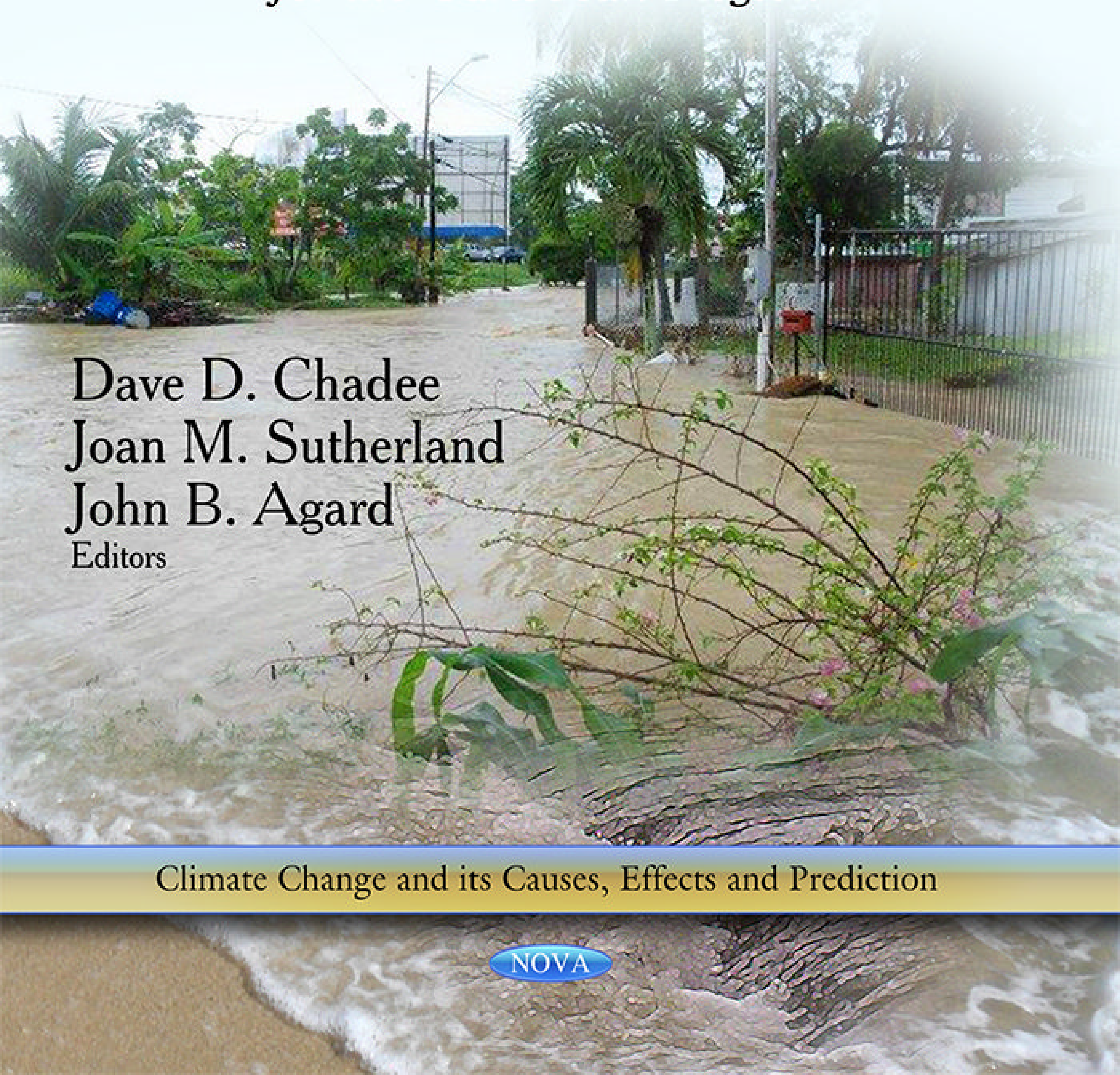
Flooding and Climate Change

Sectorial Impacts and Adaptation Strategies for the Caribbean Region



Dave D. Chadee
Joan M. Sutherland
John B. Agard
Editors

Climate Change and its Causes, Effects and Prediction

NOVA

FLOODING AND CLIMATE CHANGE

SECTORIAL IMPACTS AND ADAPTATION STRATEGIES FOR THE CARIBBEAN REGION

CLIMATE CHANGE AND ITS CAUSES, EFFECTS AND PREDICTION

Additional books in this series can be found on Nova's website
under the Series tab.

Additional e-books in this series can be found on Nova's website
under the e-book tab.

CLIMATE CHANGE AND ITS CAUSES, EFFECTS AND PREDICTION

FLOODING AND CLIMATE CHANGE

SECTORIAL IMPACTS AND ADAPTATION STRATEGIES FOR THE CARIBBEAN REGION

DAVE D. CHADEE
JOAN M. SUTHERLAND
AND
JOHN B. AGARD
EDITORS

nova publishers
New York

For permission to use material from this book please contact us:
Telephone 631-231-7269; Fax 631-231-8175
Web Site: http://www.novapublishers.com

Additional color graphics may be available in the e-book version of this book.

Library of Congress Cataloging-in-Publication Data

ISBN: 978-1-63117-751-4 (eBook)

Published by Nova Science Publishers, Inc. † New York

CONTENTS

PREFACE

At the beginning of the 21st century the science of climate change reached a pivotal stage during which the evidence of its reality had become overwhelming and both developed and developing countries similarly experienced the impacts of extreme global climate-change events such as flooding, heat waves and drought. However, what was instructive was the rate of recovery of developed versus developing countries and their contrasting rates of implementing adaptation measures to reduce future impacts. In poor developing countries like Small Islands Developing States (SIDS), recovery periods were notably longer as a result of limited financial resources, lack of political will, need for regional and international aid, the lack of technical expertise for reconstruction of homes and villages, and the failure to develop adaptation measures which could potentially prevent or reduce the impact of future extreme events. This failure may be partially explained by the fact that economic losses from natural disasters in SIDS (as a percentage of GDP) have been >1% and 8% in the worst cases, as opposed to <0.1% in high-income countries (IPCC, 2012).The Caribbean islands represent a prime example of developing countries with inadequate resilience to cope with extreme events. Most islands' coastlines are vulnerable to sea-level rise (Pulwarty et al. 2010, Nurse 2011), and, since most villages and townships, and much of the agriculture sector, are located along the coast, they are, therefore exposed to sea-level rise and storm surges as well as the ravages of hurricanes (IPCC 2013). However, regional institutions have held consultations with major stakeholders and have tried to identify and address many of these obvious vulnerabilities, but their success in building resilience is, thus far limited. Some gray literature exists within the Caribbean region but this data is often unreliable or lacking the scientific rigor required for data that can be used to inform policy and ultimately planning.

Within the Caribbean region three books have been written relating to global climate change and the vulnerability of SIDS. The first examined the available literature on vulnerability in the Caribbean in the context of both 'globalisation' and climate change (McGregor et al. 2009), while the edited book by Baban (2008) addressed the hydrology and flow dynamics of rivers which cause flooding but did not address the issue of extreme events and how adaptation strategies should be approached to build resilience. The third book addressed the key issues of dengue and climate change in the Caribbean region and provided the evidence required for developing early warning systems for reducing both the vector, *Aedes aegypti* mosquitoes and transmission of the dengue virus (Chen et al. 2006) but little follow-up action has been undertaken to develop the adaptation measures recommended.

The current book has built on the work described in these previous publications and has consciously adopted a sectorial approach with the purpose of to providing sufficient within-sector information for actors in other sectors to appreciate how their planned or proposed adaptation actions can have wider benefits. In other words 'starting again' in the iterative process between various stakeholders and their differing approaches that is necessary to reconcile these, and to ensure the development of cost-effective "low regrets"[1] adaptation strategies to counter climate change vulnerabilities. The book begins by addressing the key issues of vulnerability relating to global and projected climate change in the Caribbean (Chapters 1 and 2). Important vulnerabilities are described in agriculture (chapter 3) and in the wetland and mangrove ecosystems described in chapters 4 and 5. Chapters 6 & 7 provide recent relevant scientific research data on health and social attitudes to flooding vulnerability. Hard and soft engineering solutions to flooding management are dealt with in chapters 7 & 8, while in chapter 9 the adaptation solutions to Jamaica's serious flooding problem are described. The chapter on the law relating to flooding in Trinidad and Tobago is instructive in that it highlights the need for a cross-sectorial solution to man's exacerbations of flooding vulnerabilities. The final chapter provides an explanation of the scenarios used in the most recent IPCC report (IPCC, 2013), and how international science and modeling will allow future assessment of the cost effectiveness of adaptation and mitigation efforts.

This book is intended for both undergraduate and post graduate students pursuing climate change courses and programs at the University of the West Indies, Cave Hill, Mona and St. Augustine campuses, as well as for government technocrats and other relevant stakeholders. The various chapters are written by current academics from all three campuses, together with regional experts. This book, therefore, adds to a growing body of work by Caribbean scientists/experts tackling Caribbean issues and developing adaptation measures relevant, not only to the region, but to the rest of the world. The authors recognize that flooding affects many other sectors e.g., transportation and security. Therefore, as other rigorously collected and scientifically researched data become available, and new adaptation strategies are developed, it is envisaged that this information will be included in a second edition of this book thus making it as policy- relevant especially for SIDS as we believe this edition to be.

REFERENCES

Baban, S.M.J. (2008). Enduring Geohazards in the Caribbean: Moving from the reactive to the Proactive. The University of the West Indies Press, Trinidad.

Chen, A.A., Chadee, D.D. and Rawlins, S.C. (2006). Climate Change Impacts on Dengue: The Caribbean Experience. Phoenix Press, Jamaica.

IPCC (2012). Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptations [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea,K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds)] A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 1-19.

[1] Used in IPCC(2012) Special Report: Managing the Risks of Extreme events and disasters to Advance Climate Change Adaptation

IPCC (2013). The Physical Science Basis. IPCC Working Group 1 Contribution to AR5. Working Group 1 Contribution to the 5th Assessment of the International Panel on Climate Change, Cambridge University Press, Cambridge, UK.
McGregor, D, Dodman, D and Barker, D (2009). Global Change and Caribbean Vulnerability. University of the West Indies Press, Jamaica
Nurse, L.A (2011). The implications of global climate change for fisheries management in the Caribbean. Climate and Development, 3: 228-241.
Pulwartry, R.S., Nurse, L.A. and Trotz, U.O. (2010) Caribbean Islands in a Changing Climate. Environmental Science and Policy for Sustainable Development. Nov-Dec 2010 p. 9.

Editors:

Dave D. Chadee Ph.D., D.Sc.
Professor of Environmental Health
Department of Life Science
University of the West Indies, St Augustine
Trinidad, West Indies

Joan M. Sutherland, Ph.D.
Consultant/Ecophysiologist
Department of Life Science
University of the West Indies, St Augustine
Trinidad, West Indies

John B. Agard, Ph.D.
Professor of Tropical Island Ecology
Department of Life Science
University of the West Indies, St Augustine
Trinidad, West Indies

ACKNOWLEDGMENTS

The preparation of this book was aided by the 2013 Anthony N Sabga Caribbean Awards for Excellence Prize in Science & Technology which was awarded to Prof Dave Chadee. The St Augustine Campus, University of the West Indies also provided a study and travel grant (2013) which facilitated the completion of this book. The authors also thank Dr. Fiona Williams, Reader, School of Medicine, Division of Population Health Sciences, The University of Dundee, Dundee DD1 9SY, Scotland, UK for providing the space and atmosphere required for writing and editing some of the chapters of this book and we thank Dr. Judy Raymond, Editor in Chief of the Trinidad and Tobago Guardian for permission to republish photographs. We also thank our families for their support and encouragement during the preparation of this book.

In: Flooding and Climate Change
Editors: D. D. Chadee, J. M. Sutherland and J. B. Agard
ISBN: 978-1-62948-317-7

Chapter 1

INTRODUCTION TO FLOODING AND CLIMATE CHANGE IN THE CARIBBEAN

Dave D. Chadee*[*] *and Joan M. Sutherland
Department of Life Sciences, The University of the West Indies,
St. Augustine, Trinidad, West Indies

ABSTRACT

The factors associated with climate change are reviewed and discussed in the context of flooding and its impacts on Small Island Developing States (SIDS) within the Caribbean region. The natural factors which contribute to flooding including rainfall, hurricanes, storm surges, tidal flooding and tsunamis; and the anthropogenic factors such as deforestation, quarrying, urbanization, poor maintenance of canals, rivers and water courses, and the destruction of natural coastal barriers such as mangroves, are discussed with respect to the development of appropriate adaptation strategies. The vulnerabilities to climate change of the differing island types are also identified and reviewed.

1. INTRODUCTION

There is overwhelming evidence that the world's climate is changing (IPCC 2007, 2012, 2013) and the debate no longer centers on whether the primary triggers are anthropogenic, or are due to natural or cyclical changes in the earth's atmosphere, or to a combination of these factors. Earlier evidence showed that the earth's climate was affected by natural processes, including changes in volcanic activity, solar radiation output and the earth's orbit around the sun (IPCC 2012). Volcanic eruptions are often considered cyclical and can have short term effects on the climate, while solar irradiance has contributed to climate change over the last century. However, since the Industrial Revolution, the addition and increase of 'greenhouse gas es ' (water vapour, methane, carbon dioxide, nitrous oxide, CFCs), that trap solar radiation within the earth's atmosphere, has increased the scale of change to approximately 10

[*] E-mail: Chadee@tstt.net.tt; Dave.chadee@sta.uwi.edu.

times that of the Sun 's output. In 2013, IPCC provided the evidence that atmospheric CO_2 was the main driver of climate change since 1750 and that it is *"extremely likely*[1] that human influence has been the dominant cause of the observed warming since the mid-20th century ". In addition, there is evidence that the "Global surface temperature for the end of the 21st century will *likely*[2] exceed 1.5^{o}C relative to 1850 to 1900 for all RCP (Representative Concentration Pathways) scenarios[3] except RCP2.6[4], and *more likely than not* to exceed 2^{o}C for RPC 4 (see Chapter 12).

Therefore, we live in a world which cannot continue to adopt a "business as usual approach" as there is overwhelming evidence to support the fact that the observed changes have impacted various sectors including agriculture, ecosystems and their services, health, and tourism, and there is currently a suite of adaptation measures which can be applied by countries to 'slow-down' these impacts. However, while many of these adaptation measures may be effective under local conditions, they are not generic ('one-size -fits-all') tools, because of differences in geography and socio-economic conditions. The efficacy of these adaptation measures depends on differences and changes in adaptive capacity and/or the resilience of the affected individuals, communities and countries.

The specific impacts anticipated by climate change scientists are listed below.

- *Sea level rise*
  A rise in global sea level of 19 centimetres (7.5 inches) occurred between 1901 and 2010. Based on current acceleration levels, the projected rise for the current century will be almost double that observed during the last century (IPCC 2013).
- *Global temperature rise*
  Global models have shown that the earth's surface temperature has seen warming since 1880 but with significantly faster warming occurring since the 1970s. The warmest years have occurred since 1981 and, even though a solar output decline was reported in 2007-2009, surface temperatures continue to increase (Peterson et al. 2009, Allison et al., 2009).
- *Warming oceans*
  The top 700 metres (circa 2,300 feet) of the ocean have absorbed significant amounts of heat generated/trapped as a result of global warming and has shown a warming of 0.302 degrees Fahrenheit since 1969 (Allison et al., 2009).
- *Shrinking ice sheets*
  Reports from the NASA's Gravity Recovery and Climate Experiment show "Greenland lost 150 to 250 cubic kilometers (36 to 60 cubic miles) of ice per year between 2002 and 2006, while Antarctica lost about 152 cubic kilometers (36 cubic miles) of ice between 2002 and 2005"
- *Declining Arctic sea ice*
  The extent and thickness of the Arctic sea ice have both decreased over the last 50 years (Polyak et al., 2009).
- *Glacial retreat*

[1] 95-100% probability (IPCC, 2012).
[2] 66-100% probability (IPCC,2012).
[3] See chapter 12.
[4] Level of radiative forcing (see IPCC2013), in watts per square. The RCPs 2.6,4.5,6,and 8.5 are equivalent to CO_2 concentrations of 490,650,850 and >1370 ppm respectively.

Glaciers in the Alps, Himalayas, Andes, Rockies, Alaska and Africa are retreating at a rapid rate (IPCC 2007).

- *Extreme events*
  Globally the numbers of recorded days with high temperatures and heat waves have been increasing, while the number of low temperature events has been decreasing. Flooding episodes have also increased due to an increase in the number of intense rainfall events (IPCC 2007, IPCC 2012).
- *Ocean acidification*
  The acidity of the surface ocean water has been modified by anthropogenic factors, largely beginning with the industrial revolution, when a 30% increase in acidity occurred. The on-going emission of carbon dioxide into the atmosphere by human activity is continuing to be absorbed by the oceans. It is estimated that the amount of carbon dioxide absorbed by the upper layer of the ocean increases by 2 billion tons per year (Sabine et al., 2004, IPCC 2007, IPCC 2012).

In the following chapters we review the role of flooding which is an extreme event increasingly associated with climate change, and examine the potential impacts on Small Island Developing States (SIDS) within the Caribbean region.

2. CAUSES OF FLOODING

Flooding occurs when the volume of water within water courses or rivers exceeds its ‘carrying capacity’ and occurs along low-lying areas especially along coastlines, many of which are constantly inundated and have limited capacity for extra water absorption.

Flooding in the Caribbean region occurs:

- during and after meteorological events such as storms when intense and prolonged rainfall occurs;
- during coastal storm surges or during peak high tide;
- when peak high tide or seiche (a wave that oscillates in lakes, bays, or gulfs from a few minutes to a few hours as a result of seismic or atmospheric disturbances) coincide with episodes of heavy rainfall which drain into the same coastal margin;
- when natural storm barriers such as mangroves are destroyed by man and/or natural forces; and
- when seismic waves affect the ocean floor, triggering tsunamis.

Table 1.1. Summary of the main possible causes of flooding within the Caribbean region

Natural	Artificial (Man-made)
Rainfall	Deforestation
Hurricanes	Quarrying/ Blasting
Storm surges	Urbanization
Tidal flooding	Canals and Poor water course maintenance
Tsunamis (seismic waves)	Destruction of mangroves and other natural barriers along the coastal zone

The principal causes of flooding can be divided into two categories: *natural* and *man - made.* These are summarized in Table 1.

2.1. Natural Causes of Flooding

2.1.1. Rainfall

The observed changes in rainfall patterns include not only torrential downpours during thunderstorms, but also the recently observed phenomenon of excessively heavy rainfall of short duration which nevertheless overwhelms the drainage systems e.g., waterways, drains, canals. In the Caribbean region flash flooding can occur within 1 to 2 hours of heavy rainfall in the small mountainous islands because of their size and the steepness of the gradients. Major contributing factors include the frequency and intensity of recent rainfall events and soil saturation levels.

2.1.2. Climate

Within the Caribbean region there are two seasons: the dry season which generally occurs from January to May and the wet season from June to December. As expected, climate influences the relationship between rainfall and runoff. During the dry season less than 1/3 of the annual rainfall occurs and during this period the soil becomes dry and increases its water holding potential (cracks and fissures may occur depending on the soil type). During the wet season the soil becomes saturated within weeks of the onset of the rains and much of the rainfall flows quickly over these saturated soils into water courses. These aspects of climate change and flooding are covered in Chapter 2.

2.1.3. Coastal Storms

Coastal storms often lead to flooding of low-lying coastlines. The combination of high tides and storms is likely to lead increasingly to flooding of coastal communities given the fact that sea-level s have risen by approximately 19centimetres (IPCC, 2013). The deposition of sea-water and action of powerful waves can potentially destroy coastal community infrastructure, contaminate coastal aquifers and result in saltwater intrusion of agricultural lands. On very rare occasions tsunamis occur in which large volumes of water are displaced in the ocean by the action of earthquakes or marine volcanic eruptions. The role of mangroves and wet lands in the prevention of floods and coastal erosion are outlined in Chapters 4 and 5.

2.1.4. Hurricanes

A tropical cyclone with winds of 64 knots or greater is called a hurricane in the Caribbean region. Hurricanes occur in various sizes and can range from several hundred metres to a thousand kilometres across. Hurricanes develop over warm tropical and subtropical waters and follow seasonal tracks. Early season hurricanes of June and July tend to begin in the Gulf of Mexico and western Caribbean while those of August, September and October tend to originate in a broad band stretching from Florida to the Cape Verde Islands. Most significant flooding occurs during hurricanes when considerable amounts of rainfall are added to already saturated soil. Impacts of flooding on the agricultural sector are described in

Chapter 3 and other related sectors including the Law relating to these man -made or natural disaster s are outlined in Chapters 4, 7 and 11.

2.1.5. Urban Storm Water Runoff

Urbanization has dramatically changed the drainage patterns of natural catchment areas by increasing the volume and rate of surface runoff. Very often the volume of water is within the carrying capacity of rivers prior to urbanisation but the runoff from intense rainfall cannot percolate through the soil due to built structures, and large surface area s covered with concrete and tarmac. In these circumstances the rainwater quickly exceeds the carrying capacity of drains, water courses and sewer systems creating torrents, which flood roads, basements and city centres (Figure 1). The impact of flooding on health is outlined in Chapter 6.

2.2. Artificial or Man-Made Causes of Flooding

2.2.1. Deforestation and Quarrying

Large areas of forest on mountain sides have been cleared in north Trinidad and in Jamaica largely to access areas for the quarrying of building materials, for urban housing and for road construction. The removal of the protective vegetation from the sides of mountains results in erosion of the top soil which finds its way into water courses and into the sea. The resultant mud flows move at a rapid rate and are usually more destructive than flood water alone. Mud slides destroy crops, flood streets, engulf homes and destroy infrastructure along their path due to the velocity of the moving wall of mud and water. In addition, numerous deaths have been reported due to flooding in the Caribbean region. Chapters 3, 4, 5 and 6 cover some of these issues in greater detail.

Figure 1.1. Urban flooding in Diego Martin, Trinidad during 2013 (Photo: Kristian De Silva, Republished courtesy the T &T Guardian).

2.2.2. Urbanization

The rapidly-growing global population and their need for housing have resulted in unprecedented land use changes, with the conversion of prime agricultural lands into housing areas.

This urban sprawl has forced farmers to advance into unsuitable lands, even very steep hillsides, destroying vegetation cover and drastically changing hydrological systems. In the Caribbean region such patterns are occurring at an alarming rate with the development of housing communities on the hills and mountain sides whether by legal means or by squatting, thereby increasing the risk of flooding. For example, a recent flooding episode which occurred in Diego Martin, Trinidad was blamed by disaster officials "on the denudation of hillsides by builders and 'slash and burn ' farming" (Figure 2).

As the demand for housing increases populations also move to geographic areas which are low lying and prone to flooding (see Chapter 7) but unfortunately many such householders report no insurance coverage and must rely on government hand-outs after flooding episodes.

2.2.3. Canals and Poor Maintenance

The construction of large canals, box drains and the desilting of major water courses is a major annual capital expenditure necessary to prevent flooding and for waste water management.

Unfortunately some of these structures are poorly constructed and maintained leading to their collapse during heavy rains – leading to flooding. Chapters 9 and 10 outline hard and soft engineering solutions to flood-prone areas with their wider application to the Caribbean region.

Figure 1.2. Flooding in Trinidad caused by the denudation of hillsides by builders and "slash and burn" farming. (Photo: Kristian De Silva, Republished courtesy the T &T Guardian).

2.2.4. Destruction of Wet Lands and Mangrove Habitats

An important ecosystem service provided by wet lands including mangrove ecosystems is in absorbing the water from rivers and slowing down the release of surface water into the surrounding oceans and seas.

These vegetation barriers including mangroves also protect the land from storm surges and from salt water intrusions into agricultural lands. Chapters 4, 5 and 6 outline the role of the coastal margins and wet lands in protecting small island states from e.g., sea-level rise, hurricanes and storm surges.

Figure 3 shows the destruction of the Godineau mangrove forest area in south Trinidad which is already causing flooding in areas which have had no history of flooding.

3. FLOODING PHYSICAL RISK FACTORS IN THE CARIBBEAN REGION

Table 2 shows the physical risk factors associated with climate extremes which can affect Caribbean islands. Regional climate models raise significant questions regarding the amount of rainfall, reliability of rainfall and environmental responses to triggers of climate change. However, extreme events such as flooding will have a profound impact on sectors with close links to climate, such as water, agriculture and food security, forestry, health, and tourism. In fact there is *high confidence* that changes in the climate have the potential to severely affect water management systems. The challenge therefore is to find suitable adaptation strategies for both the short and long term - especially as small island developing states will be the first to be affected (Table 2).

Figure 1.3. Photograph of the destruction of the Godineau mangrove area in south Trinidad during 2013 (http://www.newsday.co.tt/day/1,61836.html).

Table 1.2. Caribbean island type and exposure to climate extremes

Island type	**Exposure to climate risk**
Plate-Boundary Islands large land areas high elevation high biodiversity well-developed soils river flood plains orographic rainfall	Jamaica and Trinidad are affected by flooding due to rivers and high elevations. Many housing areas are found on the steep slopes of the Northern Range (Trinidad) and Blue Mountains (Jamaica). Most major settlements are on the coast and exposed to storm surge and sea-level rise. In addition, many housing settlements are found within river flood plains (Caroni).
Inter–Plate (Oceanic) Islands-Volcanic islands steep slopes different stages of erosion barrier reefs relatively small land area less well developed river systems orographic rainfall	Most of the Windward and Leeward islands are small and exposed to hurricanes, which cause the most damage in coastal areas and housing areas. Barrier reefs often regulate storm surges and tsunamis.
Raised Limestone Islands steep outer slopes concave inner basins sharp karst topography narrow coastal plains no or little surface water no or minimum soil	Barbados, Carriacou and some Bahamas Islands experience storm surges and wave damage. These islands experience fresh water shortage and drought. Potable water problems can trigger health problems associated with water storage and poor soils may impede agricultural cultivation.

Adapted from Campbell 2006.

CONCLUSION

SIDs are vulnerable to the ravages of Climate Change and urgently require implementation of appropriate adaptation measures (Chapters 2 and 12). In addition, there is an urgent need for a ‘common sense ’ approach to water course management by clearing debris during the dry season (Chapter, 2), and using education programs to elicit community awareness and participation (Chapter 7). However, to ensure water courses remain clear, agencies should enforce appropriate legislation (Chapter 11).

REFERENCES

Allison EH, Perry AL, Badjeck MC, Adger NW, Brown K., Conway D, Halls AS, Pilling GM, Reynolds JD, Andrew NL, Dulvy NK. 2009. Vulnerability of national economies to the impacts of climate change on fisheries. *Fish and Fisheries*, 10:173-196.

Campbell, J. 2006. Traditional Disaster Reduction in Pacific Island Communities. *GNS Science Report 2006/38, Sciences*, Lower Hutt, New Zealand, 46 pp.

Church, J.A & White, N.J. 2006. A 20th century acceleration global sea-level rise. *Geophysical Review Letters* 33: L01602.

IPCC, 2007. Summary for Policymakers. In Climate Change 2007: The Physical Science Basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Chang*e (IPCC AR4) S. Solomon et al. eds (Cambridge University Press).

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

IPCC, 2013. Summary for Policymakers. 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.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Peterson, T. C., X. Zhang, M. Brunet-India, and J. L. Vázquez-Aguirre, 2008. Changes in North America n extremes derived from daily weather data. *J. Geophys. Res.*, 113, D07113, doi:10.1029/2007JD009453.

Polyak, L, Bischof, J, Ortiz, J.D, Darby, D.A., Channell, J.E.T., Xuand C., Kaufmane, D.S., Løvlie, R., Schneider, D.A., Eberl, D.D., Adler, R.E., Council, E.A. 2009. Late Quaternary stratigraphy and sedimentation patterns in the western Arctic Ocean. *Global and Planetary Change* 68: 5–17.

Sabine, C.L, Feely, R.A, Gruber,N, Key, R.M, Lee, K, Bullister, J.L, Wanninkhof, R, Wong, C.S, Wallace, D.W.R, Tilbrook, B, Millero, F.J, Peng, T.H, Kozyr, A, Ono, T, Rios, A.F. 2004. The oceanic sink for anthropogenic CO2. *Science*, 305 : 367-371.

In: Flooding and Climate Change
Editors: D. D. Chadee, J. M. Sutherland and J. B. Agard
ISBN: 978-1-62948-317-7

Chapter 2

FLOODING AND CLIMATE CHANGE IMPACTS IN THE CARIBBEAN REGION

Kishan Kumarsingh*
Ministry of the Environment and Water Resources,
Port of Spain, Trinidad, West Indies

ABSTRACT

Flooding issues in selected Small Island Developing States (SIDS) are examined; in particular those in the Caribbean, where data and information are available, and where the potential for flooding could result from projected climate change. Data show an increase in heavy rainfall events, including in places where total precipitation has decreased. In the Caribbean some areas of increased precipitation are noted for the months of December, January and February, while the region-wide decrease is enhanced in June, July and August, particularly around the Greater Antilles, where the model consensus is also strong. Future projections of precipitation changes for the Caribbean region shows a general annual mean decrease in precipitation across the entire region. Results from the HadCM3 model (Global Climate Models), downscaled for two scenarios, show a near-linear decrease in summer precipitation to the 2080s for a station in Jamaica. Downscaled results for Barbados and Trinidad, however, show increases rather than decreases.

While these results are indicative for a particular downscaled model and data set, it is important to note that there is no consensus across all models for changes in precipitation. Notwithstanding any uncertainty in changes in future precipitation, the unique and specific circumstances of small island states make them particularly vulnerable to these projected changes. In particular, the majority of socio-economic activity takes place on or near the coast in small island states. Management of risks, therefore, is of paramount importance in mitigating the impacts of future climate change in respect of increased flooding risks. The main management tools available for the future include: developing strategies for disaster risk management, sustainable land management, ecosystem management and ecological restoration and insurance to counter the expected increased risk of flooding impacts on SIDS may face in the future.

* E-mail: anamika_tt@yahoo.com.

1. INTRODUCTION

Flooding is usually caused by natural weather events, and may be exacerbated by anthropogenic influences. For example, heavy rainfall and thunderstorms, or intense precipitation over a short period; prolonged, extensive rainfall, all in combination with high tide conditions can be described as the natural causes of flooding in any given geographic area. However, other factors, in particular those that are man -made and generally within man's control, can also contribute to flooding severity e.g., poor maintenance of sewer and drainage networks and inadequate or poorly maintained watercourses. Land use and development issues are also factors that influence flooding, both in respect of severity and damage incurred as a result. For example, inappropriate development in flood plains; building on land in a way that prevents rainfall from draining away naturally, including paved areas such as highways, roads, car parks and recreational areas that are not only impermeable to water, but increase the risk of flooding from rainwater runoff ; and badly designed flood defence infrastructure. In this regard, land use change from natural vegetation such as deforestation in watershed catchments to built development causes greatest run-off of surface water and siltation of natural waterways. Natural geographic features such as elevation and distance from the coast (e.g., low lying coasts and small islands) may also determine ease and extent of flooding. Notwithstanding the synergistic effect s of natural and anthropogenic factors on flooding, in this chapter we focus on how climate variability and projected climate change can affect flooding and issues incidental thereto. Specifically, an examination of the following is undertaken:

- observed climate trends in respect of precipitation and sea level rise insofar as they affect inundation and flooding ;
- projected changes in precipitation with projected climate change under various scenarios with particular reference to the Caribbean region;
- potential impacts arising from these projections in the context of flooding ; and
- management of potential risks.

Flooding issues in selected Small Island Developing States (SIDS) are then examined; in particular those in the Caribbean, where data and information are available, and the potential flooding that may result from projected climate change.

2. OBSERVED CLIMATE TRENDS AND FUTURE PROJECTIONS - PRECIPITATION AND SEA LEVEL RISE

2.1. The Intergovernmental Panel on Climate Change Fourth Assessment Report

The Intergovernmental Panel on Climate Change (IPCC) (2007) in their Fourth Assessment Report stated that observations since 1970 indicate that precipitation has generally increased over land north of 30°N over the period 1900 to 2005 but downward trends tend to be dominant over this 105 years. From 1900 to the 1950s, precipitation increased significantly in the area 10°N to 30°N, but decreased after circa 1970. In the deep tropics from 10°N to 10°S, there has been an observed decrease in precipitation especially after 1976/1977. However, it is noteworthy that observations of significant precipitation changes, where they do occur, are consistent with measured changes in streamflow.

The IPCC (2007) report further stated that

> "... changes are occurring in the amount, intensity, frequency and type of precipitation. These aspects of precipitation generally exhibit large natural variability, and El Niño and changes in atmospheric circulation patterns such as the North Atlantic Oscillation have a substantial influence. Pronounced long-term trends from 1900 to 2005 have been observed in precipitation amount in some places: significantly wetter in eastern North and South America, northern Europe and northern and central Asia, but drier in the Sahel, southern Africa, the Mediterranean and southern Asia. In northern regions more precipitation now falls as rain rather than snow. Widespread increases in heavy precipitation events have been observed, even in places where total amounts have decreased. These changes are associated with increased water vapour in the atmosphere arising from the warming of the world's oceans, especially at lower latitudes. There are also increases in some regions in the occurrences of both droughts and floods ", and that.... "substantial increases are found in heavy precipitation events. It is likely that there have been increases in the number of heavy precipitation events (e.g., 95th percentile) within many land regions, even in those where there has been a reduction in total precipitation amount, consistent with a warming climate and observed significant increasing amounts of water vapour in the atmosphere. Increases have also been reported for rarer precipitation events (1 in 50 year return period), but only a few regions have sufficient data to assess such trends reliably".

Observed trends in sea level rise as reported by Bindoff et al. (2007) are) summarized in Figure 1. They have assessed the rate of sea level rise for 1961 to 2003 as 1.8 ± 0.5 mm yr^{-1} and for the 20th century as 1.7 ± 0.5 mm yr^{-1}. Sea level is determined by the thermal expansion due to sea surface warming as well as from contributions due to the melting of ice sheets.

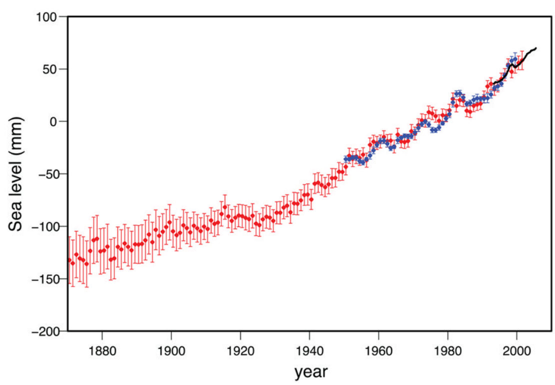


Figure 2.1. Annual averages of the global mean sea level (mm). The red curve shows reconstructed sea level fields since 1870; the blue curve shows coastal tide gauge measurements since 1950, and the black curve is based on satellite altimetry as presented in the IPCC Fourth Assessment Report (2007).

Projected changes in precipitation and sea level rise are based on various future scenarios. Without going into too much detail on the development and meaning of the scenarios, it is sufficient to say that the scenarios are based on possible future biophysical and socio-economic conditions, (including concentrations of greenhouse gas es in the atmosphere, technology development, and changes in socio-economic behavior) on which models of changes in the future climate are based and for different future time periods. These models are generally referred to as General Circulation Models or Global Climate Models (GCMs), which are sometimes statistically downscaled to bring it to a finer resolution, particularly for smaller land masses such as SIDS.

Globally, the IPCC (2007 see Parry et al., 2007) has estimated that based on models ; mean global temperature is expected to increase, as are mean water vapour, evaporation and precipitation. There is also a projected increase in precipitation in those regions that have tropical precipitation maxima (e.g., monsoons) and over the tropical Pacific in particular. However, it is projected that there would be general decreases in the subtropics, and increases at high latitudes as a consequence of a general intensification of the global hydrological cycle. Future projections of precipitation changes for the Caribbean region are summarised in Figure 2, which shows a general annual mean decrease in precipitation across the entire region.

Some areas of increased precipitation are noted for the months of December, January and February, while the region-wide decrease is enhanced in June, July and August, particularly around the Greater Antilles, where the model consensus is also strong. Results from the HadCM3 model (a GCM), downscaled for two scenarios, show a near-linear decrease in summer precipitation to the 2080s for a station in Jamaica. Downscaled results for Barbados and Trinidad, however, show increases rather than decreases. While these results are indicative for a particular downscaled model and data set, it is important to note that there is no consensus across all models for changes in precipitation.

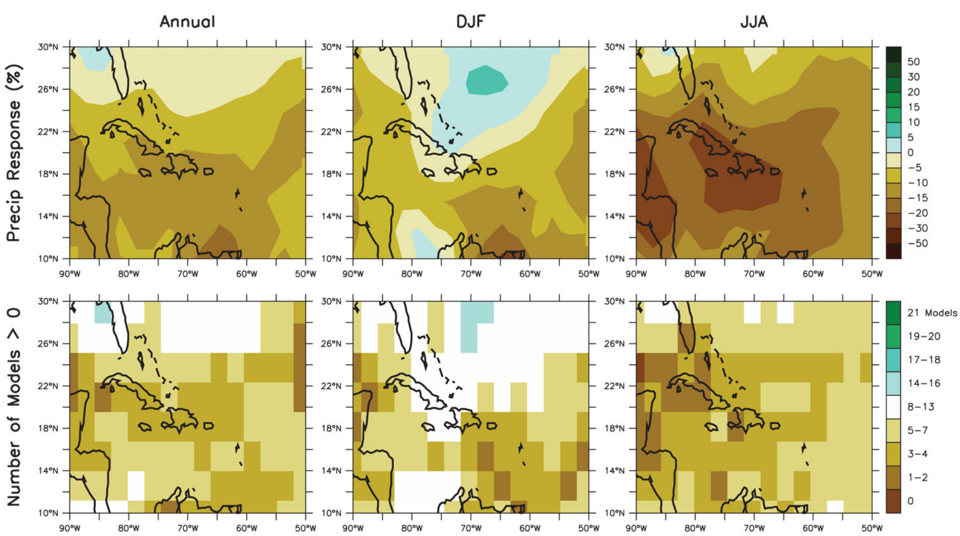


Figure 2.2. Precipitation changes over the Caribbean Top row: Annual mean, December, January, February and June, July, August fractional precipitation change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Bottom row: number of models out of 21 that project increases in precipitation (From IPCC 2012).

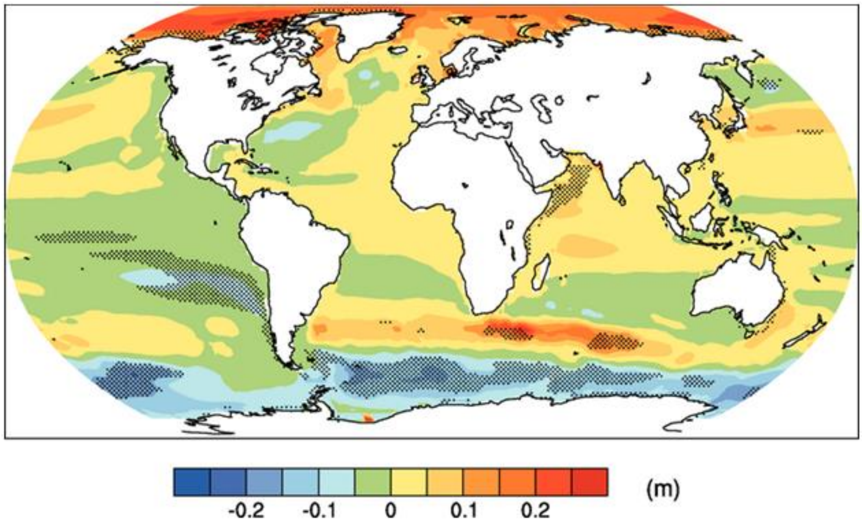


Figure 2.3. Local sea level change (m) due to ocean density and circulation change relative to the global average (i.e., positive values indicate greater local sea level change than global) during the 21st century, calculated as the difference between averages for 2080 to 2099 and 1980 to 1999, as an ensemble mean over 16 GCMs forced with one future scenario. Stippling denotes regions where the magnitude of the multi-model ensemble mean divided by the multi-model standard deviation exceeds 1.0. (From IPCC 2012).

In respect of sea level rise, the IPCC estimates an increase in sea level within the range 0.18 to 0.59 m to the year 2100. However, these changes will not be uniform across the globe as a result of changes in ocean circulation and density as shown in Figure 3. It is to be noted here as well that this Figure is a synoptic indication based on a single future scenario and therefore does not provide absolute values.

2.2. Recent Scientific Reports

Since the publication of the IPCC Fourth Assessment report in 2007, there has been a number of scientific publications providing up-to-date data on precipitation and sea level rise. For example Levitus et al., (2012) have shown a strong positive linear trend in world ocean heat content since 1955, with one third of the observed warming occurring in the 700-2000 m layer of the ocean (Figure 4), thereby indicating higher than previously estimated sea level rise potential.

Observed sea level s from satellite altimetry (Meyssignac and Cazenave 2012) indicate that the global mean sea level rose at rates of 1.77 mm/yr and 3.2 mm/yr during the 20th century and the last two decades respectively, as a result of both an increase of ocean thermal expansion and land ice loss (Figure 5). Additionally, there is evidence that islands have suffered significant sea level rise since 1950 (Becker et al., 2012). Projections of sea level rise have also been estimated to be higher than those estimated in the IPCC Fourth Assessment Report (2007). Other studies (Verimeer and Rahmstorf 2009; Nicholls and Cazenave 2010) have estimated a global sea level rise ranging from 75 to 190 cm for the period 1990–2100.

In a new study (Durack et al., 2012) analyzing ocean salinity found consistency with earlier model-based suggestions that dry regions will become drier and wet regions will become wetter in response to warming (Giorgi et al., 2011) and that the water cycle has intensified twice as much as that simulated by climate models over the same period. Furthermore, it has been suggested that the more extreme rainfall amounts closely follow the rainfall intensity (Benestad et al., 2012), implying that we can expect more extremes in both floods and droughts.

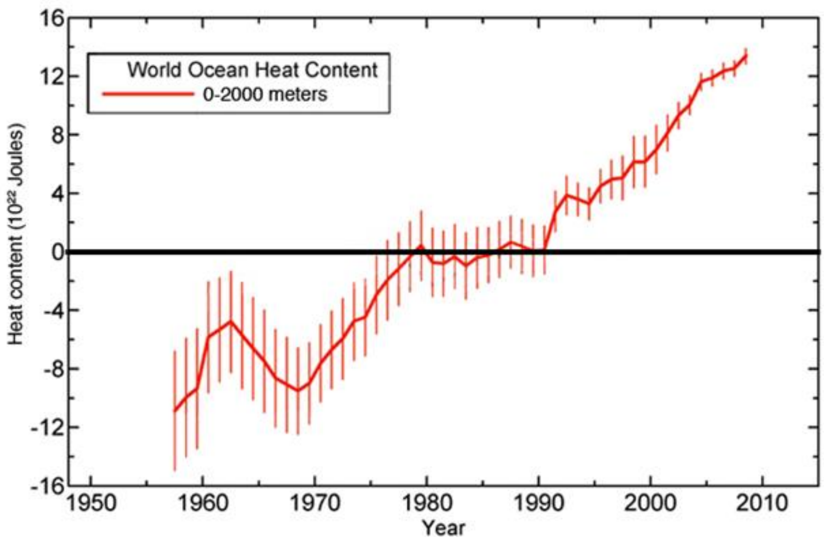


Figure 2.4. World ocean heat content and thermosteric sea level change (0-2000m) from 1955 to 2010. Adapted from Levitus et al. (2012), Geophysical Research Letters at the time of writing. (C*ourtesy Bill Hare and Climate Analytics - Survive Project*).

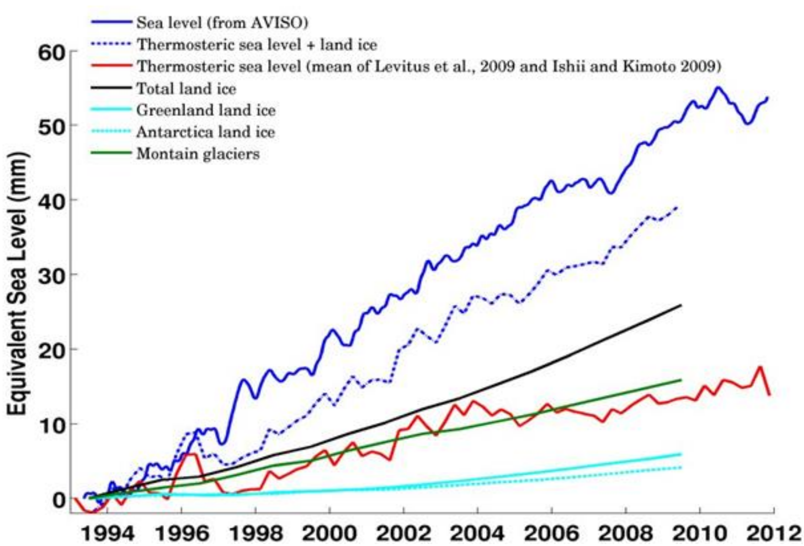


Figure 2.5. Observed sea level from satellite altimetry over 1993-2010 (blue solid curve); thermal expansion (red curve); contribution from Greenland and Antarctica (cyan curves) and glaciers (green curve). The black curve represents the total land ice contribution while the blue dotted curve represents the total climatic contribution (sum of thermal expansion and land ice). Adopted from Meyssignac and Cazenave (2012), Levitus et al. (2009), Ishii and Kimoto (2009) (C*ourtesy Bill Hare and Climate Analytics - Survive Project*).

The IPCC (2012) Special Report on managing the risks of extreme events and disasters to advance climate change adaptation (SREX) has indicated that the frequency of heavy precipitation or the proportion of total rainfall from heavy falls will likely increase, and future flood losses in many locations will increase in the absence of additional protection measures. In respect of tropical cyclones, the IPCC SREX has projected that the global frequency of tropical cyclones will likely either decrease or remain essentially unchanged. However, a recent study (Bender et al., 2010) using an operational hurricane-prediction model that produces realistic distribution of intense hurricane activity for present-day conditions, predicted a nearly doubling of the frequency of category 4 and 5 Atlantic storms by the end of the 21st century.

The IPCC (2012) SREX report has also indicated that it is very likely that mean sea level rise will contribute to upward trends in extreme coastal high-water levels in the future.

3. Potential Impacts from Projected Changes and Management Approaches

The IPCC (2007) has estimated that *"coasts are projected to be exposed to increasing risks, including coastal erosion, due to climate change and sea-level rise. The effect will be exacerbated by increasing human -induced pressures on coastal areas".* They further assert that "*many millions more people are projected to be flooded every year due to sea-level rise by the 2080s. Those densely-populated and low-lying areas where adaptive capacity is relatively low, and which already face other challenges such as tropical storms or local coastal subsidence, are especially at risk. The numbers affected will be largest in the mega-deltas of Asia and Africa while small islands are especially vulnerable..." and...."adaptation for coasts will be more challenging in developing countries than in developed countries, due to constraints on adaptive capacity".*

The IPCC (2012) SREX indicates that it is likely that the frequency of heavy precipitation or the proportion of total rainfall from heavy rainfalls will increase in the 21st century over many areas of the globe. The very likely contribution of mean sea level rise to increased extreme coastal high water levels, coupled with the likely increase in tropical cyclone maximum wind speed, is a specific issue for tropical small island states. Notwithstanding any uncertainty in changes in future precipitation, the unique and specific circumstances of small island states make them particularly vulnerable to these projected changes.

In particular, the majority of socio-economic activity takes place on or near the coast in small island states. Coastal flooding due to increases in storm surge as a result of increased intensities of tropical cyclones provides a significant risk to the economic and social well-being of island states.

Management of risks therefore is of paramount importance in mitigating the impacts of future climate change in respect of increased flooding risks. It is not the intention in this chapter to analyse the merits or demerits of management approaches to mitigating future climate change impacts but merely to highlight the various approaches that can be taken given the peculiar nature of the circumstances to which they can be applied. In this regard, several approaches are identified. Those identified in the IPCC SREX (Cutter et al., 2012) in the context of flooding include:

- *developing strategies for disaster risk management* in the context of climate change requires a range of approaches, informed by and customized to specific local circumstances given that disasters, including flooding occurs largely at a localised level;
- *sustainable land management* is an effective disaster risk reduction tool, and includes land use, land use planning, zoning for specific uses, conservation and preservation zones, buffer zones, as well as land acquisition for such purposes. Small island states are faced with this specific challenge given their limited land space as well as the need for development, often resulting from political and economic pressures. However, such measures can prove to be more sustainable at the local level than structural measures.
- *ecosystem management and ecological restoration* activities that focus on addressing deteriorating environmental conditions are critical approaches given the invaluable ecosystem services that they can provide. Such activities include, among others, watershed rehabilitation, agro-ecology, and forest landscape restoration, for example, sustainable agricultural practices that exclude slash-and-burn on hillsides, a practice that is prevalent in some Caribbean islands, can go a long way in mitigating floods.
- *insurance* is a risk transfer mechanism that can be used at the local level to minimize costs and encourage recovery

4. Selected Case Studies in Small Island States (Caribbean and, Where Available, Pacific and IMA Region)

The following case studies illustrate the impacts of climate -related events on selected small island developing states in the context of flooding risks. Future climate change and climate variability are projected to increase the intensity of these extreme events and so increase the potential risk of flooding impacts that island states may face in the future.

4.1. Caribbean

According to the Caribbean Disaster Emergency Management Agency (http://weready.org/flood/index.php), flooding in the Caribbean occurs most frequently during the hurricane season, which lasts from June 1st to November 30th, and is attributed to the heavy rains that accompany these extreme events. Not all Caribbean countries are affected equally as the extent of flooding is largely dependent on topography, level of development as it relates to infrastructure, and whether they have been affected by an intense hurricane or weather system.

Historically, countries such as Haiti, Dominican Republic, Barbados, Antigua and Barbuda, St. Vincent and the Grenadines, the British Virgin Islands, Bermuda and Belize, Jamaica and St. Lucia have been most affected by flooding.

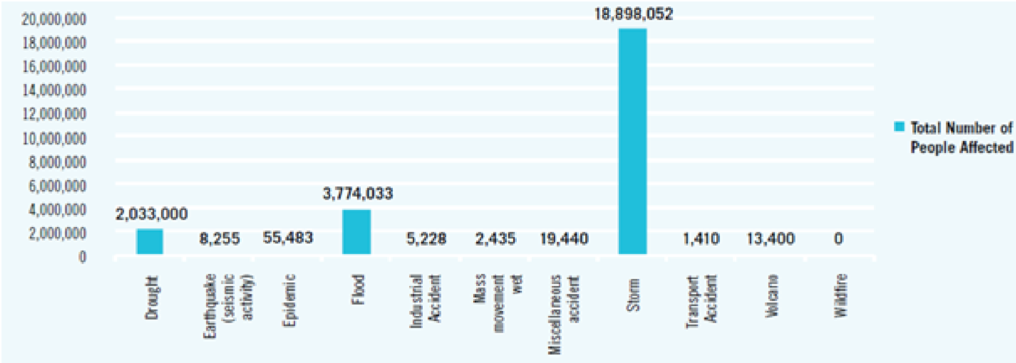


Figure 2.6. Total number of people affected by different types of disasters in the Caribbean (1980-2009) (From UNDP 2011).

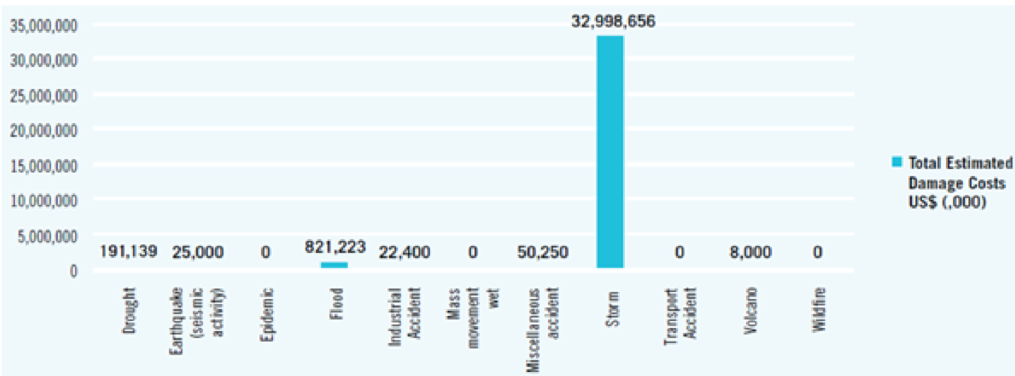


Figure 2.7. Total estimated damage costs in US dollars for different types of disasters in the Caribbean (1980-2009) (From UNDP 2011).

Figure 6 illustrates that climate -related events affected the majority of persons in the Caribbean during the period 1980 -2009 (UNDP 2011). This is also reflected in Figure 7 which shows the associated damage costs (UNDP 2011).

5. Case Studies

5.1. The May 2004 Caribbean Floods

The May 2004 flooding occurred in the Caribbean from May 18 to May 25 2004 and affected the Caribbean islands, mainly Haiti, the Dominican Republic, and some parts of northern Puerto Rico (Flood Archive 2004), and caused severe damage in the Dominican Republic and Haiti, with over 1,300 homes being destroyed and about 2,000 people being killed, caused mainly by landslides and drowning (NOAA 2004). Significant rainfall accompanied the storm, with over 9.7 inches of rain falling in Haiti, and 10 inches falling in the Dominican Republic (NOAA 2004). Meteorologically, the heavy rainfall started with the development of a broad low pressure system over Central America that was accompanied by heavy rainfall on May 19 (NHC 2012), which drifted into the Caribbean Sea (http://australiasevereweather.com/cyclone/2004/summ0405.htm.). By May 23 the system was located in the Central Caribbean producing heavy rainfall over Jamaica, eastern Cuba, Haiti and the Dominican Republic. This flooding event occurred outside of the traditional hurricane season and reflects the susceptibility of the region to flooding events as a result of climate events.

5.2. The January 2012 Fiji Floods

The Pacific island of Fiji suffered severe and unprecedented flooding and losses in January 2012. The floods killed 11 people, with more than 319,000 people being affected in low-lying areas. Fiji officials estimated that 55 per cent of export crops, mostly sugar cane, were destroyed, with the estimated damage costs at around $F30.6 million ($US17 million) (UNDP 2011, http://www.wsws.org/articles/2012). Significantly, it is also suggested that flood damage was exacerbated by changes in land use which have seen increases in the intensity of water run-off (Chaudhary 2012). Meteorologically, on January 19, 2012 the Fiji Meteorological Service reported the development of a tropical disturbance along an active trough of low pressure to the north of Fiji which then developed into a tropical depression and moved across Vanua Levu during January 21. (Fiji Island Climate Summary 2012). The depression remained stationary over central parts of the country causing widespread heavy rainfall.

References

Becker, M., B. Meyssignac, C. Letetrel, W. Llovel, A. Cazenave and T. Delcropix. 2012. Sea level variations at tropical Pacific islands since 1950. *Global and Planetary Change*. V. 80-81. pp85-98.

Bender, M.A., T.R. Knutson, R.E. Tuleya, J.J. Sirutis, G.A. Vecchi, S.T. Garner and I.M. Held. 2010. “Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes.” *Science;* 454-458.

Benestad, R.E., D. Nychka, and L.O. Mearns 2012. “Spatially and temporally consistent prediction of heavy precipitation from mean values”, *Nature Climate Change* 2: 544-547.

Bindoff, N.L., J. Willebrand, V. Artale, A, Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley and A. Unnikrishnan, 2007: Observations: Oceanic Climate Change and Sea Level. In: Climate Change 2007. The Physical Science Basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Chaudhary, F. 2012. *“Fiji flood damage exacerbated by land use changes*.” http://pidp.eastwestcenter.org/pireport/2012/February/02-03-13.htm (Accessed June 13 2012).

Cutter, S., B. Osman-Elasha, J. Campbell, S.-M. Cheong, S. McCormick, R. Pulwarty, S. Supratid, and G. Ziervogel, 2012. Managing the risks from climate extremes at the local level. In: Managing the Risks of Extreme Events and Disasters to Advance Climate

Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 291-338.

Durack, P.J., S.E. Wijffels, and R.J. Matear, 2012. "Ocean Salinities Reveal Strong Global Water Cycle Intensification During 1950 to 2000", *Science* 336: 455-458.

FICS 2012. *Fiji Islands Climate Summary January* 2012 Volume 33 Issue 1.

Flood Archive 2004.. http://www.dartmouth.edu/~floods /Archives/2004sum.htm (Accessed June 13 2012).

Giorgi, F., E. Im, E. Coppola, N.S. Diffenbaugh, X.J. Gao, L. Mariotti, and Y. Shi, 2011. "Higher Hydroclimatic Intensity with Global Warming", *Journal of Climate*, 24: 5309-5324.

http://australiasevereweather.com/cyclones /2004/summ0405.htm. Monthly Global Tropical Cyclone Summary May 2004.

http://weready.org/flood/index.php?option=com_content&view=article&id=16&Itemid=17 (accessed June 13 2012).

http://www.wsws.org/articles/2012/apr2012/fiji-a11.shtml (Accessed June 13 2012).

IPCC 2007. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2007. Summary for Policymakers. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 7-22.

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. *Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

Ishii M, Kimoto M. 2009. Reevaluation of historical ocean heat content variations with varying XBT and MBT depth bias corrections. *J. Oceanogr.* 65:287–99.

Levitus, S., J. I.Antonov, T. P. Boyer, R. A. Locarnini, H. E. Garcia, and A. V. Mishonov 2009. Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems, *Geophys. Res. Lett.*, 36.

Levitus, S., J.I Antonov, T.P Boyer, O.K Baranova, H.E. Garcia, R.A. Locarnini, A.V. Misonov, J. Reagan, D. Seidov, E.S. Yarosh, and M.M Zweng. 2012. World ocean heat content and thermosteric sea level change (0-2000), 1955-2010, *Geophys. Res. Lett.*, 39: 10 doi:10.1029/2012GL051106.

Meyssig nac, B. and A. Cazenave 2012. Sea level: A review of present-day and recent-past changes and variability. *Journal of Geodynamics* 58: 96-109.

Nicholls, R.J. and A. Cazenave (2010). Sea level rise and its impact on coastal zone. *Science.* 328: 1517-1520.

NOAA 2004. *Special Tropical Disturbance Statement (Report)*. National Hurricane Center. http://www.nhc.noaa.gov/archive/text/DSAAT/2004/DSAAT.200405191247 (Accessed June 13 2012).

NOAA 2012. *Global Hazards and Significant Events: May 2004*". National Oceanic and Atmospheric Administration. http://www.ncdc.noaa.gov/sotc/hazards /2004 (Accessed June 13 2012).

UNDP 2011. Caribbean Implementation of the Hyogo Framework for Action. *Mid-Term Review.* 2011. UNDP Caribbean Risk Management Initiative.

Vermeer M. and S. Rahmstorf, 2009, "*Global sea level linked to global temperature"*, doi10.1073pnas.0907765106.