe that many will not be operational until 2019. This is especially impactful because most of the population is employed by the tourism sector (ECLAC 2018).
SEA LEVEL RISE AND STORM SURGE	**Sea level rise will inundate coastal roads and lead to flooding of low-lying coastal plains where many human settlements are located:** In the Caribbean, more than 50% of the population lives less than 1.5 km from the shoreline (ECLAC 2011). Sea level rise therefore presents one of the most significant and widely recognised climate change threats to low-lying coastal areas especially in small islands where there are limited relocation opportunities for human communities and infrastructure, most of which are located in the coastal zones (CDKN 2014).

Table 7.8: Impacts of Climate Change on Caribbean Society

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
INCREASING TEMPERATURE	**Warmer seas threaten continuity of fishing communities.** Further warming of 1-2 degrees threatens natural ecosystems including risk of loss for marine and coastal systems and the goods and services they provide for coastal livelihoods especially fishing communities in the tropics (CDKN 2014 p.10). **Vector borne diseases put a strain on household resources.** Extreme temperatures may lead to the emergence of vector borne diseases like dengue fever. Households consisting of disabled or ill members are considered more vulnerable since this affects the number of people available for productive labour and puts a strain on household resources (Chen et.al. 2006).
DROUGHTS, STORMS, HURRICANES, FLOODS	**Storm surges, coastal flooding and sea level rise, as a result of extreme events will increase risk of death, injury, ill-health or disrupted livelihoods in small island developing states** (CDKN 2014). The circumstances, of many elderly persons who are already socially vulnerable due to limited income and health challenges, will likely be worsened by climate impacts such as extreme temperatures, droughts and hurricanes (CDEMA 2014). The geographical remoteness of many indigenous communities and their lack of access to education and health care, will likely increase their vulnerability to the impacts of climate change (CDEMA 2014), especially as it relates to evacuation after the passage of a tropical storm/hurricane. **Extreme events may increase the likelihood of Caribbean youth engaging in risky behaviour**. The Caribbean has a significant population of unattached youth (not employed or in school). Climate change is likely to worsen the circumstances of this group. Consequently, loss of homes and livelihoods as a result of an extreme event may increase the likelihoods of Caribbean youth to engage in transactional sex as a survival strategy (Dunn 2013).

Table 7.9: Impact of Climate Change on Education

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
INCREASING TEMPERATURE	**Increasing temperature can disrupt the learning process**. There is a correlation with body temperature, work performance and alertness, which has implications for students in classrooms without cooling aids. Higher temperatures can lead to lower productivity. This is due to the fact that heat exposure can affect physical and mental capacity and lead to exhaustion or heat strokes in extreme cases. There is the potential threat of increasing temperature on youth and their educational development. Reading speed, reading comprehension and multiplication performance of schoolchildren could be affected by temperatures of 27-30 degrees (CSGM 2012).
INCREASING TEMPERATURES AND PRECIPITATION (MOISTURE)	**Impact of vector-borne diseases on student and teacher attendance.** Extreme temperatures and moisture have led to the emergence of vector-borne diseases such as the Chikungunya and Zika viruses, which affected the productivity of the labour force including those in the education system. It was reported that in 2014, many students affected by the chikungunya virus were absent for many days from school in Jamaica (Ramrattan 2015).
INCREASING TEMPERATURE, HUMIDITY, CIRCULATION OF WIND PATTERNS AND CONCENTRATION OF DUST FROM THE SAHARA	**Saharan dust increases may induce and worsen respiratory problems across the region, with potential threat to students.** The increase of dust from Sub-Saharan Africa has been noted in several Caribbean territories, with special reports on its adverse impacts arising from 2011-2015 in some islands such as Grenada, Antigua, and Trinidad (Observer 2013a, Miami 2013, Observer 2013b, CSGM 2012). The dust, which peaks between May to September, coincides with the months marking the beginning and end of the school year (Observer 2013a, Lau 2007). This has been reported to have caused increases in paediatric asthma cases in territories such as Trinidad (Gyan 2005). It also has direct implications for students who are already prone to respiratory illnesses such as asthma, with particularly critical effects in the May-June months, which coincides with the sitting of regional examinations.
STORMS/ FLOODS/ HURRICANES/TROPICAL CYCLONES	**Hurricane activity during the school term affects Caribbean students' academic performance in Mathematics and Science subjects.** A detailed study of schools across the Caribbean region suggested that hurricane activity during the school term had a negative effect on student performance in Mathematics and the sciences (Biology, Chemistry and Physics) in the Caribbean Examinations. This is because the number of hurricanes occurring during the year increases the likelihood that school days and classroom time for required guided teaching, practicing problems and laboratory experiments are reduced. However, no significant impact was observed in academic performance in humanities (French, Geography, Spanish) subjects (Spencer 2016). **Hurricanes affect student school attendance.** Hurricanes and flooding events negatively affect student school attendance due to infrastructural damages affecting roads and school buildings and disruptions to electricity and water supply (Spencer 2016). **Hurricanes and storms affect the school term across the region**: For the past 20-25 years, hurricane events in the region have impacted the length of the school term, as many have been used as shelters for extended periods. For some events, resulting school disruption lasted for over a month on-end, e.g. 25-40 days disruption in schools in the Cayman Islands following the passage of Hurricane Ivan (2004) (Spencer 2016, ECLAC 2004b). Even in the event of extra days added to the normal duration of the school term, the disruption in lessons caused by the disasters have affected the productivity of teachers (Spencer 2016). **Hurricanes adversely impact school infrastructure**: During the period of 1993-2010, Caribbean countries were affected by at least 17 hurricanes with damages varying by territory and severity of the event. For example, following Hurricane Ivan in 2004, around 1000 public schools in Jamaica were reported to have severe infrastructural damage, affecting over 200,000 students (Spencer 2016, ECLAC 2004a).In 2016, it was reported that Hurricane Irma destroyed 130 schools in Anguilla, Antigua and Barbuda and the Turks and Caicos Islands affecting 20,000 children (Time 2017).

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
SEA LEVEL RISE	**Schools among infrastructure vulnerable to sea level rise**. Schools and other educational institutions are highlighted among the most vulnerable infrastructure that are likely to be adversely affected by sea-level rise and floods in the region, given the proximity of these institutions to the coast. Guyana, with an approximate 80% of their population by the coast, has about a quarter of their coastline infrastructure now protected by seawalls (Statistics 2007).
DROUGHTS	**Prolonged drought conditions from 2009-2015 disrupted the school term for many schools across the Caribbean**. Severe drought events in the recent past have caused school closure in the Caribbean due to a lack of water needed for proper hygiene and sanitation. For example, the 2009/10 drought event, resulted in countries in the Eastern Caribbean (Barbados, Grenada, and St Lucia (Jessop 2010) having to close some schools. During the 2014/15 event, several primary-level schools in Jamaica, were forced to close early for the Easter break during April 2014 due to critically low piped water supply. This period also coincided with the Grade Four Literacy Test examinations, which forced this cohort to have to still attend school. It was reported that the situation reached a 'crisis' proportion as trucked water was not available to alleviate the schools' situation (Cunningham 2014). **Drought may affect school feeding programs:** Several school feeding programs in the region are supplied primarily by local agriculture, e.g. Nippes region, Haiti through the World Food Program initiative (WFP n.d., 2016). Drought may impact school feeding programs that depend on local agriculture.

Table 7.10: Impacts of Climate Change on the Finance and Insurance Sectors across the region

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
DROUGHTS	**Droughts are very costly and will cause disruptions to key economic activities.** There were notable price increases for basic commodities during drought periods. This was experienced in the 2009/2010 drought when vegetable prices increased by 250% per lb (St. Vincent) and the price of fruit prices increased by between 40.7-60.8% (Farrell et al. 2010). There is a noted increase in bush fires during severe droughts and these too can be very costly. Forest fires destroyed large areas of citrus farms in Trinidad and Tobago resulting in a TT$12 million increase in citrus imports in 2010, when compared with 2008 (Farrell 2010).
HEAVY RAINFALL/FLOODING	**Heavy rainfall damage will occasion the need for additional insurance coverage.** Heavy rainfall events not associated with tropical cyclones and hurricanes will be costly to most Caribbean islands. The Caribbean Catastrophe Risk Insurance Facility Segregated Portfolio Company (CCRIF SPC) which provides parametric insurance for *inter alia* heavy rainfall events, reported a pay out of over US$ 4.7 million in just two years (2014 and 2015) for only three member states of the CDB: St. Kitts & Nevis, Barbados, and Dominica (CCRIF 2015). With projections suggesting that rainfall events could be more intense, islands will have to allocate financial resources to deal with associated damage.
INCREASING TEMPERATURES	**Increasing temperatures may lead to the emergence of more vector borne diseases which may increase premiums and expenditures across the region.** In Jamaica, there was an increase in health insurance premiums during the outbreak of the chikungunya virus (Ramrattan 2015). Jamaica also allocated US$ 3.62 million to control the chikungunya virus in 2014 (Ramrattan 2015).
STORMS/ HURRICANES/ TROPICAL CYCLONES	**More severe storms will result in costly damages to most islands.** Most projections of climate change suggest that hurricanes and tropical cyclones will be more intense in the future. The damage resulting from these more intense systems will be more costly for the Caribbean and this could significantly derail economic development, since funds would have to be diverted from other development priorities to finance recovery efforts. For example, following the passage of Hurricane Ivan in 2004, the fiscal position of Central government in Grenada deteriorated from a surplus of EC$17 million to a deficit of EC$54 million, or 4.5% of gross domestic product (OAS, 2004). In two hurricane seasons (2008 and 2010), pay-outs for damages to four Caribbean (Turks and Caicos Islands, Barbados, St. Lucia and St. Vincent & the Grenadines) amounted to US$19.2 million (CCRIF 2015). **Landslide hazards resulting from hurricanes are not covered by insurance.** This was a major problem faced by the government of St. Lucia in 2010, where despite suffering greater damage (rainfall and landslide events) from tropical cyclone Tomas, it received a much lower pay-out (US#3.24 million) than that received by Barbados (US$8.56 million) from the same cyclone (CCRIF 2015). For hurricanes Irma and Maria in 2017 (both category 5 hurricanes, the estimates of insured damage in the Caribbean is US$6-12.75 billion and emphasizes how destructive these severe events can be (Insurance Journal, 2017). Moreover, separate premiums have to be paid for hurricane/tropical cyclone versus heavy rainfall damage, resulting in costly insurance coverage (maximum coverage per year per hazard is US$100 million), which does not cover all damage that could result. **Insurance premium rates will likely increase across the region due to property damage from more severe extreme events,** In 2017, the Insurance Association of Jamaica reported that Jamaican property owners will be expected to pay 30-35% more for their premium as reinsurers have been adjusting to their rates to recover from the massive losses incurred during the active 2017 Atlantic Hurricane season. While Jamaica did not suffer from any hurricanes, it shares similar risks with other Caribbean islands (RJR News Online, 2017).

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
STORMS/ HURRICANES/ TROPICAL CYCLONES	**More severe extreme events will increase insurance premiums for Caribbean hoteliers.** Caribbean hoteliers should now anticipate paying increased premiums for their facilities ranging from 10-40% due to the very active hurricane season which affected several countries across the region (Caribbean Hotel and Tourism Association 2017).

7.4. IMPACT TABLES: CLIMATE CHANGE AND CROSSCUTTING THEMES

Table 7.11: Impact of Climate Change on Gender

CLIMATE CHANGE VARIABLE/EXTREME EVENT	IMPACTS
HURRICANES/TROPICAL STORMS/FLOODING	**Hurricanes threaten the livelihood of many women across the region.** Majority (18.1 million) of the 19.6 million household workers across the Caribbean are women and they are particularly vulnerable to climate change because hurricane passage could result in the destruction of their workplace (the home). This job loss has a negative multiplier effect because in Jamaica, for example, many of these women are heads of single parent households and occupy the poorest section of the society (Dunn 2013**).** **Women are at an increased risk of sexual violence in shelters. Furthermore, these shelters lack facilities to accommodate pregnant women and lactating mothers (Dunn 2013; UNDP 2009)** **Human trafficking during extreme events disproportionately affects women and girls.** Trafficking increases in low income communities during hurricanes and floods, with 85% of its victims being women and girls being sex trafficked, while 15% of men and boys are trafficked for forced labour (Dunn 2013). **Educational value has gender biases.** After the passage of a tropical storm, in some cases, girls have the opportunity to continue with their education, while boys are removed from school and sent to assist with recovery efforts (CDEMA 2014; IGDS 2013). **HIV rates increase among women in times of disasters, especially among those who engage in transactional sex as a survival strategy** (Dunn 2015a). **Disasters overburden women (especially in poor communities) to fulfil duties considered "women's work".** These responsibilities include collecting water, caring for the infants and elderly, providing medical support and food, washing and cleaning in the house. They would be burdened with 'trying to get things back to normal' and get the children back to school (CDEMA 2014). **Post disaster, men prioritise rebuilding efforts outside the home.** After a disaster (especially in poorer communities) men focus on reparation efforts outside the home, including removing debris, rebuilding, putting roofs back on and where possible obtaining resources (CDEMA 2014). **Men and women's vulnerabilities increase after a disaster due to their gendered roles.** In some post disaster analyses, it has been shown that men suffer higher mortality rates than women because they take more risks trying to save themselves and their families (IGDS 2015) On the contrary, many women sacrifice themselves during disasters when their own caregiving roles hamper their own rescue efforts. This also reflects women's social exclusion because they are less able than men to run, and have behavioural restrictions that limit their mobility in the face of risk especially since their voices often do not carry as much weight as men's in their households (UNDP 2009; Dunn 2015). **Indigenous peoples tend to have limited rights and access to resources which make them particularly vulnerable to disasters** (CDEMA 2014). **Rural women are particularly vulnerable to climate change.** Across the Caribbean, women residing in rural areas are particularly vulnerable to climate change because they have less opportunities to earn a living than their urban counterparts and experience higher levels of poverty. Many rural women experience various forms of inequality, related to their gender roles in the household(primary caregivers of their families) and more limited support services Also their livelihoods (vending and small scale farming) are climate sensitive. All of these socioeconomic circumstances affects their abilities to respond and recover from disasters (Dunn 2013)**.** **Greater loss of income for women in rural areas due to breakdown in road infrastructure.** Women in rural areas also experience greater income losses than their male counterparts from the breakdown of road infrastructure after a disaster due to their role in market vending and their dependence on road transportation, which would affect their food and livelihood security (IGDS 2015). In Jamaica, for example, women comprise over half of the population but represent 70% of persons living below the poverty line. With higher levels of poverty, poor women are more vulnerable to the impacts of climate extremes such as droughts, floods and hurricanes. They are also likely to bear the heaviest burdens when these disasters occur (UNDP 2009).

CLIMATE CHANGE VARIABLE/EXTREME EVENT	IMPACTS
HURRICANES/TROPICAL STORMS/FLOODING	**The elderly, women and children (especially girls) are particularly vulnerable in post disaster situations.** This is because they lack land and other assets that could help them cope. Therefore, they are more likely to face food shortages, sexual harassment, unwanted pregnancies and vulnerability to diseases and could be forced to drop out of school or marry earlier (Dunn 2015). **Hurricanes exacerbate the pre-existing gender inequalities in islands in the Caribbean.** Hurricane Ivan (2004) served to emphasize this in Grenada. Grenadian women, prior to the event had restricted skills bases, higher rates of poverty and were burdened with caregiving, while Grenadian men had mobile skills, no special restrictions and were excluded from childcare responsibilities. Due to these disparities, the women disproportionately had limited access to the labour market and less wage-earning possibilities than their male counterparts and therefore took a longer time to recover from the ill-effects of hurricanes. For example, within the nutmeg industry female farmers, due to Hurricane Ivan took a longer time to come back to their income stream than the men because of these realities (Kambon et.al 2005).
DROUGHTS	**Women in drought affected areas have time-consuming water carrying responsibilities which limits ability to earn and diversify their income.** Women and children have the main responsibility for securing water supplies daily from springs or other sources. Significant commuting time/ work is spent performing these duties This has implications for how they use their time which can be considerable because of the distances they have to travel to get water (IGDS 2013).

Table 7.12: Impacts of Climate Change on Poverty

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
HEAVY RAINFALL	**Heavy rainfall likely to affect public health, especially in riverbank communities.** Heavy rains contaminate watersheds by transporting faecal products and other waste into groundwater. Heavy rainfall also affects the health and sanitation of some communities without proper toilet facilities. Flooded pit latrines release waste directly into the rivers. This solid waste then threatens the health of the people in the communities and especially the health of the children who use the river for bathing purposes. This has led to an increase in diseases associated with water sanitation and poor hygiene practices (CSGM 2012).
INCREASING TEMPERATURES	**Heat waves may lead to increased fatalities in poor communities.** Increased frequency or severity of heat waves in the Caribbean will possibly cause an increase in human mortality and illness, especially in poor communities without access to cooling aids like air conditioners or refrigerators (CARIBSAVE 2009). **Poor communities more susceptible to vector disease transmission.** In low income communities and squatter settlements, people are more susceptible to vector borne diseases because of the necessary water storage and lack of immunisation to the virus (dengue) (Chen et. al 2006).
HURRICANES/TROPICAL STORMS/FLOODING	**The passage of extreme events increase the risk of human trafficking in low income communities.** This is because hurricanes, floods and other climate extremes increase the possibility of human displacement especially in poor communities which lack security. Children are particularly vulnerable to trafficking (Dunn 2013). **Housing quality and location increases poor communities' vulnerabilities to tropical storms/hurricanes.** In these communities, houses are made of poorer quality material and are often located on marginal lands or high-risk areas. Because of this, these communities tend to suffer great losses from extreme climatic events and take longer to recover (CDEMA 2014). **Flooding and landslides may lead to population displacement because of the vulnerabilities of those settlements in floodplains** (CSGM 2012).
DROUGHTS	**Longer drought periods increase likelihood of disease transmission**. During water shortages in some communities diseases spread because of poor infrastructure, waste disposal issues and lack of access to clean water resources (Silva 2015). **Elderly poor increasingly vulnerable to climate impacts.** The elderly poor living in rural areas across the Caribbean, may face serious health threats from the lack of water or adequate sanitation associated with droughts and other climate impacts (ECLAC 2011).

Table 7.13: Impacts of Climate Change on Development

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
INCREASING TEMPERATURES	**Chikungunya virus and economic loss in Jamaica and Trinidad and Tobago** Extreme temperatures have led to the emergence of vector borne diseases like the chikungunya virus (Chik-V) in Trinidad and Tobago and Jamaica in 2014 which devastated the economies of both countries. Chik-V led to US$60 million in financial losses in Jamaica in 2014 with 81% of the companies reported having workers affected by the virus. There were also severe losses of production as a result of absent workers affected by Chik-V and loss of productive time by the sick workers unable to work at full capacity because of the infection .10% of the population (130,000) in Trinidad contracted the chikungunya virus, resulting in the country incurring US$13.2 million dollars in losses (Ramrattan 2015). **Declines in productivity as a result of increasing temperatures**. Across the region, increasing temperatures have the potential to threaten social and economic development. This is due to the correlation with body temperature, work performance and alertness, which has implications for outdoor workers such as sportspeople, farmers, manual labourers and indoor workers and students in classrooms without cooling aids. Higher temperatures can lead to low productivity, given that heat exposure can affect physical and mental capacity and lead to heat exhaustion or heat stroke in extreme cases. (CSGM 2017).
STORMS, FLOODS, HURRICANES	**More frequent extreme events increase the risk of disease infection**. With a rise in the occurrence of extreme events, availability of freshwater may also be constrained and contaminated. This could lead to communities experiencing food-borne, water- borne and respiratory diseases (cholera, salmonellosis and asthma). This happens especially in rural or remote communities that have minimum public health care infrastructure. (CARIBSAVE 2009) Haiti has been dealing with a cholera outbreak since 2010 which is now categorised as the largest in the Western Hemisphere (United Nations Haiti Country Team, 2015). **Improper land use/ development in watershed/flood prone areas increases vulnerabilities to landslides and floods (CSGM 2012)** Flooding from heavy rainfall and other climate extremes increases the incidence of land slippage in unstable mountainous areas**.** In some Caribbean islands including Dominica, Jamaica, Haiti and St Lucia, many mountainous communities are prone to land slippage. In extreme cases deaths do occur (Edwards 2012; UNDP 2010).
DROUGHTS	**Drought induced water shortages will negatively impact socioeconomic development.** This will create disturbances in agriculture and tourism among other climate sensitive sectors. These shortages will create a need for increased food importation (UNECLAC 2011) Malnutrition resulting from these disturbances in food distribution and production may occur (CARIBSAVE 2009).
SEA LEVEL RISE	**Continued coastal development and removal of natural barriers increases exposure of coastal communities and infrastructure (roads and bridges) to flooding and erosion** (CSGM 2017). This may exacerbate the impacts of tropical storms and hurricanes on coastlines which will intensify as the sea level rises (Simpson 2010). With 4 degrees warming, sea level rise could lead to the displacement of between 1.2 and 2.2 million people from the Caribbean and other regions (CDKN 2014). More than 550 km of roads are projected to be inundated by a 1 metre rise in sea level in CARICOM nations (UNDP 2010).

Table 7.14: Impacts of Climate Change on Security

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
SEA LEVEL RISE	**Sea level rise threatens livelihood security in many small island developing states.** Land loss, due to sea level rise threatens livelihood security in small island developing states, which has implications for food supply and rural livelihoods. It is estimated that a one metre rise in sea level will lead to a loss of agricultural land by (4% in Suriname, 3% in Bahamas and 2% in Jamaica) (CDKN 2014; Simpson 2010). **Further sea level rise and storms may affect coastal military facilities and hamper regional counter drug trafficking efforts.** Sea level rise and more intense storms may lead to destructive inundation and erosion of coastal military facilities. This will impact not only these facilities' clean water supply but will also increase maintenance costs. As a result, this will degrade military readiness, which will adversely affect the American-led counter-trafficking fight in the region since Caribbean military's coastal facilities often serve as launching pads for maritime patrol and interdiction operations (Barrett 2015). **National security policies are likely to become influenced by the impacts of climate change on critical infrastructure and territorial integrity of many small island states.** Land inundation as a result of sea level rise poses a risk to those countries with extensive coastlines (CDKN 2014)
INCREASING TEMPERATURES	**Increasing temperatures may lead to increased incidence of aggression.** Increasing temperatures affect aggression because of a positive correlation with increased testosterone and adrenaline production (fight or flight) responses (Silva 2016).
HURRICANES/STORMS/ FLOODING	**Rivalries are also likely to occur among some island states due to the impacts of climate change on shared water resources and pelagic fish stocks (**CDKN 2014). **Crop loss and flooding will devastate farming communities across the region**. Crop loss and flooding are some of the effects of extreme weather conditions that also affect farming communities which are largely vulnerable to climatic variability (ECLAC 2011). Flooding from hurricanes Irma and Maria destroyed homes and farms in the coastal areas of Haiti, affecting 18,000 poor families who lost food crops. Haiti's population consists mainly of subsistence farmers (VOA 2017). **More frequent extreme events may continue to displace island people and damage critical infrastructure**. The 2017 hurricane season in the Caribbean affected 20,000 children, displaced 32,000 people with 17,000 of those people in need of shelter and over 1.2 million people were affected by damages to water infrastructure. Electrical lines, houses and public buildings such as schools and hospitals, as well as private sector structures which are significantly important to Caribbean economies and people's livelihoods were also affected (The Gleaner 2017). **The declines in the availability of food, water and other critical resources after an extreme event may lead to an increase in looting across the Caribbean**. It was reported that after Hurricane Maria there was widespread looting in the island of Dominica where the local police detained over 100 persons (Caribbean National Weekly 2017) Looting in Antigua and Barbuda and British Overseas Territories (Anguilla, British Virgin Islands and Turks and Caicos Islands) after Hurricane Irma was also reported (Time 2017). **More frequent and severe extremes may increase migration within the region and sometimes even within the same country**. IIt is likely that there will be increased migration from fragile countries like Haiti into neighbouring countries like Dominican Republic as a result of hurricanes (Barrett 2014). Hurricane Irma's landfall forced the migration of 1700 persons from Barbuda into Antigua rendering the island of Barbuda uninhabitable for the first time in 300 years (CNN 2017)

CLIMATE CHANGE VARIABLE/ EXTREME EVENT	IMPACT
HURRICANES/STORMS/ FLOODING	**More hurricanes and tropical storms will overburden the military's search and rescue efforts and recovery operations across the Caribbean**. Caribbean military forces especially those supporting national civil authorities and CDEMA can expect increased search and rescue efforts and recovery operations in the wake of more storms and hurricanes of increasing frequency and severity (Barrett 2014). Hurricane Irma's devastation in Dominica necessitated the deployment of 120 personnel from the Jamaica Defence Force who assisted with security, distribution of relief supplies, medical care and recovery planning (Jamaica Observer 2017). **More frequent storms will also necessitate further capacity building and intraregional cooperation.** Militaries will have to build capacities in equipment procurement and training exercises to assist distressed communities and will also be required to work with regional defense organisations such as the Inter American Defense Board to pool resources and share best practices (Barrett 2014). **More frequent extreme events can damage economically important infrastructure**. More severe hurricanes can destroy coastal infrastructure like ports and roadways which many Caribbean countries depend on to facilitate key economic activities like agriculture and tourism. Such destruction of infrastructure can have a devastating impact on the region's economies (Barrett 2014).
DROUGHTS	**Longer drought periods threaten food and water availability and may possibly cause civil unrest.** Due to shortfalls in these critical resources, governments across the region will be stressed to provide alternative supply and improve water infrastructure management. In these times the military will be expected to provide emergency food packages to the most affect citizens and assume non-traditional roles as crisis responder and peacekeeper (in extreme cases of civil unrest) (Barrett 2014).

8. ADDING VALUE TO CLIMATE INFORMATION THROUGH SERVICES

8.1. INTRODUCTION

8.1.1. CARIBBEAN CLIMATE AS RISK AND OPPORTUNITY

The main sectoral drivers of socio-economic development of Caribbean States remain highly reliant on and sensitive to the dynamics of Caribbean climate (See Chapter 7). For example, in a region that is the most tourism dependent in the world (WTTC 2016), tourism offerings are promoted year round due to average annual temperatures in the general range of 24°C-32°C - ideal for recreation and visitor comfort. Moreover, in a region dominated by rain-fed agriculture, for most rain-fed crops, the growing season spans the wet season, from May to November, with the type of crops and cultivars usually selected to match anticipated rainfall (Mahon et al. 2015a). Irrigation sources such as ponds, streams and rivers which are also influenced by climate add to the length of the growing season in many parts of the region.

Regional experience shows that most states bear a heavy public debt burden, brought on in large measure by losses incurred and costs of recovery efforts after major weather and climate events (CARICOM 2017). Key sectors within states are particularly sensitive to the impacts of climate variability and extremes. For example, periods of excessively high rainfall or droughts have historically had devastating consequences on Caribbean economies. For droughts, insufficient water supplies have led to crop failure, the increased incidence of bush fires, the proliferation of vector-borne diseases, reduced industrial activity and decreased energy production (Lowe et. al. 2018; Trotman et al. 2017; Farrell et al. 2010). On the other hand, extreme wet spells and floods have led to landslides, damage to property, displacement of populations and failure of critical infrastructure such as roads and bridges (Mahon et al. 2015a).

8.1.2. THE NEED FOR ADDING VALUE TO CLIMATE INFORMATION THROUGH SERVICES

The need to reduce the adverse impacts of climate and enable critical revenue generation and cost saving activities presents a compelling case for the production and use of tailored, user-driven climate information which form the basis of value added climate services. *Climate information* refers to knowledge and advice about the past, present and future characteristics of the Earth's system (as discussed in detail for the Caribbean in Chapters 2 to 7). *Climate services* involve the preparation and delivery of climate information to meet users' needs (WMO, 2011). Climate services add value to generic climate information by tailoring the interpretation of this information for specific application to sectoral decision-making. The development and delivery of climate services therefore requires significant interaction and/or partnership among providers, researchers and users of climate services to transform climate information by blending climate knowledge with sector-specific knowledge into user-oriented climate services (WMO 2018). By tailoring climate messages to include a specific and targeted sectoral focus, the usefulness and usability of the information for sectoral application is enhanced, and end-user uptake and use is catalysed.

Climate services can play a key role in facilitating the Caribbean's transition to a resilient future by enabling sectoral decision-makers to engage in a systematic and coordinated process of using climate information to reduce related risks and to take advantage of opportunities to improve resilience. This is at the core of climate risk management (Martínez et. al. 2012).

8.1.3. THE GLOBAL FRAMEWORK FOR CLIMATE SERVICES

Though climate services is a young and growing field, the awareness of the importance of climate services to support decision-making has grown particularly since the Third World Climate Conference (WCC-3) in 2009. WCC-3 drove the establishment of the WMO-led Global Framework for Climate Services (GFCS) in 2009 (WMO 2011) to guide the development and application of science-based climate information and services in support of decision-making in five priority climate-sensitive sectors (WMO 2017). These are the agriculture and food security, water, health, disaster risk reduction and energy sectors. The GFCS can be seen as an international response to the need for more user-driven climate services (Vaughan and Dessai 2014). As a framework, the GFCS is built upon five pillars that individually and combined, support essential elements for the development and delivery of climate services to a range of user groups (WMO 2011) (Figure 8.1). The function of each GFCS pillar is described in Table 8.1.

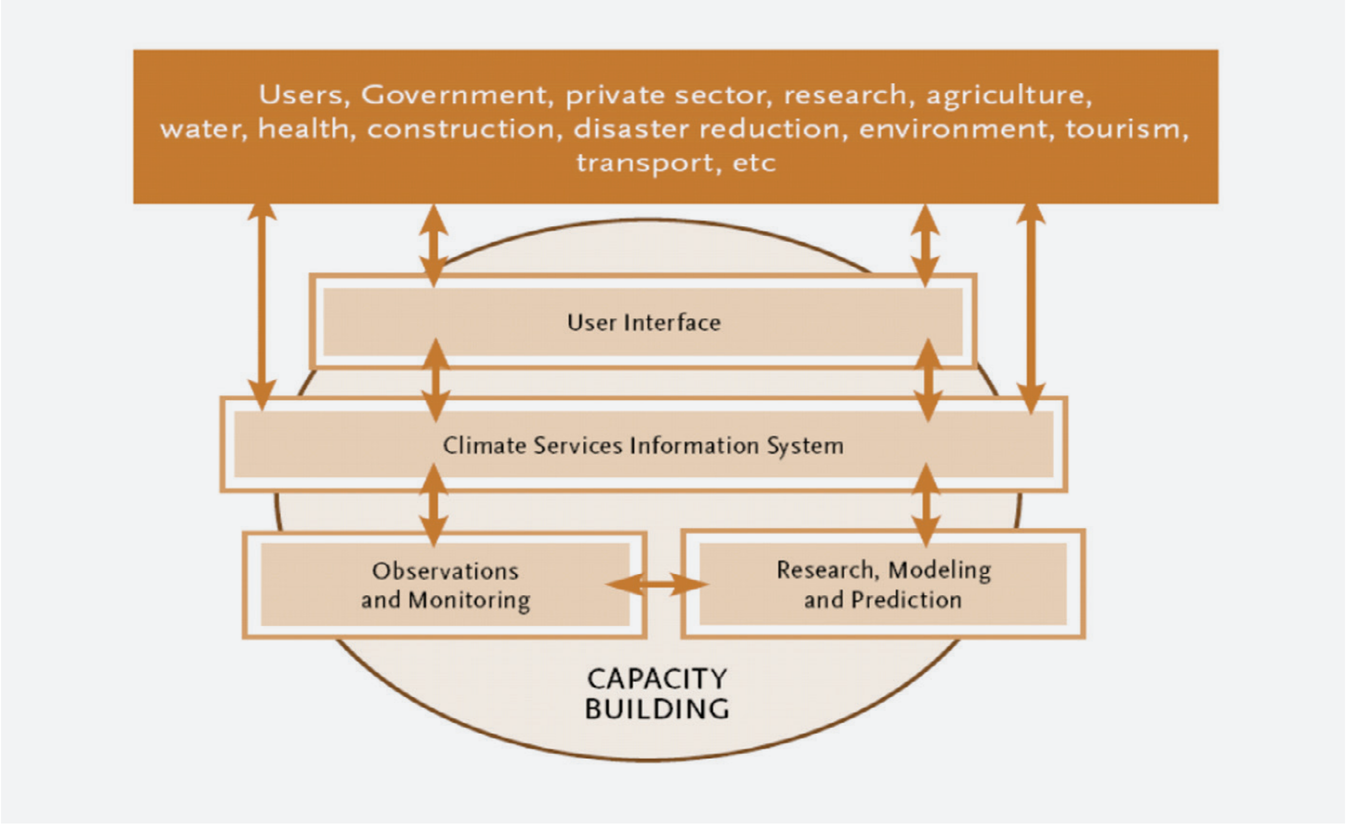


Figure 8.1: Conceptual model of the GFCS' five pillars. Source: WMO, 2011.

Table 8.1: The Functions of the Five GFCS Pillars. Source: WMO, 2011.

PILLAR	FUNCTION
OBSERVATIONS AND MONITORING	Generates the necessary data from which climate information products and services are built
RESEARCH MODELLING AND PREDICTION	Advances the science needed for improved climate services that meet user needs
CLIMATE SERVICES INFORMATION SYSTEM (CSIS)	Supports the mechanisms through which information about climate (past, present, and future) is routinely collected, stored, and processed in ways that enable the generation and distribution of products and services
USER INTERFACE PLATFORM (UIP)	Facilitates a structured means for users, climate researchers and climate information providers to interact at all levels ensuring that climate services are relevant to user needs
CAPACITY BUILDING	Supports the systematic development of the institutions, infrastructure and human resources needed for effective climate services

8.2. THE CARIBBEAN APPROACH TO CLIMATE SERVICES

Since its inception in 1967, the Caribbean Institute for Meteorology and Hydrology (CIMH) - the technical arm of the Caribbean Meteorological Organization (CMO) – in association with its constituency of National Meteorological and Hydrological Services (NMHS) in 16 CMO States has been building the regional and national observational network of in situ surface data instruments and archiving the acquired data that form the foundation for the production of climate information and services.

With the establishment of its Applied Meteorology and Climatology (AM&C) Section in 2007 dedicated to advancing science-based applications of climate data, the CIMH has cumulatively invested in upgrading the Caribbean's climate research, modelling and prediction capabilities at regional and national levels, which led to its designation by the WMO as the Regional Climate Centre (RCC) for the Caribbean. Through coordinated research networks such as the Caribbean Drought and Precipitation Monitoring Network (CDPMN) and the Caribbean Climate Outlook Forum (CariCOF), since 2009, the routine production of a range of generic, regional climate-oriented monitoring products and consensus long-range (seasonal) forecasts has been catalyzed and sustained.

Over time, the suite of operational products has increasingly included early warning information on climate variables that have implications for a range of sectors. These include information on drought and dry spells, heat wave days, and extreme wet spells (see Chapter 6 for a detailed description on those information products). In 2014, the CIMH established its regional programme on Early Warning Information Systems across Climate Timescales (EWISACTs). The aim of EWISACTs is to deliver climate information and services to alert stakeholders in Caribbean climate-sensitive sectors and general public entities of potential risks due to a range of climate hazards including extreme events, across timescales from daily, monthly to seasonal and multi- decadal.

The Caribbean approach to sectoral EWISACTs development embraces all five pillars of the GFCS, as well as the five global priority sectors and ultimately contributes to regional level implementation of the GFCS. The Caribbean programme also prioritizes services to the tourism sector, which is of great economic importance to the region. In this way, for the region, tourism is a sixth priority sector.

8.2.1. THE SECTORAL EWISACTS PHILOSOPHY AND METHODOLOGY

The Sectoral EWISACTs programme embraces the philosophy of Pulwarty and Sivakumar (2014) in providing climate early warning information with tailored communication of sector-specific risks and recommendations for sectoral action in response to the information. Three principles guide the sectoral EWISACTs development process: (i) better use of existing data and information platforms; (ii) maximizing of synergies between climate and sectoral activities; and (iii) partnership and consultation for climate services (Figure 8.2).

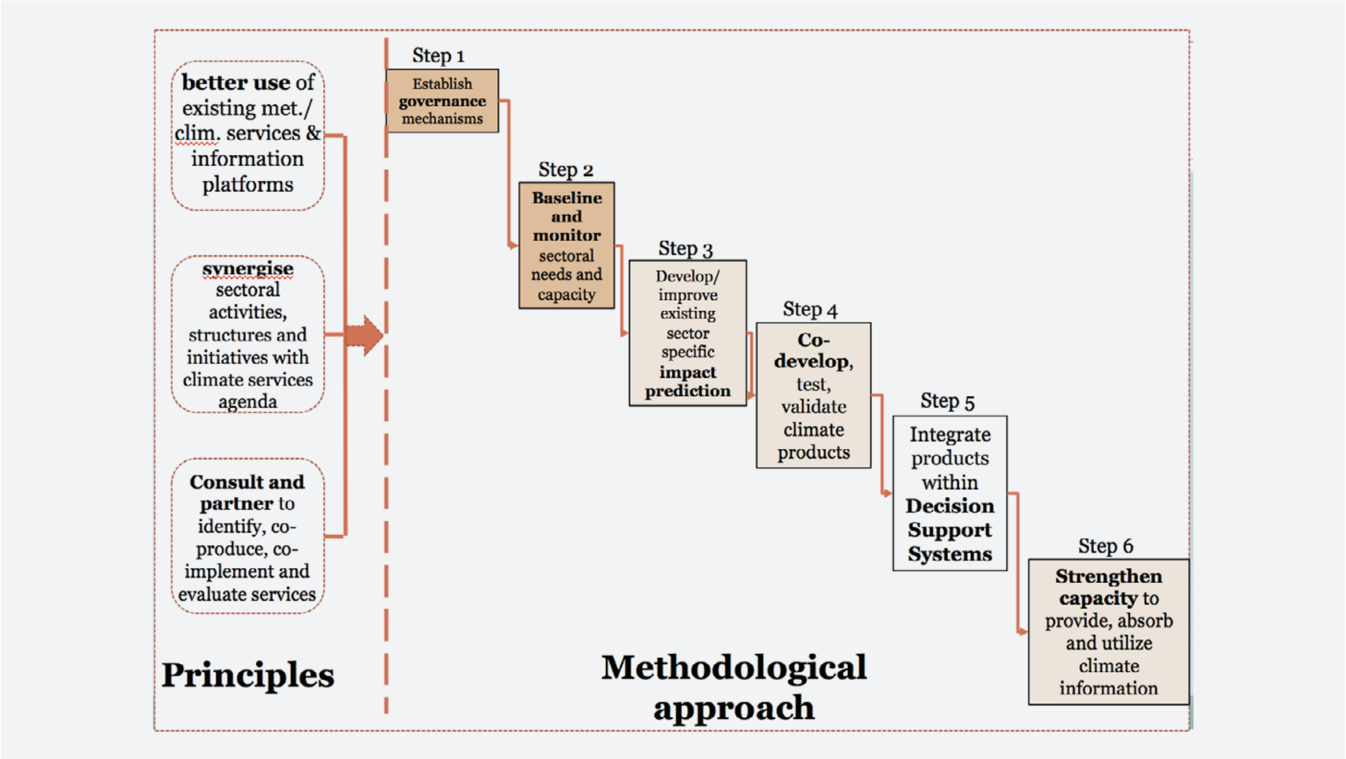


Figure 8.2: Methodological approach to the co-design, co-development and co-delivery of climate services in the Caribbean. *(Shading indicates progress made to date at varying degrees of implementation).* Source: Mahon et al (2015a)

Collectively, the six-step methodological process highlights the *co-design*, *co-development* and *co-delivery* of sector-specific climate services using innovative and sophisticated modelling and prediction techniques in tandem with a highly participatory and inter-disciplinary workflow that engages user communities at all stages of the climate services value chain (Mahon et. al. 2015a). It is a co-production process that at its core is underpinned by the principle and practice of *partnership and consultation to add value to generic climate information through services*.

STEP 1: ESTABLISH GOVERNANCE MECHANISMS: THE SECTORAL EWISACTS CONSORTIUM

One of the keys to the success of the sectoral EWISACTs programme was the early establishment of a representative stakeholder governance mechanism at the regional level (Mahon et al. 2015a,b). The Consortium of Regional Sectoral Early Warning Information Systems across Climate Timescales Coordination Partners was established in 2017 under the USAID-supported Building Regional Climate Capacity in the Caribbean (BRCCC) Programme (2014-2017) as a multi-agency alliance for climate resilience and a high level manifestation of a formalized UIP.

The arrangement leverages the technical resources and expertise of lead technical organizations such as the Caribbean Agricultural Research & Development Institute (CARDI), the Caribbean Water and Wastewater Association (CWWA), the Caribbean Disaster Emergency Management Agency (CDEMA), the Caribbean Public Health Agency (CARPHA), the Caribbean Tourism Organization (CTO) and the Caribbean Hotel and Tourism Association (CHTA) (Figure 8.3).

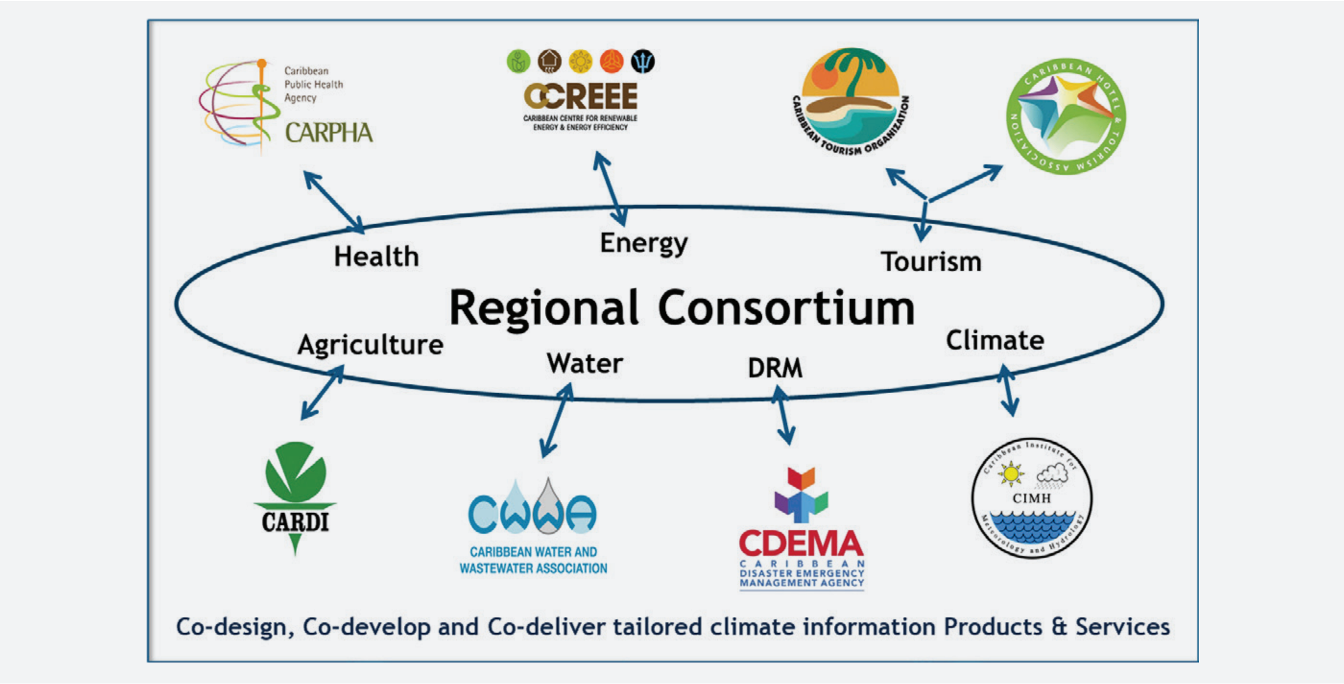


Figure 8.3: The Consortium of Regional Sectoral EWISACTs Coordination Partners. Source: Mahon et al (2018).

Individual Consortium members serve hundreds of sectoral practitioners through multi-faceted initiatives in the six Caribbean prioritized sectors, and as such, are well positioned to inform and influence sectoral decision-making at regional and national levels. Importantly, as a formal, inter-sectoral collaboration mechanism, the Consortium arrangement allows for the identification of areas of joint complementary work and overlapping interests as a basis for partnership (CIMH et al. 2015; Mahon et al. 2015a,b).

STEP 2: BASELINE AND MONITOR SECTORAL NEEDS AND PROVIDER CAPACITY

Since 2015, CIMH has invested in a comprehensive baseline assessment of user needs and provider capacity (Mahon & Trotman 2018; Mahon et al. 2019). This assessment has since informed product tailoring and capacity development for sector-specific applications. For example, it is now clear that very few NMHSs are engaged in producing specialized products for major sectors mainly because they lack the capacity to do so. On the end-user side, the research revealed that a significant number of end-users are unaware of key climate information tools and products that are routinely available to them. There is also differentiated ability across end-user communities to interpret and use climate information.

STEP 3: DEVELOP/IMPROVE EXISTING SECTOR SPECIFIC IMPACT PREDICTION

The development of sector-specific climate-driven monitoring and forecasting models is inherently complex and must be anchored in a robust knowledge of climate thresholds for sectoral operations. A core future task for the Caribbean will be the collection and the integration of socio-economic indicators from sectoral surveillance/monitoring with climate and environmental observations (Mahon et al. 2015b).

There are clear advantages of approaching this step starting from an evaluation of users' needs and using this information to inform the development of impact forecasting systems. Doing so has identified priority applications such as climate services for *Aedes aegypti* borne diseases such as dengue fever, Chikungunya, Zika and Yellow fever that have historically placed a serious health burden on Caribbean societies (Shepard et al. 2011). The CIMH in partnership with the CARPHA, the Pan American Health Organization (PAHO), national Ministries of Health, NMHSs and an international, inter-disciplinary research team is working to co-design and co-develop a climate-driven spatio-temporal modelling framework that provides early warning of the increased risk of *Aedes aegypti* diseases. Preliminary analyses from this work piloted in Barbados and Dominica provide evidence for the role of climate extremes in seasonal and inter-annual variability in *Aedes aegypti* dynamics and dengue transmission and lay the groundwork for developing a climate-driven early warning system for *Aedes aegypti* transmitted viruses in the Caribbean Lowe et al. 2018; Trotman et al. 2018. Efforts are already underway to extend the scope of the research to other Caribbean countries. Over time, the outputs of this modelling framework can be used for operational, evidence-based decision making in the area of vector control.

The CIMH is also partnering with the CTO and the CHTA to develop a tourism-climate spatio-temporal modelling framework that predicts the influence of intra- and extra- regional climate on tourist arrivals to the Caribbean. Over time, the outputs of this modelling framework can be used to inform strategic and operational marketing decisions – helping the region to take advantage of revenue opportunities that can arise from unfavourable climate conditions in tourist-generating regions in the US, UK and Europe, or alternatively, to manage risks associated with an adverse climate forecast such as severe drought conditions in the Caribbean (Mahon et al. 2018).

These innovative research-to-operations advances are beginning to address the limited number of sector-specific climate indices for the Caribbean context. In time, these research streams will also seek to correlate past physical and socio-economic impacts associated with past climate conditions in order to better understand the link between climate information and expected impacts and, where possible, provide operational impacts-based forecasts. This enhanced understanding is expected to contribute to a matching of appropriate response strategies to deal with potential impacts. There are future plans to develop decision support tools designed to enable sectoral users to link current climate information to appropriate response strategies (Mahon et al. 2015b). The interface tool and the research that underpin it will bring the region closer to the operationalization of an integrated CSIS that harmonizes climate and sectoral modelling outputs.

STEP 4: CO-DEVELOP, TEST AND VALIDATE CLIMATE PRODUCTS

The development of climate-driven sector-specific monitoring and forecasting models and associated full scale information systems will arguably take some time to fully materialize. In the interim, the CIMH and its Consortium partners have harnessed the opportunity to synthesize, tailor and package the key climate messages from CIMH's existing suite of technical climate information products into operational sector-specific climate Bulletins. As the first tangible outputs of the Consortium partnership, the Caribbean Health-Climatic, Caribbean Tourism-Climatic and the revamped Caribbean Agro-Climatic Bulletins communicate sectoral risks and opportunities associated with recent past and upcoming climate conditions for up to 3 to 6 months in advance (Figure 8.4).

Regional CAMI Bulletin (since 2011), now the Caribbean Agro-Climatic Bulletin (since 2017)

Caribbean Health-Climatic Bulletin (since 2017)

Caribbean Tourism-Climatic Bulletin (since 2017)

Figure 8.4: Co-developed sector-specific climate Bulletins. Source: Mahon et. al (2018)

Of significance here was the initial process of co-design involving several rounds of Bulletin prototype testing and validation with hundreds of sectoral practitioners. Today, *operational co-development* is practiced through the co-authorship of each Bulletin issue between CIMH and the regional sector leads for agriculture, health and tourism. Leveraging the knowledge and background of regional sectoral experts in their relevant fields makes it possible to tailor the language of generic climate information for easier sectoral uptake and response. For example, assessment of the risk posed by recent and future climate conditions are contextualized and communicated using language that is salient and understandable for sectoral stakeholders with recommendations for response expressed as customized advisories. Given the differentiated ability across end-user communities to interpret climate information, each sector-specific climate bulletin is communicated with its own nuance and is *co-delivered* online through the Caribbean RCC and Consortium partner platforms.

STEP 5: INTEGRATE PRODUCTS WITHIN SECTORAL DECISION SUPPORT SYSTEMS

Ultimately, both existing and planned climate products, will need to be integrated into sectoral decision support systems such as the CARPHA's CARISURV health surveillance system, and the CTO's Tourism Information Management System. Alternatively, CIMH and its Consortium partners may invest in upgrading the CIMH hosted Caribbean Dewetra platform - a real-time, integrated risk-based data fusion and decision support platform for weather, climate and hydrological information – to serve as a 'one-stop' integrated Caribbean CSIS. At the regional sectoral level, the CDEMA Coordinating Unit already views the Caribbean Dewetra platform as the operational platform to be utilized going forward within its 18 Participating States. Improvements required relate to the expansion of the Platform into the other five climate sensitive sectors, the integration of sectoral DSSs with the Dewetra platform, as well as, the expansion of the Caribbean Dewetra Platform application to the broader Caribbean Region (Mahon et al. 2015b).

STEP 6: STRENGTHEN CAPACITY TO PROVIDE, ABSORB AND UTILIZE CLIMATE INFORMATION

The CIMH, along with its donor partners, continues to invest in a programme of training and capacity building both at the regional level and within CMO Member States for NMHS providers and sectoral users. Since 2012, the CIMH has convened the Caribbean Climate Outlook Forum. At the CariCOF, meteorologists and climatologists from NMHSs receive seasonal forecasting and analytical training prior to a Forum. At the Forum, sectoral practitioners and these meteorologists and climatologists discuss early warning information including seasonal climate forecasts, other experimental products, and share experiences (Mahon et al. 2019; Gerlak et al. 2018). In addition, a series of technical thematic capacity building workshops have been convened to strengthen national and sectoral capacity to access, interpret and use climate information and transform users into 'climate smart' professionals. These include the bi-annual CariCOF, national sectoral EWISACTs Workshops, drought management workshops, as well as, national level climate information downscaling workshops. These interactive forums facilitate provider and end-user interaction and technical capacity building and have no doubt contributed to increasing the capacity of Caribbean practitioners to make climate-informed decisions. However, going forward, the support of all agencies within the Consortium, their affiliate members, international development partners and donors will be required.

8.3. TAILORED CLIMATE SERVICES AT THE NATIONAL LEVEL

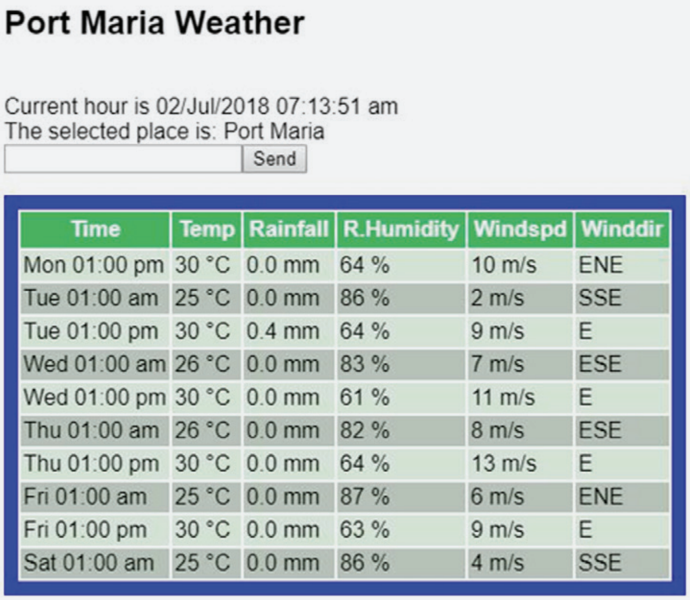
Climate services have been developed at the national level within some Caribbean islands. Jamaica and Trinidad and Tobago provide good examples of the tailoring process.

8.3.1. JAMAICA

In 2009, the European Commission sponsored the Caribbean Agro-Meteorological Initiative (CAMI) through its

Science and Technology Programme for Member States of the African, Caribbean and Pacific (ACP) Group of Countries. The objective of CAMI was to increase and sustain agricultural productivity at the farm level in the Caribbean region through improved applications of weather and climate information using an integrated and coordinated approach in ten countries, including Jamaica. One of the CAMI activities was the delivery of farmers' forums across the pilot States where NMHSs interface with agriculture extension officers and farmers to discuss climate-related issues important for on-farm operations. This series of forums - a compelling example of a sector-specific UIP - led to the formalization of a partnership between the Meteorological Service of Jamaica (MSJ) and the Rural Agriculture Development Agency (RADA) of Jamaica through an MOU that remains in force and active up to today.

The first meaningful outcome was the MSJ responding to a request from farmers during the 2011 forums to provide higher resolution, district-specific weather forecasts (Figure 8.5) and other information (Figure 8.6) which the MSJ subsequently delivered on its web portal (http://agrilinksja.com).



Port Maria Weather

Current hour is 02/Jul/2018 07:13:51 am
The selected place is: Port Maria

Time	Temp	Rainfall	R.Humidity	Windspd	Winddir
Mon 01:00 pm	30 °C	0.0 mm	64 %	10 m/s	ENE
Tue 01:00 am	25 °C	0.0 mm	86 %	2 m/s	SSE
Tue 01:00 pm	30 °C	0.4 mm	64 %	9 m/s	E
Wed 01:00 am	26 °C	0.0 mm	83 %	7 m/s	ESE
Wed 01:00 pm	30 °C	0.0 mm	61 %	11 m/s	E
Thu 01:00 am	26 °C	0.0 mm	82 %	8 m/s	ESE
Thu 01:00 pm	30 °C	0.0 mm	64 %	13 m/s	E
Fri 01:00 am	25 °C	0.0 mm	87 %	6 m/s	ENE
Fri 01:00 pm	30 °C	0.0 mm	63 %	9 m/s	E
Sat 01:00 am	25 °C	0.0 mm	86 %	4 m/s	SSE

Figure 8.5. Weather forecast information for Port Maria in Northern Jamaica

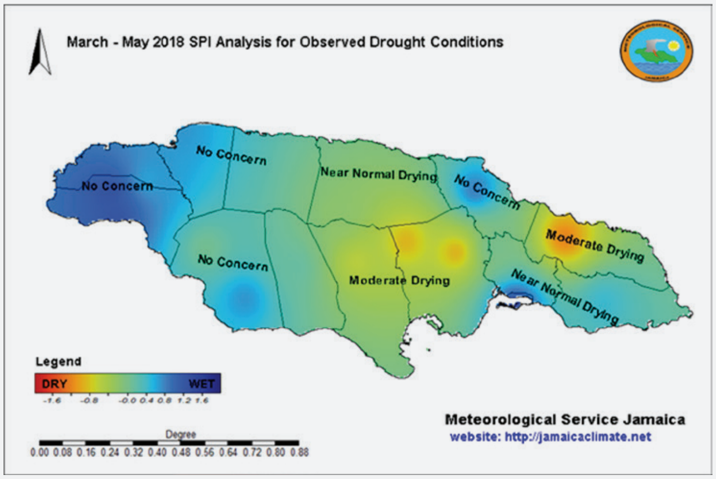


Figure 8.6. Observed drought severity in Jamaica from March to May 2018 using the Standardised Precipitation Index (SPI)

These products have all been made available on the purpose-built Jamaica Climate website which is specifically aimed at “Enhancing Farming through Weather and Climate Information” (www.jamaicaclimate.net). The MSJ and RADA continue to work together to enhance the national observational network, in an arrangement where the MSJ recommends and installs new instruments procured by RADA.

Importantly, the capacity of the MSJ continues to be built through CIMH’s traditional, routine training programmes. Specific climate services delivery capacity is routinely upgraded through the CariCOF’s training for meteorologists, and other climate related workshops and seminars, including those that are sector-specific in nature. Climate services support has also been provided by the Climate Studies Group Mona, University of the West Indies related to climate change information and projections.

8.3.2. TRINIDAD AND TOBAGO

The Trinidad & Tobago Meteorological Service (TTMS) has actively delivered national weather and climate services since the early 1960s. By the 1980s, in addition to providing generic weather forecasts, monthly climate summaries and dry and wet seasons rainfall forecasts, the TTMS produced customized agro-meteorological forecasts for local farmers and monthly rainfall forecasts for water resources management. Although the TTMS ceased providing daily agriculture forecasts during the 1990s, by May 2013, through the Caribbean climate services programme that coincided with a programme to upgrade the human resource capacity in applied meteorology at the TTMS, there was a relaunch of services for the agriculture sector in the form of dekadal (10-day) agro-meteorological forecasts (Figure 8.7) and bulletins. More recently, the TTMS has collaborated with the Telecommunications Company of Trinidad and Tobago on SMS delivery of its daily weather forecast to farmers’ and fisher-folk’s mobile phones.

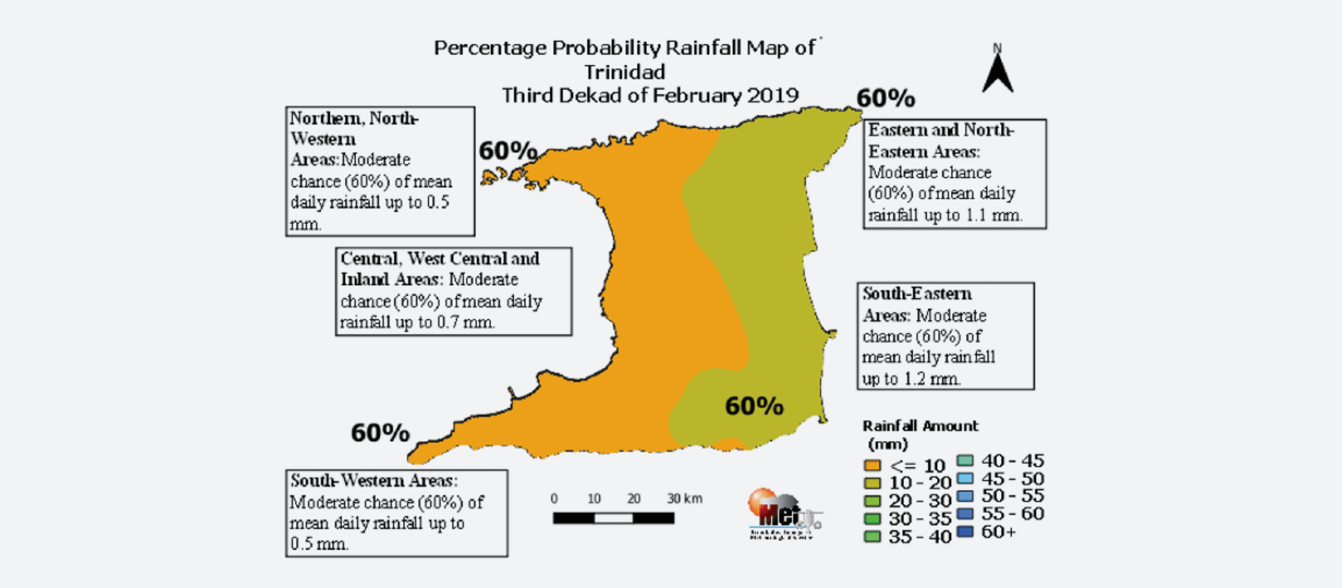


Figure 8.7. Colour-coded ten-day rainfall forecast for various farming districts with percentage probability of occurring.Text boxes show expected regional average daily rainfall totals.

Apart from these, the TTMS has performed climate analysis and monitoring of climate extremes and delivered authoritative climate information and products at the national level. The TTMS delivers a suite of national seasonal climate outlook products on a range of conditions related to rainfall and temperature for the wet and dry seasons. Within each season, three-month climate monitoring and forecast products for rainfall (Figure 8.8), temperature, and dry spells/drought are delivered and updated monthly along with a bi-monthly El Nino-Southern Oscillation Watch. These products are provided directly to key stakeholders within the energy, agriculture and food security, health, disaster risk management, health, water, tourism and financial sectors via emails. Apart from these, the TTMS implemented a health-climate services tab where it provides dengue early warning information based strictly on climate signals for the country. In particular, the early warning is provided for the county with the highest dengue risk potential in the country. Heat and human health products provided include hot spell alerts/ warnings/watches when set percentile thresholds are forecasted or met; as well as current observed feels-like (temperature) index and UV index data.

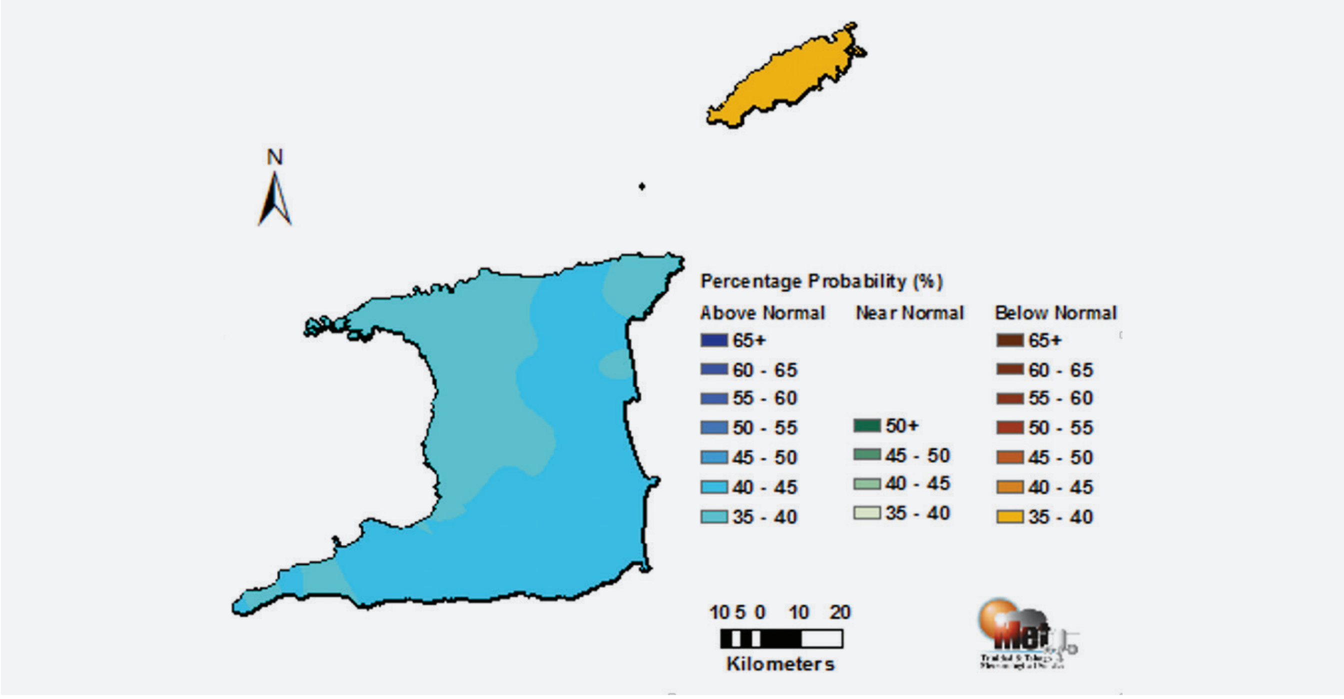


Figure 8.8. Probabilistic seasonal 3-month rainfall outlook presented as the most likely tercile category for the season, colour coded on the map.

The TTMS has been providing specific climate services for water resource management in the form of reservoir site-specific rainfall totals outlooks that are critical for the assessment of reservoir projections, water supply and water availability, as well as risks arising from floods and droughts. These services which contribute to the sustainable management of water resources are made available online (https://www.metoffice.gov.tt/ or the TTMS's weather app) and emailed to key stakeholders.

Additionally, seven National Climate Outlook Forums (NCOFs) – the national flagship UIP - have been hosted under various themes targeting the GFCS priority sectors. Focus areas have included agriculture, disaster risk reduction, rural adaptation, health and disaster risk management. The NCOFs align with the TTMS' thrust to engage stakeholders at the policy, decision-making and planning levels with government ministries, departments and agencies, to share and assist with climate science knowledge, risk management skills and early warning system expertise in support of government's policy development and implementation. The TTMS also supports capacity building across key stakeholder agencies, and provides advice to the Economic Management Division of the Ministry of Finance regarding risk transfer.

The TTMS recently developed and implemented an adverse weather and climate early warning system based on the concept of impact-based warnings and forecasting. It is fashioned after the Common Alerting Protocol international standards that support disaster preparedness, prevention and response for the disaster risk management sector and the public at large. The much needed tool took into consideration, understanding of stakeholder requirements in the key sectors, such as disaster risk management, fishing, agriculture, water, health, oil and gas, and the public, and has shifted focus towards impact factors tailored towards communities. This service now enables the TTMS to issue colour-coded severe weather warnings to various government ministries and authorities including the disaster management units and reaches the widest possible audience. It is preventative in nature as it is expected to prompt advanced action and proactive adaptation to reduce hydro-meteorological hazard-associated risks and costs (i.e. loss of human life, economic costs).

8.4. ADVANCING CARIBBEAN CLIMATE SERVICES IN THE FUTURE

A key lesson emerging from the Caribbean's cumulative experience with the development and use of climate services to date is that considerable investment is still needed to:

1. Strengthen the institutional context for climate services at regional, national and sectoral levels,
2. Enhance and harmonize NMHS and sectoral information production systems,
3. Increase the generation of sector-specific climate information products, and
4. Build the capacity of sectoral practitioners to use these products to make evidence-based, climate-informed decisions.

8.4.1. THE SECTORAL EWISACTS ROADMAP AND PLAN OF ACTION

In an effort to address these gaps and guided by the GFCS philosophy, the Caribbean has established its own consensus-based, regionally tailored framework for climate services - the Sectoral EWISACTs Roadmap and Plan of Action (PoA) 2020-2030. The Roadmap and PoA articulates the main components of the Consortium's proposed cross-agency portfolio of climate service initiatives in the long-term. In this way, it serves as a guide for the implementation of a coordinated, multi-sectoral climate services portfolio.

8.4.2. EXTENDING THE CLIMATE SERVICES PARTNERSHIP

Within the framework of the Sectoral EWISACTs Roadmap and PoA, extending operational climate services beyond the sectors currently being supported is seen as key. It is expected that, in the near future, operational climate services will be integrated implicitly and explicitly in the financial, construction and insurance sectors, among others. Interventions in the new sectors will require discussions and stakeholder mapping strategies to define the areas and styles of intervention.

8.4.3. DOWNSCALING AND COORDINATION OF CLIMATE SERVICES AT THE NATIONAL LEVEL

Recognizing that capacity levels for national coordination of the delivery of climate services are largely embryonic throughout CMO Member States, an area of increased investment going forward is strengthening national level infrastructure, processes and mechanisms for downscaling and coordination of climate services. This will entail supporting Caribbean NMHSs to identify critical gaps and opportunities for inter-sectoral linkages and synergies at the national level; and using this as the basis for inter-sectoral collaboration on the co-design, co-development and co-delivery of tailored national climate products and services in their climate-sensitive sectors.

9. CONCLUSIONS & RECOMMENDATIONS

This chapter presents a summary of the key report findings and some recommendations for the way forward. The scientific analysis presented in this report is clear. Climate change has been, and will continue to be, a real danger to survivability and resilience in the Caribbean. This makes a strong and urgent case for effective decision-making that will form the foundation of enhanced and integrated preparedness and response systems in the Caribbean.

9.1. CONCLUSIONS

A summary of climate trends and projections for the Caribbean have been presented in Table 9.1. In general, the Caribbean is characterized by increasing temperatures, variable rainfall (with a drying trend in the future), rising sea levels and intense extreme events (Chapters 3-6), the impacts of which have proven damaging to development across the region (Chapter 7). Early warning and other value-added climate services (Chapters 6 and 8) are critical to improving individual and collective resilience to climate change, and as such, these efforts will need to be strengthened, with increased application at sectoral, national and regional levels.

Table 9.1: Summary of Climate Trends and Projections for the Caribbean

HISTORICAL TREND[20]	PROJECTION[21]
RAINFALL	
» Caribbean region has a defined dry (December to April) and wet (May to November) season. » Caribbean countries can be divided into six rainfall zones, based on the pattern of rainfall received. » Central Caribbean (Zones 3 and 4) receives smaller rainfall amounts (2-17 mm/month) while the far western and southern Caribbean (Zones 1 and 6) receive rainfall amounts ranging from 2 to 27 mm/month. » More than 70% of the rainfall occurs in the wet season for each zone. » In the long-term historical record (1900-2014), the Caribbean has not gotten wetter or drier (no significant observed linear trend).	» The Caribbean as a whole will gradually dry through to the end of the century. Drying is expected to be less in the far north Caribbean and more in the south and southeast. » Global Climate Models (GCMs) suggest for the central and southern Caribbean basin, drying up to 20 per cent for annual rainfall, while Regional Climate Model (RCM) based projections suggest up to 25 and 35 per cent less rainfall by the end of the century » GCMs suggest that mid-2020s will see up to 2% less rainfall in the annual mean. By the 2050s, the region is in the mean up to 6% drier, and by the end of century, the region may be up to 17% drier. » The Caribbean drying trend is likely driven by drying in the late wet season (September-November). » Dry season rainfall generally shows small increases or no change. » RCMs suggest sub-regional variation in projections with some parts of the region being more significantly impacted by drier conditions than others. A general pattern is for Belize in the far west Caribbean (Zone 1) and the Lesser Antilles and southern Caribbean (Zones 5 and 6) to be the most severely impacted once drying has begun, as well as the central Caribbean (Zone 4) to a lesser extent.

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[20] Historical trends are based on observations made over 1900-2014.

[21] GCM-generated projections are relative to a 1986-2005 baseline, RCM-generated projections are relative to a 1961-1990 baseline.

HISTORICAL TREND[20]	PROJECTION[21]
RAINFALL	
» Decadal variations account for 7% of the observed variability in Caribbean rainfall. Year-to-year (interannual) variations account for up to 91%. » The number of consecutive dry days is increasing, as well as the amount of rainfall during rainfall events.	» Changes to mean annual rainfall in the far north and north Caribbean (Zones 2 and 3) may suggest slightly wetter conditions through to mid-century, which change to drier conditions by the end of century. It is important to note however, that even for the far north Caribbean, the rainy seasons are projected to dry from as early as the 2020s. » Small to large increases in consecutive dry days are projected across the region.
AIR TEMPERATURES	
» Most of the variability observed (~65%) in temperature in the Caribbean is due to a significant upward (linear) trend. » Increase in temperature in Caribbean is consistent with global warming trend. » There is an increasing trend in very warm days and nights for the Caribbean as a whole.	» The Caribbean as a whole will gradually warm through to the end of the century. » Minimum, maximum and mean temperatures increase irrespective of scenario through the end of the century. » The mean temperature increase (in °C) from GCMs will be 0.48-0.56°C by the 2020s; 0.65-0.84°C by the 2030s, 0.86°-1.50°C by the 2050s, and 0.83-3.05°C by the end of the century with respect to a 1986-2005 baseline over all four RCPs. » RCMs suggest higher magnitude increases for the downscaled grid boxes - up to 4°C by end of century. » Temperature increases across all seasons of the year. » There are regional variations in warming evident in the RCM results. The far western Caribbean (Zone 1) and the southern Caribbean (Zone 6) show slightly higher warming than the rest of the region. » Projections based on statistical downscaling show an increase for both warm days and warm nights by the end of the century - warm days ranged between 51 and 251 days, and warm nights between 24 and 360 days for RCP 8.5. » The trend is for a decrease in both cool days and nights. The range for cool days was between 1 and 41 days, and between 1 and 32 days for cool nights for the end of century under RCP 8.5.
SEA SURFACE TEMPERATURES	
» Range from 25°C to 30°C over the period of the year and follows a normal distribution pattern, with the lower temperatures in December/January and the highest temperatures in July.	» Recent warming trend in SSTs will continue in the future. » Under a business-as-usual scenario, SSTs increase by 1.76 ± 0.39°C per century in the wider Caribbean. » The mean annual SST range (~ 3.3°C) currently observed in the Caribbean Sea is projected to contract to 2.9°C in the 2030s, and to 2.3°C in the 2090s. By the end of the century, years of coolest projected SSTs fall within the range of the warmest years in the present.

HISTORICAL TREND[20]	PROJECTION[21]
SEA LEVELS	
» There is a general increasing trend in the sea level of the Caribbean region: » A regional rate of increase of 1.8 ± 0.1 mm/year between 1950 and 2009. » Higher rate of increase in later years: 1.7 ± 1.3 mm/year between 1993 and 2010. » Caribbean Sea level changes are near the global mean. » Larger sea level increases observed for post 2000 period during which hurricane intensity and sea level interannual variability have both increased.	» For the Caribbean, the combined range for projected SLR spans 0.26-0.82 m by 2100 relative to 1986-2005 levels. The range is 0.17-0.38 for 2046 – 2065. Other recent studies suggest an upper limit for the Caribbean of up to 1.5 m under RCP8.5. » Regional variation in SLR is small with the north Caribbean tending to have slighter higher projected values than the southern Caribbean. By the end of the century, sea level rise is projected to reach or exceed 1m across the Caribbean.
HURRICANES	
» Significant increase in frequency and duration of Atlantic hurricanes since 1995. » Increase in category 4 and 5 hurricanes; rainfall intensity, ass°Ciated peak wind intensities, mean rainfall for same period.	» No change or slight decrease in frequency of hurricanes. » Shift toward stronger storms by the end of the century as measured by maximum wind speed increases of +2 to +11%. » +20% to +30% increase in rainfall rates for the model hurricane's inner core. Smaller increase (~10%) at radii of 200 km or larger. » An 80% increase in the frequency of Saffir-Simpson category 4 and 5 Atlantic hurricanes over the next 80 years using the A1B scenario.

9.2. RECOMMENDATIONS

While this report provides a significant repository of climate data and information, there are a number of critical data-related gaps and challenges that need to be addressed as the region seeks to employ evidence-based approaches to decision-making. These data challenges are linked to inadequate coverage of weather and climatological stations that will (i) facilitate analysis at sectoral, national and regional scales (ii) enable automatic reporting and (iii) improve continuous monitoring and analysis of key variables for sufficiently long timescales (greater than 30 years). Also to be addressed in support of better decision-making are (i) inadequate data collection and monitoring systems at the sectoral level that limit the understanding of climate-sectoral linkages (ii) the need for higher resolution modelling outputs as well as more impacts-based modelling and (iii) coordination and capacity challenges that have reduced the effectiveness of climate action in the region.

It should be noted that this section of the report does not seek to provide specific recommendations for the many and varied implications of climate and its impacts for Caribbean way of life. There are several studies that have done this and there are several institutions at the regional, and even national level, that have done work in this regard. Rather, this report puts forward three simple measures or principles that can strengthen decision-making. The success of the measures and ultimately of a regional response is dependent on the commitment or buy-in of national and regional decision-makers (within government, private sector, civil society, academia and other relevant stakeholder groups) to commit to (i) working together to decide upon and achieve agreed climate resilience targets (ii) employ evidence-based approaches as well as adaptive and scenario planning in support of decision-making (iii) support and strengthen existing expertise, resilience-building initiatives and use these to guide decision-making processes.

KEY MESSAGE 1: PLAN FOR THE CURRENT CLIMATE - BUT BE GUIDED BY LESSONS OF THE PAST.

It is important that the Caribbean (individual states and the region as a whole) learns the lessons of the past and use them to guide current and future decision-making processes. This report highlighted the Caribbean's inherent sensitivities to climate phenomena, from prolonged droughts, increasing temperatures, intense and variable rainfall to catastrophic hurricanes. The region has struggled with addressing climate-related threats in an anticipatory manner, and this has increased individual and collective vulnerability. One key example of this is the frequently reactive manner in which slow-onset events such as droughts are addressed. Despite significant efforts such as work led by the CIMH to improve early warning for drought (see Chapter 8), there has been limited implementation of major long-term adaptation initiatives by decisionmakers to reduce drought's damaging impacts. The lessons of the past indicate that we can no longer afford to wait until an event happens, or is about to happen, before action is taken to deal with climate hazards. It is important that planning and decision-making efforts are (i) proactive (ii) not curtailed or stalled once the threat is deemed to be past, and (iii) guided by past lessons and available expertise.

KEY MESSAGE 2: PLAN FOR THE FUTURE CLIMATE – BUT DO IT COLLABORATIVELY.

Prioritized collective action, coordinated across sectoral, national and regional levels, will be critical for successful decision-making. The projections for the Caribbean (presented in Chapter 5) are for rising sea levels, hotter temperatures, more variable rainfall with increased drying, increased sea surface temperatures, and more intense hurricanes. These projections, especially in light of the recent extremes discussed in Chapter 6 and the climate impacts in Chapter 7, call for urgent and coordinated action even while the region tries to grapple with existing threats. The climate-related phenomena that so drastically affect Caribbean countries are not locally derived, and as such, our response mechanisms must also be regionally driven and locally applied. The small size of Caribbean islands is one factor pointing to the need to work together to strengthen regional response mechanisms. In identifying those prioritized actions that the Caribbean should take, consideration should be given to (i) the social and economic costs of inaction or delayed action against the value to be derived from resilience efforts (ii) the levels of resilience that can sustainably be targeted, and (iii) the systems that will need to be in place to support the transition to a more resilient Caribbean.

KEY MESSAGE 3: PRIORITZE HARNESSING AND ENHANCING REGIONAL STRENGTHS AND EXPERTISE IN SUPPORT OF IMPROVED DECISION-MAKING.

Chapter 8 presented an overview of climate services in the region, as well as national and regional mechanisms for supporting same. These efforts, which stand as key examples of regional strengths, have been led by the CIMH in collaboration with a consortium of regional partners. There is significant scope for bolstering these and similar services as well as the implementing institutions so that critical data, information, products and tools to improve decision-making are readily available to end users. As the region tackles climate change, identification and exploitation of regional strengths and opportunities, such as those for integrated, interdisciplinary and targeted research and development programmes as well as climate products and services, must play a substantial role in decision-making.

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11. APPENDIX 1: CLIMATE RESOURCES

This appendix provides information on climate resources that are available for the region. These resources include data sources, tools, and available literature for the region. The information provided on regional resources has been adapted from the State of the Jamaican Climate 2015 (CSGM, 2017), which includes comprehensive lists of decision-making services, tools, data, and software specific to the Caribbean Region.

Following this outline is a list of scientific publications relevant to Caribbean climate. These publications cover the topics:

- About Caribbean climate
- Historical changes in rainfall and temperature
- Climate extremes
- Sea level rise
- Hurricanes
- Sea surface temperature and large scale systems
- Modelling and future climate
- Renewable energy
- Impacts of climate change

11.1. CLIMATE RESOURCES

11.1.1. CLIMATE TOOLS FOR DATA ANALYSIS AND DECISION-MAKING

Table 1: Climate tools that can provide users with local, regional, and international climate information and future climate outputs.

CLIMATE SERVICE ITEM	COMMENT	RELEVANCE
KNMI CLIMATE CHANGE ATLAS	The KNMI Climate Change Atlas is a web-based interface that allows users to generate global or regional projections of temperature and rainfall using the most recent IPCC climate projections scenarios. The tool also allows for comparisons from a historical baseline period. https://climexp.knmi.nl/plot_atlas_form.py	The KNMI Climate Change Atlas provides global, regional, and country level observations and projections generated from both global climate models (GCMs) and regional climate models (RCMs).
CLIMATE INTERACTIVE	The Climate Interactive suite of tools and simulations that help people understand the long-term effects of emissions levels, global temperature and sea level rise on climate. Climate Interactive includes such tools as C-ROADS and C-Learn. https://www.climateinteractive.org/	The Climate Interactive suite of tools and simulations are good learning aids at for students, professionals, and non-professionals alike.
IRI CLIMATE MAP ROOM	The Climate Map Room developed by the International Research Institute for Climate and Society provides interactive maps and time series of large-scale atmospheric variables. https://iridl.ldeo.columbia.edu/maproom/	This tool can provide a more detailed look at climate on global and regional scales, and how climate analyses may be applied to addressing climate impacts on health and food security for select regions.
SIMPLE MODEL FOR THE ADVECTION STORMS AND HURRICANES (SMASH)	SMASH is a simple model to allow planners and decision makers the opportunity of examining differing scenarios of tracks and intensity for hurricanes that traverse through the region, and determining the associated rain rates and wind speeds for a given location in a SIDS island. It is the University of the West Indies' contribution to a suite of climate tools developed under the Caribbean Weather Impacts Generator (CARIWIG) Project. http://cariwig.caribbeanclimate.bz/#simulations	SMASH allows planners and decision makers the opportunity of examining differing scenarios of storm tracks and intensities and the associated rain rates and wind speeds for a given location in a Caribbean island.
REGIONAL CLIMATE OBSERVATIONS DATABASE (RECORD)	ReCORD is a climate tool that allows decision makers to analyze climate trends across the Caribbean region. http://173.230.158.211/ReCORD	The tool provides a full suite of carefully selected and packaged projected climate data for rainfall and temperature. This is complemented by the historical frequency of tropical storm passage close to that location, and climatologies of the same climate variables for stations located within the chosen sub-region.

CLIMATE SERVICE ITEM	COMMENT	RELEVANCE
CARIBBEAN WEATHER IMPACTS GENERATOR (CARIWIG)	The CARIWIG data portal is a web service that provides local and regional summaries of climate trends and weather projections based on observed climate data and climate model outputs. http://cariwig.caribbeanclimate.bz/#info	The data portal also sports the following three simulators: i) weather generator that provides synthetic scenarios for variables, such as temperature and rainfall, for select meteorological stations across the Caribbean; ii) tropical storm model that generates weather scenarios using past tropical storms (see the SMASH tool outlined above); iii) threshold detector that allows for the post-processing of synthetic weather outputs.
SIMCLIM 2013	SIMCLIM2013 allows users to generate site-specific climate scenarios using superimposed shapefiles and future climate projections. The software was built for better informed climate change risk assessments for both governmental and non-governmental organizations and students. http://www.climsystems.com/simclim/	SIMCLIM allows users to better assess the impact of projections by pairing projections with geospatial information.

Table 2: Climate tools that allow decision makers and policy makers to make informed decisions on climate-sensitive projects.

CLIMATE SERVICE ITEM	COMMENT	RELEVANCE
CARIBBEAN CLIMATE ONLINE RISK AND ADAPTATION TOOL (CCORAL)	The CCORAL tool is a web-based support system that provides decision makers with tools that assess the degree of climate influence in proposed projects. The tool helps decision makers to consider projects within a climate context. http://ccoral.caribbeanclimate.bz/	Allows decision makers to view project proposals within the climate context; assesses the degree of climate sensitivity and impact.
CARIBBEAN CLIMATE IMPACTS DATABASE	The Caribbean Climate Impacts Database (CCID) provides users with a platform for impacts reporting and also evidence-based information for improved climate risk management. The CCID helps to guide disaster risk planning and implementation. http://rcc.cimh.edu.bb/cid/	The CCID provides evidence-based information for improved climate risk management for various sectors.
REGIONAL CLEARINGHOUSE DATABASE	The Caribbean Community Climate Change Center (CCCCC) is an online platform that provides a variety of climate information. Such information includes local and regional vulnerability and impacts assessments, climate-related project documents, and country profiles. http://clearinghouse.caribbeanclimate.bz/	The database provides a collection of sector-specific vulnerability and impact assessments at the local and regional level. The database also provides regional climate outputs from the PRECIS regional climate model.
C-ROADS WORLD CLIMATE	C-ROADS is a climate change policy simulator that helps people understand the long-term climate impacts of actions that reduce greenhouse gas emissions. https://www.climateinteractive.org/tools/c-roads/	The C-ROADS tool runs real-time policy analysis, easily translates climate mitigation scenarios into emissions, concentrations, temperature and per-capita emissions outcomes. It allows for comparisons between other regions.

11.1.2. SECTOR-SPECIFIC TOOLS, PRODUCTS, AND SERVICES

Table 3: Outline of climate products and services specific to the Agriculture sector.

AGRICULTURE SECTOR		
CLIMATE SERVICE ITEM	**COMMENT**	**RELEVANCE**
Local Climate Products: Seasonal Forecast, Farmers Bulletin, Rainfall Summary, Drought and Evapotranspiration (ET0) Map	Examples include: Jamaica http://www.jamaicaclimate.net/ Dominica http://www.weather.gov.dm/ Trinidad http://www.metoffice.gov.tt/	Hosted by the Meteorological Services in respective Caribbean islands.
The Caribbean Society for Agricultural Meteorology (CariSAM).	Information available via: http://carisam.cimh.edu.bb/ Serves as an interface between Meteorologists, Climatologists, and the Caribbean Agriculture Community.	Hosted by the Caribbean Institute for Meteorology and Hydrology and used throughout the Caribbean
Caribbean Climate Products: Agro-climatic bulletin, drought bulletin, coral reef bulletin, rainfall outlook (including extremes) and temperature outlook, weather forecast	Information available via: http://carisam.cimh.edu.bb/	Hosted by the Caribbean Institute for Meteorology and Hydrology and used throughout the Caribbean. Helps to predict and forecast inhospitable conditions for fisheries, livestock and crops and allows for preemptive remedial actions to be taken
World AgroMeteorological Information Service (WAMIS)- Global website for Agromet	http://www.wamis.org/	Hosted by the World Meteorogical Service, with links to multiple countries
Climate Impacts on Agriculture (Climpag)- A site that seeks bring together various aspects and interactions between weather, climate and agriculture in the general contat of food security	http://www.fao.org/nr/climpag/about_en.asp	Hosted by the FAO with links to multiple countries
FAOSTAT- A global database providing free access to agriculture data for over 245 countrie and terrirtories.	http://www.fao.org/faostat/en/#	Data available for most countries from 1961 to most recent records
The Caribbean Dewetra Platform- Dewetra is an IT system aimed at weather-related risk and forecasting and monitoring. It collects and systematizes all data, automatically or manually and produces value-added products. Forecast models, and in situ observations are integrated with vulnerability and exposure data to produce risk scenarios in real time.	Different modules aimed at forecasting specific hazards such as fires, landslides, stream flow and floods can be easily integrated into the platform. It can produce haard maps, details of land cove-land, land use and vegetation	Used at National level in Italy, Bolivia, Lebanon, Albania and the Caribbean (coordinated in the Caribbean by the CIMH). (http://www.cimafoundation.org/wp-content/uploads/doc/DEWETRA_english.pdf)

AGRICULTURE SECTOR		
CLIMATE SERVICE ITEM	**COMMENT**	**RELEVANCE**
Caribbean Climate Impacts Database (CID)- a comprehensive open source geospatial inventory of impacts occurring from climate events	Provides historical records (both quantitative and qualitative) of severe events from prior to 1900. The site also Includes information of loss and damage to the Caribbean agriculture sector resulting from severe weather systems. Can be used to aid decision making especially with respect to hazard prone areas	Available via: http://rcc.cimh.edu.bb/cid/about.php and used throughout the Caribbean. Also consulted frequently by global users.
Caribbean Climate Outlook Forum (CARICOF)- hosted by CIMH	Incorporates weather data from 18 Caribbean countries to produce region-wide climate seasonal outlooks. Recent outlooks can be found at: https://rcc.cimh.edu.bb/climate-outlooks/	Forecasts are made at both the national level by local meteorological services, and at the regional level by the CIMH. Multiple large scale oscillations are considered in these forecasts, which are made twice per year- during the major Caribbean dry and wet seasons.

Table 4: Outline of climate tools, software, sensors and models specific to the Agriculture and Water sector.

AGRICULTURE SECTOR		
CLIMATE SERVICE ITEM	**COMMENT/DESCRIPTION**	**RELEVANCE**
Modelling System for Agricultural Impacts of Climate Change (MOSAICC)	An integrated package of models for assessing the impacts of climate change on agriculture including the variations in crop yields and their effect on national economies. The Four main components include: 1. Climate (downscaled data); 2. Hydrology (estimate of future water resources), Crops (Yield simulations under climate change); and Economy (economic impacts of future crop yields and water resources projections)	Developed by the Food and Agriculture Organization (FAO) of the United Nations. Links (climate) information and decision making to improve food security
FAO- AquaCrop Model	A Yield to water response model for herbaceous plants (i.e. plants with a known annual cycle). It has capability to predict yield and biomass changes under multiple scenarios of climate change and can also simulate production with saline intrusion considerations	Model is freely available via: www.fao.org/nr/water/infores_databases_aquacrop.html. Model has been parameterized for several crops and is used globally. **(Has been applied successfully to Sweet Potato in Jamaica and relevant to several other crops)**
CROPWAT Model	Used to simulate crop growth and water flow in the rootzone in deficit irrigation studies. It is a powerful tool for extrapolating findings and conclusions from field studies. Very useful for drought impact assessment under climate variability and change	An FAO Model that has global utility
Ex-ACT: Climate Impact Assessment	A software that estimates the likely impacts of agricultural and forestry development projects on greenhouse gas emissions and sequestration in terms of carbon balances	Developed and hosted by the FAO
Decision Support System for Agrotechnology Transfer (DSSAT)	This is a software application programme that comprises crop simulation models for over 42 crops. It allows for various simulations to be made based on soil, weather, crop management (including fertilizer treatments, crop sequencing/rotation, and varietal selection)	Very widely used crop model globally. Highly documented model, which has several crops grown in the Caribbean. More information available at: http://dssat.net/

AGRICULTURE SECTOR

CLIMATE SERVICE ITEM	COMMENT/DESCRIPTION	RELEVANCE
Adapt-N Advanced Nitrogen Recommendation Software	The Adapt-N tool is a user friendly, web-based nitrogen (N) recommendation tool for corn crops. The tool provides precise N fertilizer recommendations that account for the effects of seasonal conditions using high-resolution climate data, a dynamic computer model, and field-specific information on crop and soil management.	The tool is used widely in the USA and can be accessed via- http://adapt-n.cals.cornell.edu/
Tensiometer	An instrument used to determine the matrix water potential (soil moisture tension) in pounds per square inch (PSI). High readings indicate low moisture content (drier soil) and hence the need for irrigation	Used in the Caribbean as a useful means of monitoring soil moisture, allowing for watering only according to the evaporative demand of the crop and therefore improves water conservation
(5TM) Soil Moisture & Temperature Sensor	One in a series of at least 8 different types of Soil Moisture and temperature Sensors. Allows for digital real time monitoring of soil conditions. Other sensors also measure electrial conductivity. More information available at http://www.decagon.com	Can be very useful for mitigating the impacts of heat stress on crops and for reducing impacts of drought. It also allows for monitoring of progress towards maturation through the different phases of crop development. Accumulation of heat units (termed growing degree days) is significantly controlled by temperature.
Spectral Reflectance Sensors (SRS). These are two band radiometers designed to measure Normalized Difference Vegetation Index 9NDVI) or Photochemical Reflectance Index (PRI)	The Normalized Difference Vegetation Index (NDVI) is a numerical indicator that uses the visible and near-infrared bands of the electromagnetic spectrum, and is adopted to analyze remote sensing measurements and assess whether the target being observed contains live green vegetation or not.	Very useful for rapid assessment of vegetation status and for constantly monitoring canopy development under different climate regimes.
Ceptometer (ACCUPARLP-80)- used to measure canopy photosynthetically active radiation (PAR) for non-destructive leaf area index (LAI) measurements	LAI is one of the most commonly used measurement of canopy expansion, which is a key parameter for monitoring crop development. It allows you to measure canopy PAR interception and calculate LAI at any location within a plant or forest canopy. PAR data can be used with other climate data to estimate biomass production without destroying the crop. With the AccuPAR there is no need to wait, it uses radiation measurements and other parameters to accurately calculate leaf area index in real time, in the field	One in a series of three other tools used to measure canopy development (available via www.decagon.com). Can be useful for field work, especially as inputs for crop models
Lysimeter	A measuring device which can be used to measure the amount of actual evapotranspiration which is released by crops. It is a powerful tool since it allows better understanding of soil water balance, including deep drainage.	Very useful for soil water monitoring to maximise crop yields, reduce impacts of drought and improve water conservation.

FISHERIES SECTOR

CLIMATE SERVICE ITEM	COMMENT/DESCRIPTION	RELEVANCE
NOAA Coral Reef Watch Satellite Monitoring	Continuous monitoring of sea surface temperature provide reef monitoring environmental conditions to quickly identify areas at risk for coral bleaching. Bleached corals lead to mortality and eventual death of the whole colony, which in turn cause habitat and spawning ground destruction for most fish species	Used globally and provides input for Caribbean Coral reef watch. The watch provides different alert levels: No stress, Bleaching Watch, Bleaching Warning; Alert Level 1 (Bleaching likely); Alert level 2 (Mortality likely)

LIVESTOCK SUB-SECTOR

CLIMATE SERVICE ITEM	COMMENT/DESCRIPTION	RELEVANCE
Digital Infrared Thermometer	Used to measure animal skin temperature which is an effective means to monitoring and predicting heat stress	Heat stress reduces reproductive rate in small ruminants, retards milk production and affects egg production in chickens

WATER SECTOR

CLIMATE SERVICE ITEM	COMMENT/DESCRIPTION	RELEVANCE
Water Evaluation and Planning (WEAP) System	Modelling tool for estimating water resources, demand and supply. The WEAP aims to incorporate these issues into a practical yet robust tool for integrated water resources planning. WEAP is developed by the Stockholm Environment Institute's U.S. Center. http://www.weap21.org/	WEAP is a unique approach for conducting integrated resources planning assessments and has several uses: 1) offers transparent structure facilitates engagement of diverse stakeholders in an open process 2) a database maintains water demand and supply information to drive mass balance model on a link-node architecture 3) calculates water demand, supply, runoff, infiltration, crop requirements, flows, and storage, and pollution generation, treatment, discharge and instream water quality under varying hydrologic and policy scenarios 4) evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems 5) dynamic links to other models and software, such as QUAL2K, MODLFOW, MODPATH, PEST, Excel and GAMS
The Hydrologic Modeling System (HEC-HMS) http://www.hec.usace.army.mil/software/hec-hms/	HEC-HMS is physically-based, semi-distributed hydrologic model that simulates the response of a watershed subject to a given hydro-meteorological input. The model has four basic components: the basin models, meteorological models, control simulations and input data. The outputs are represented as discharge hydrographs at junction points of the river system as well as volume of runoff with abstraction or losses from infiltration for each sub-basin.	The HEC HMS is designed to simulate the complete hydrologic processes of dendritic watershed systems. The software includes many hydrologic analysis procedures such as event infiltration, unit hydrographs, and hydrologic routing.
The Geospatial Hydrologic Modeling Extension (HEC-GeoHMS)	Developed as a geospatial hydrology toolkit for engineers and hydrologists with limited GIS experience. HEC-GeoHMS uses ArcGIS and the spatial analyst extension to develop a number of hydrologic modeling inputs. http://www.hec.usace.army.mil/software/hec%2Dgeohms/	HEC-GeoHMS is a GIS-based pre-processor that may be used to simulate watershed features and parameters such as slope, length, parameters for loss or abstraction, which are in turn used as input for HEC-HMS. Along with HEC-GeoHMS, the Arc Hydro Tool and ARC MAP 10.2 are used as pre-processor tools for extraction of catchments or sub-basins from the Digital Elevation Model (DEM) of the watershed.
Simple Model for the Advection of Storms and Hurricanes (SMASH)	SMASH allows users to simulate different scenarios of storm track and intensity by historical hurricanes moving across a Caribbean island along a path determined by the user. SMASH has three basic steps: data collection, execution and data distribution. http://173.230.158.211/SMASH/	SMASH has been used with the HEC-HMS to generate rainfall run-off simulations with the HEC-HMS (please refer to Mandal et al. (2016)).

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NOTES

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