an overview of modelling

CLIMATE CHANGE

FULL REPORT

Impacts in the Caribbean Region with contribution from the Pacific Islands

CARICOM

CARIBBEAN COMMUNITY CLIMATE CHANGE CENTRE

DFID Department for International Development

caribsave

UNDP

FULL REPORT

This publication is to be cited as follows:

Simpson, M.C.,[1] Scott, D.,[2] New, M.,[1] Sim, R.,[2] Smith, D.,[1] Harrison, M.,[3] Eakin, C.M.,[4] Warrick, R.,[11] Strong, A.E.,[4] Kouwenhoven, P.,[5] Harrison, S.,[3] Wilson, M.,[3,6] Nelson, G.C.,[7] Donner, S.,[8] Kay, R.,[9] Geldhill, D.K.,[4] Liu, G.,[4] Morgan, J.A.,[4] Kleypas, J.A.,[10] Mumby, P.J.,[11] Christensen, T.R.L.,[4] Baskett, M.L.,[12] Skirving, W.J.,[4] Elrick, C.,[12] Taylor, M.,[13] Bell, J.,[13] Rutty, M.,[2] Burnett, J.B.,[14] Overmas, M.,[15] Robertson, R.[7] and Stager, H.,[2] (2009) An Overview of Modeling Climate Change Impacts in the Caribbean Region with contribution from the Pacific Islands, United Nations Development Programme (UNDP), Barbados, West Indies

UNDP is the UN's global development network, advocating for change and connecting countries to knowledge, experience and resources to help people build a better life.

1 University of Oxford, United Kingdom
2 University of Waterloo, Canada
3 Climate Change Risk Management (CCRM)
4 National Oceanic and Atmospheric Administration (NOAA)
5 CLIMsystems
6 University of the West Indies, Trinidad
7 International Food Policy Research Institute (IFPRI)
8 University of British Colombia, Canada
9 Coastal Zone Management
10 National Center for Atmospheric Research Institute for the Study of Society and Environment
11 University of Queensland, Australia
12 University of California, Davis, USA
13 Secretariat of the Pacific Community
14 Pacific Science Association
15 Pacific Islands Applied Geoscience Commission

Contents

List of Tables

List of Figures

Acronyms

ABM - Australian Bureau of Meteorology
ACIA – Arctic Climate Impact Assessment
AR4 - IPCC Fourth Assessment Report
AQUASTAT – Information System on Water and Agriculture
AuSAID – Australian Agency for International Development
CARICOM – Caribbean Community
CCA – Crutose Coral Algae
CCRM – Climate Change Risk Management
CCSM – Community Climate System Model
CDEMA – Caribbean Disaster Management Agency
CDIAC – Carbon Dioxide Information Analysis Center
CePaCT – Centre for Pacific Crops and Trees
CIP - Centro International de Papa
CNMI – Northern Mariana Islands
CRW – Coral Reef Watch
CSIRO – Commonwealth Scientific and Research Organisation
DEM –Digital Elevation Model
DHM – Degree Heating Months
DHW - Degree Heating Weeks
DIFD – Department for International Development
DJF – December- January – February
D-O - Dansgaard-Oescher
DTM - Digital Terrain Model
EAIS - East Antarctic Ice Sheet
EEZS – Exclusive Economic Zones
ENSO – El Niño Southern Oscillation
FADs - Fish Aggregated Devices
FAO – Food and Agriculture Organisation
GCM – Global Climate Models
GDP – Gross Domestic Product
GHG – Greenhouse Gas Emissions
GHHS - Global Self-consistent, Hierarchical, High-resolution Shoreline Database
GIS – Greenland Ice Sheet
GPS – Global Positioning System
IFPRI – International Food Policy Research Institute
InSAR – Synthetic Aperture Radar
IPCC - Intergovernmental Panel on Climate Change
ITCZ – Tropical Convergence Zone
JJA - June – July - August
MAGICC - Model for the Assessment of Greenhouse-gas Induced Climate Change
MMM – Maximum Monthly Mean
NAO – North Atlantic Oscillation
NAPA – National Adaptation Programmes of Action
NCAR – National Center for Atmospheric Research
NCDC – National Climatic Data Center
NEPA – National Environment and Planning Agency
NIWA - National Institute of Water and Atmospheric Research
NOAA – National Oceanic and Atmospheric Administration
NODC - National Oceanographic Data Center
OECS – Organisation of Eastern Caribbean States

PDF - Product Density Function
PDO – Pacific Decadal Oscillation
PICs - Pacific Island Countries
PICTS – Pacific Island Countries and Territories
PNG – Papua New Guinea
ppm - parts per million
SAT - Surface Air Temperature
SIDS – Small Island Developing States
SLR – Sea Level Rise
SPCZ – South Pacific Convergence Zone
SPREP - Secretariat of the Pacific Regional Environmental Programme
SRES – Special Report on Emissions Scenarios
SST – Sea Surface Temperature
TaraGen – Taro Genetic Resources Conservation and Utilization
UNDP – United Nations Development Programme
UNESCO – United Nations Educational, Scientific and Cultural Organisation
UNFCCC - United Nations Framework Convention on Climate Change
USACE – United States Army Corps of Engineers
WAIS - West Antarctic Ice Sheet
WRI – World Resource Institute
WTTC – World Travel and Tourism Council

Authors List

Dr Murray Simpson[1]
Dr Daniel Scott[2]
Dr Mark New[1]
Ryan Sim[2]
Prof. David Smith[1]
Dr Mike Harrison[3]
Dr C. Mark Eakin[4]
Dr Richard Warrick[11]
Dr Alan E. Strong[5]
Dr Peter Kouwenhoven[5]
Dr Stephan Harrison[3]
Dr Matt Wilson[3,6]
Dr Gerald C. Nelson[7]
Dr Simon Donner[8]
Dr Robert Kay[9]
Dr Dwight K. Geldhill[4]
Dr Gang Liu[4]
Jessica A. Morgan[4]
Dr Joanie A. Kleypas[10]
Dr Peter J. Mumby[11]
Tyler R.L. Christensen[4]
Dr Marissa L. Baskett[12]
Dr William J. Skirving[4]
Carmen Elrick[12]
Dr Mary Taylor[13]
Dr Johann Bell[13]
Michelle Rutty[2]
John Burke Burnett[14]
Dr Marc Overmas[15]
Richard Robertson[7]
Heather Stager[2]

1 University of Oxford, United Kingdom
2 University of Waterloo, Canada
3 Climate Change Risk Management (CCRM)
4 National Oceanic and Atmospheric Administration (NOAA)
5 CLIMsystems
6 University of the West Indies, Trinidad
7 International Food Policy Research Institute (IFPRI)
8 University of British Colombia, Canada
9 Coastal Zone Management Pty Ltd
10 Coastal Zone Management Pty Ltd National Center for Atmospheric Research Institute for the Study of Society and Environment
11 University of Queensland, Australia
12 University of California, Davis, USA
13 Secretariat of the Pacific Community
14 Pacific Science Association
15 Pacific Islands Applied Geoscience Commission

Introduction

The nations of CARICOM[16] in the Caribbean together with Pacific island countries contribute less than 1% to global greenhouse gas (GHG) emissions (approx. 0.33%[17] and 0.03%[18] respectively), yet these countries are expected to be among the earliest and most impacted by climate change in the coming decades and are least able to adapt to climate change impacts. These nations' relative isolation, small land masses, their concentrations of population and infrastructure in coastal areas, limited economic base and dependency on natural resources, combined with limited financial, technical and institutional capacity all exacerbates their vulnerability to extreme events and climate change impacts. Stabilising global GHG emissions and obtaining greater support for adaptation strategies are fundamental priorities for the Caribbean Basin and Pacific island countries. CARICOM leaders recently unveiled their collective position that global warming should be held to no more than 1.5°C[19] and continue to develop a Climate Change Strategic Plan. The Pacific island countries have expressed their priorities for addressing climate change regionally through the Pacific Leaders' Call to Action on Climate Change[20] and the Pacific Islands Framework for Action on Climate Change 2006-2015.[21]

The people of the Caribbean and the Pacific have a long history of resilience to volatile climate conditions. However, the ability of Caribbean and Pacific island countries to adapt to the likely impacts of climate change is diminished by their exposure to these impacts, and their limited adaptive capacity. The high sensitivity of low-lying atolls to increases in sea level rise (SLR) in particular will threaten water, food security, coastal settlements, health and infrastructure.

This report was commissioned by the United Nations Development Programme (UNDP) Sub-Regional Office for Barbados and the Organization of Eastern Caribbean States (OECS) and by the UK Department for International Development (DFID), with support from Australia's International Climate Change Adaptation Initiative. The report was produced by The

16 Members of CARICOM: Antigua and Barbuda, The Bahamas, Barbados, Belize, Dominica, Grenada, Guyana, Haiti, Jamaica, Montserrat, Saint Lucia, St. Kitts and Nevis, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago

17 The Caribbean Islands contribute about 6% of the total emissions from the Latin America and Caribbean Region grouping and the Latin America and Caribbean Region is estimated to generate 5.5% of global CO2 emissions in 2001 (UNEP 2003)

18 According to the IPCC TAR. Cited in: Pacific Islands face up to global warming. http://www.acp-eucourier.info/Pacific-Islands-face-up-t.244.0.html and see Pacific Islands Applied Geoscience Commission (SOPAC), 2007. Funding for renewable energy and energy efficiency projects under the Kyoto Protocol's Clean Development Mechanism, SOPAC Miscellaneous Report 630.

19 The "1.5°C to Stay Alive" campaign. See: http://www.caribbeanpressreleases.com/ articles/5831/1/CARICOM-Unveils-Climate-Change-Strategy-Ahead-of-Copenhagen/Page1.html

20 http://www.pif2009.org.au/docs/call_to_action_final.pdf

21 http://www.sprep.org/att/publication/000438_PI_Framework_for_Action_on_Climate_Change_2006_2015_FINAL.pdf

CARIBSAVE Partnership and authored by members of 15 key institutions around the world dealing with climate change (see page 10). This report provides an overview for all CARICOM member states of the risks from climate change and includes a section on the common threats of climate change for Pacific island countries. The report focuses on: climate change projections for the Caribbean region under +1.5° and +2°C global warming scenarios; the implications of ice sheet melt for global sea level rise (SLR); the projections and implications of SLR for the Caribbean region; evaluation of the differential impacts of +1.5° and +2°C on coral reefs, water resources and agriculture in the Caribbean, with additional analysis for the Pacific islands.

The impacts of a changing climate on the Caribbean and the islands of the Pacific are increasingly being manifested in economic and financial losses. According to the World Bank (2009), in 2007 the Caribbean suffered US $10 billion in economic losses from weather related events, representing over 13% of gross domestic product (GDP). While there is limited information on the economic impacts of climate change in the Pacific islands, predictions of SLR and other climate related impacts present significant risks to water, food security, coastal settlements, infrastructure and economic development, particularly for those small low lying atoll countries.

The lack of long-term datasets and high-resolution elevation data in the Caribbean region and Pacific islands provides a fundamental barrier to the improved quantification of the impacts of climate change and SLR. There is an urgent need for data collection and investment that would facilitate detailed risk mapping and more accurate evaluations of the impacts of climate change, as well as thorough cost-benefit analyses of different adaptation options and their abilities to cope with different levels of climate change and SLR. This would also help to secure assistance from the international community who are interested in supporting evidence-based adaptation strategies. Despite a significant and evolving effort to understand climate change impacts on small island states and developing nations, there remains the need for further assessment of practical outcomes and approaches that enhance adaptive capacity and resilience. This report provides the first thorough assessment of the consequences of projected SLR and storm surge leading to coastal inundation (+1m to +6m) for the people and economies of the 15 CARICOM nations, gives an overview of the impacts of climate change in the Caribbean region and Pacific islands, and provides recommendations for urgent future work required to enable adaptation to climate change.

1. Climate Change Scenarios for the Caribbean Region

1.1 SCENARIO DEVELOPMENT

Human activities, including the burning of fossil fuels, deforestation, cement production, and other industrial and personal activities are releasing CO_2 and other greenhouse gases (GHG) into the atmosphere at a rate that is rapid and expected to increase. Recent observations have shown that the current rate of anthropogenic CO_2 emissions is exceeding the worst case scenarios used in modelling future climate change. Projections from 14 Global Climate Models (GCMs), used as input to the IPCC's Fourth Assessment Report, AR4, in particular the report of IPCC Working Group I (WGI) on The Physical Science Basis (IPCC, 2007), have been assessed to determine changes in the climates of the CARICOM countries when average global temperatures exceed threshold increases of 1.5°C and 2.0°C above climate. An average across projections from all 14 GCM models (referred to as the ensemble mean) has been used as a basis for interpretation. Additionally, the standard deviation about the ensemble mean has been considered to illustrate the spread across the various projections. This highly simplified analysis has important limitations, and some of the more significant caveats are discussed in Section 1.1.4 to provide necessary background to interpretation of the results.

1.1.1 GCM ENSEMBLE APPROACH

No individual GCM model provides a perfect simulation of the global climate system and no two models provide identical simulations. All models are limited in their abilities to simulate important aspects of the climate system, including that at tropical latitudes, in ways that are discussed at length in IPCC (2007). Nevertheless, all models employed in IPCC assessments have been subjected to rigorous tests and all are considered to be performing at, or close to, the state of the art.

Numerous analyses of future climate published in the science literature have been based on projections from a single GCM model, a valid approach but one that requires recognition in full of its inherent limitations. A much-improved approach uses an ensemble of projections from different GCM models. This is a standard approach in the IPCC and is used widely in weather and climate predictions on shorter time scales. To an extent the strengths of each model combine to provide a higher-quality result than is available from any individual model. An alternate way of producing an ensemble is to run a single model (or several models) repeatedly, varying certain details of each run. However, this approach for climate change projections has exceeded most computational capabilities until recently and most of the 2007 IPCC report is based on single runs of different models for each GHG emission scenario (see below). This latter approach is also used in this Report.

In theory, given a number of model projections (39 in total in this Report, from the 14 GCM models), it should be possible to produce a distribution of projections for, say, temperature increases in Jamaica, each tagged with its own probability of occurring – a probability density function (PDF). Unfortunately current modelling capabilities have not yet reached a level of being able to provide such PDFs with acceptable levels of reliability, and in general (with exceptions) the IPCC to date has tended to provide information on the range of possible outcomes suggested by the ensemble of models rather than offering a PDF.

The average taken across GCM projections from all models (the ensemble mean) provides the single best-estimate deterministic projection that is available, and it is frequently used as such. That said, it is certain that most, if not all details, provided by the ensemble mean will be in error to a certain amount, and that consideration of the distribution of information carried in all models will provide a more-substantive basis for decision making. Thus the ensemble mean provides a first, coarse level of information for decision-making, but it is advisable that further information also be considered in order to complete the picture of potential climatic change.

In this Report additional information will be provided in terms of the standard deviation across the ensemble. To a first approximation, 68% of the projections will give results lying within one standard deviation of the mean, and 95% within two standard deviations. Clearly this approach does not provide information on the full ranges of values in the projections, and it is possible that one or two of the projections may produce values somewhat outside the 95% limit, a factor more likely to be significant in terms of rainfall than in terms of temperature projections.

Ensemble means, as discussed previously, provide the best-available deterministic projection, but ideally full distributions across all GCM models should be considered in decision making; the greater the spread across the ensemble (as indicated in this Report by standard deviations) the less confidence that should be placed in any values suggested by the ensemble mean.

1.1.2 GHG EMISSION SCENARIOS

Anthropogenic forcing of climate results primarily from emissions of GHG and from changes in land use. The future trends in both of these key factors is unknown, however this information is required as inputs for GCMs to provide climate change projections over the next century and beyond. To address this uncertainty the IPCC has used a scenario approach – the SRES scenarios (IPCC, 2000). In terms of emissions the IPCC has broken the 40 SRES scenarios into 4 families, within each family defining a single representative marker scenario. The GCM model runs are based on these marker scenarios only. Those families with a name including 'A' represent economically-focused futures that inevitably have greater energy requirements and higher emissions than the more environmentally-focussed development paths of the 'B' families. Those families with a name including '1' represent futures in which policies are developed more globally as opposed to those in '2' families in which more competitive regional approaches are adopted. None of the scenarios may be 'correct' but collectively are thought to represent plausible futures; none of the SRES scenarios take into consideration international actions to reduce GHG emissions such as those under the Kyoto Protocol or Copenhagen Accord.

For this report the scenarios used are A1B (economic-focused global policies – the B indicates a balance between fossil fuel intensive and alternate approaches to energy generation), A2 (economically focused regional policies) and B1 (environmentally focused global policies). The latest observations suggest that current global emissions are similar to, and in fact slightly worse than, trajectories set out in the worst-case A1B and A2 scenarios[22].

As the terms of reference in this case require analysis of differences in projections between two specified levels of

22 http://www.globalcarbonproject.org/carbonbudget/07/files/Canadell_C_Budget2007+_Copenhagen.March09.pdf http://www.globalcarbonproject.org/carbonbudget/07/index.htm

global average temperature increase (+1.5 and 2.0°C), it is reasonable to calculate ensemble averages across all three emissions scenarios; this averaging is most appropriate in the case of temperatures but, as is discussed under Regional Projections, for rainfall care must be taken in interpreting the results. Standard deviations provide some information regarding the distribution of projected values across the three emissions scenarios.

1.1.3 CLIMATE SENSITIVITY AND TIMING OF CHANGES

Climate sensitivity is simply a measure of the responsiveness of the atmosphere to changes in atmospheric GHG concentrations; it is determined by the difference in average global temperatures given the CO_2 concentration at pre-industrial levels and at double that concentration. This temperature difference cannot be measured directly but only estimated from GCM models, with those models giving relatively high change values being the more responsive (sensitive) to changes in CO_2 concentrations. The range of values for climate sensitivity as given by IPCC (2007) is 2.1°C to 4.4°C, indicating that the most responsive model produces global temperature changes more than double those of the least responsive for the same change in CO_2 concentrations. GCMs used in this report are representative of this full range.

The range of climate sensitivities given by the various GCMs introduces uncertainties in areas such as the extent of GHG emissions permissible in reaching target atmospheric concentration equilibrium levels, but the main uncertainty introduced within the context of this Report is one of timing. The standard approach in IPCC assessments is to examine projections for specific time periods, producing ensemble means and ranges averaged over, say 30 years with the central year typically 2020, 2050 or 2080. Under this approach average global temperatures will have risen by larger amounts at a given time slice in those models with higher climate sensitivities, possibly with consequent other changes simulated in the climate system. Time slice ensembles thus average across a range of simulated climates at different stages of disturbance.

In this Report the terms of reference required that differences between climate with increased average global temperatures of 1.5°C and of 2.0°C be compared in the Caribbean region at different times in the future for each GCM emissions scenario combination. Time slicing is not feasible under this requirement and instead the time that these temperature thresholds are reached within each projection has been determined independently (after smoothing of the average global temperature time series to remove inter-annual variability). In order to ensure consistency across all models, global temperature differences have been calculated against the base of model simulated global average temperatures for the years 1970 to 1990; these values were subsequently corrected by 0.7°C as the best estimate of changes between pre-industrial times and 1970 to 1990 (IPCC 2007a). Ensemble means and standard deviations were then calculated using 21-year periods centred on the year in which average global temperatures increases exceeded either 1.5°C or 2.0°C according to each particular projection. Therefore these results cannot be taken as if occurring during any particular year.

Table 1 provides a summary of the GCM models used, the GHG emissions scenarios employed in each GCM, and the year in which each model/scenario combination produced global temperature increases exceeding the two required thresholds. According to these models the earliest and latest dates the 1.5°C (2.0°C) threshold is exceeded under scenario A1B are 2023 and 2050 (2039 and 2070), under scenario A2 are 2024 and 2043 (2043 and 2061), and under scenario B1 are 2027 and 2073 (2050 and not until later than 2100; model simulations end in 2100).

Table 1: Details of the models used, scenarios under which each model was run, and years that average global temperature increase thresholds of 1.5°C and 2.0°C were passed.

Model Details	Scenarios	Year 1.5°C Threshold exceeded	Year 2.0°C Threshold exceeded
BCM2 from the Bjerknes Centre for Climate Research, Norway - http://www.bjerknes.uib.no/default.asp?lang=2	A1B	2038	2051
	A2	2036	2055
	B1	2047	2071
CGCM3.1 from the Canadian Center for Climate Modeling and Analysis - http://www.cccma.bc.ec.gc.ca/eng_index.shtml	A1B	2026	2046
	A2	2029	2045
	B1	2036	2065
CM3 from the French Centre National de Recherché Météorologique - http://www.cnrm.meteo.fr/gmme/	A1B	2029	2041
	A2	2034	2048
	B1	2036	2065
Climate Model Mark 3.0 from the Australian Commonwealth Scientific and Industrial Research Organisation - http://www.csiro.au/science/EMM.html	A1B	2050	2070
	A2	2042	2059
	B1	2073	After 2100
Climate Model Mark 3.5 from the Australian Commonwealth Scientific and Industrial Research Organisation as above	A1B	2026	2042
	A2	2027	2043
	B1	2028	2050
CM2.0 from the US Geophysical Fluids Dynamical Laboratory - http://www.gfdl.noaa.gov/research/climate/	A1B	2028	2043
	A2	2030	2045
	B1	2027	2054
CM2.1 from the US Geophysical Fluids Dynamical Laboratory as above	A1B	2030	2042
	A2	2033	2052
	B1	2034	2069
Version ER of the NOAA Goddard Institute for Space Studies climate model - http://www.giss.nasa.gov/research/modeling/gcms.html	A1B	2034	2057
	A2	2035	2054
	B1	2044	2093
CM4 of the Institut Pierre Simon Laplace - http://www.ipsl.jussieu.fr/	A1B	2023	2039
	A2	2027	2044
	B1	2028	2051
ECHAM5 from the German Max Planck Institute for Meteorology - http://www.mpimet.mpg.de/en/home.html	A1B	2034	2047
	A2	2040	2052
	B1	2043	2059
ECHO-G from the German Meteorological Institute of the Rheinische Friedrich-Wilhelms Universität Bonn, the Meteorological Institute of the Korean Meteorological Administration, and the Model and Data Group, Germany/Korea - http://www.meteo.uni-bonn.de/index.en.html and http://www.metri.re.kr/metri_home/english/Introduction/uAboutE.jsp and http://www.mad.zmaw.de/	A1B	2034	2046
	A2	2035	2051
	B1	2041	2060
GCCM2.3.2a from the Japanese Meteorological Research Institute - http://www.mri-jma.go.jp/Dep/cl/cl.html	A1B	2037	2054
	A2	2043	2059
	B1	2049	2077

Model Details	Scenarios	Year 1.5°C Threshold exceeded	Year 2.0°C Threshold exceeded
PCM1 from the US National Center for Atmospheric Research and collaborating laboratories - http://www.cgd.ucar.edu/pcm/	A1B	2037	2057
	A2	2040	2061
MIROC3.2(MEDRES) of the Centre for Climate System Research of the University of Tokyo and the Frontier Research Centre for Global Change - http://www.ccsr.u-tokyo.ac.jp/ehtml/etest.shtml and http://www.jamstec.go.jp/frcgc/eng/	A2	2024	2043

1.1.4 GUIDANCE ON THE RESULTS

Care should always be taken in interpreting any climate model projections; the ensemble means presented here are the optimal deterministic results that can be provided from the terms of reference. However it is unlikely that values from these ensemble means will be flawless and standard deviations have been used to assess the ranges of values across all projections; confidence in the results for temperature changes is higher than in those for rainfall changes.

1.2 CLIMATE CHANGE SCENARIOS FOR THE CARIBBEAN AT GLOBAL +1.5 AND +2.0ºC

Figures 1 (air temperatures), 2 (sea surface temperatures) and 3 (rainfall) illustrate annual projected changes in the Caribbean Region at global temperature changes of 1.5°C and 2.0°C above pre-industrial levels.

Average air temperatures will rise in the future in all seasons. Typical temperature increases in CARICOM countries are up to 1.5°C and 2.0°C when the same two global thresholds occur (i.e., the Caribbean region largely tracks projected global temperature changes), but less in coastal regions and over islands. The distribution of greater temperature increases over land than over oceans (Figure 1) is quite reasonable, as on the global scale the greatest temperature increases are expected over land, most specifically at latitudes rather higher than considered here, while the air over the oceans will warm less than the global average. In the continental interiors maximum temperature increases tend to follow the solar cycle on a seasonal basis. Standard deviations of temperature (not illustrated), annually and for each season, for CARICOM countries tend to be no greater than 0.2°C, exceptionally 0.3°C. Thus even removing two standard deviations (≤0.6°C) from the values in Figure 1 would leave all countries warming by at least 0.7°C by the time the 2.0°C threshold is reached. According to these projections there is little uncertainty that the trend of temperatures is upwards, the main uncertainties being in the timing and extent.

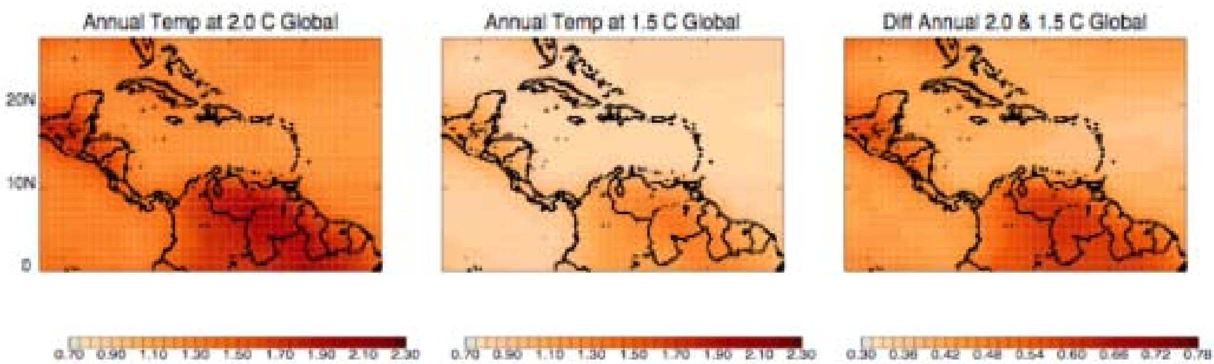


Figure 1: Changes in regional average annual temperatures compared to present day values at thresholds of 2.0°C and 1.5°C and differences between the two; all values in °C; note differences in the scales.

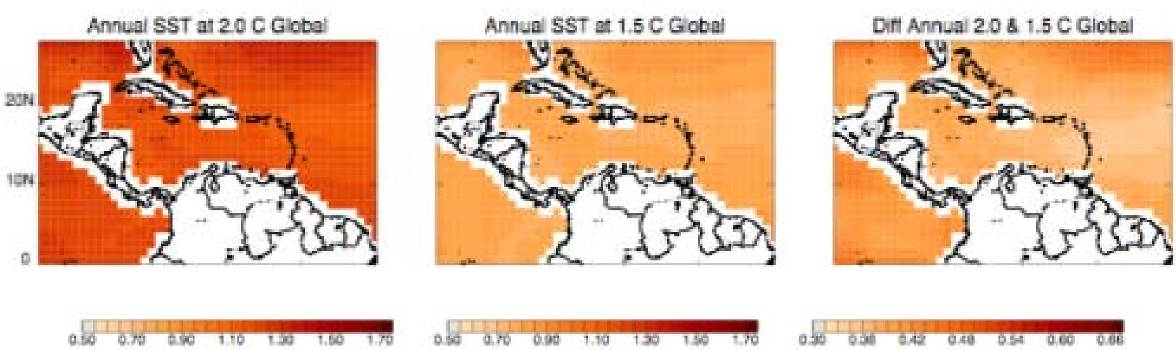


Figure 2: As Figure 1 but for changes in annual average sea surface temperatures; note differences in the scales and with the scales in Figure 1.

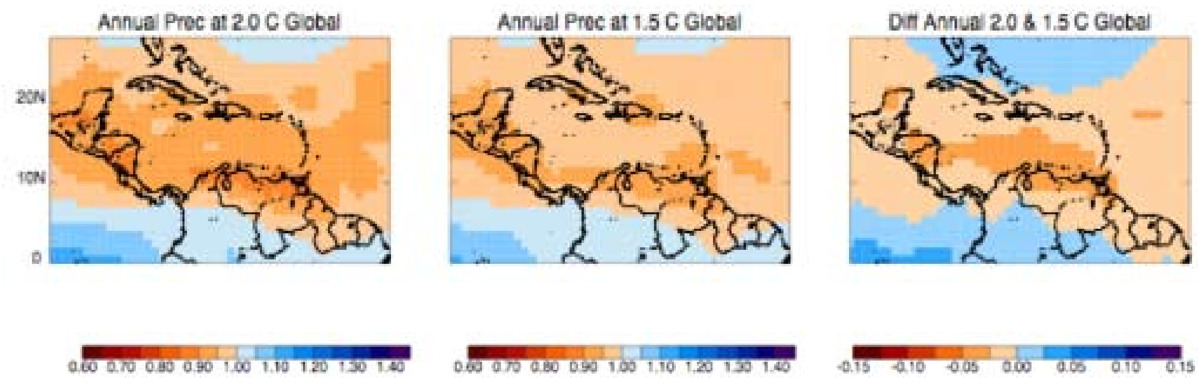


Figure 3: As Figure 1 but for fractional changes in total annual rainfall; reds indicate drying, blues increased rainfall; note differences in the scales.

Ensemble mean values for temperature increases as compared to the baseline temperatures (based on average daily temperatures) at both the 1.5°C and 2.0°C thresholds are illustrated in Figure 1 (recall that roughly 0.7°C needs to be added to convert the figures to increases compared to pre-industrial levels) for the year and for each season. Difference fields between the values at the two thresholds are also provided in Figure 1, but note that the colour scale for the difference fields varies from that of the other two fields.

Given that the models provide spatial details only on scales of a few hundred kilometres (as indicated in the grid cells/pixels apparent on the maps) the distribution of greater temperature increases over land than over oceans is as expected, and confidence may be held in that basic pattern. At both thresholds largest increases over land approximate increases in the global average temperature; this is quite reasonable as on the global scale the greatest temperature increases are expected over land, most specifically at latitudes much higher than those considered here, while the air over the oceans will warm less than the global average. Note that the highest temperature increases on the seasonal cycle tend to follow the movements of the sun. The solar cycle is also apparent in the difference fields in the right hand column of Figure 1. Inland it appears that differences may exceed the 0.5°C between the thresholds at some times of the year, while over the oceans average temperatures may rise typically by about 0.4°C, or perhaps a little more.

Standard deviations of temperature (not illustrated), annually and for each season, for CARICOM countries tend to be no greater than 0.2°C, exceptionally 0.3°C. Thus even removing two standard deviations (≤0.6°C) from the values in Figure 1 would leave all countries warming by at least 0.7°C by the time the 2.0°C threshold is reached. According to these projections there is little uncertainty that the trend of temperatures is upwards, the main uncertainties being in the timing and extent.

Changes in sea surface temperatures (SST) by and large are similar to those for minimum air temperatures (not illustrated) over coastal regions and islands. This is due to the fact that in the tropics and subtropics if air temperature should fall below the SST then heat is transferred from the ocean to the air to maintain the temperature. No equivalent rule applies to maximum air temperatures over coastal and maximum regions, or to any inland temperatures. Nevertheless, because of the preceding it might be expected to a first approximation that changes in SSTs may be similar to those of the air over the oceans, and comparison between Figure 1 and 2 reveals this to be the case[23]. Standard deviations of SSTs (not illustrated), as for air temperatures, indicate that warming is a consistent feature across most likely all projections.

Modelled changes in regional precipitation should be treated with greater caution than those in temperature. Total annual rainfall is projected to decrease through all CARICOM countries by between 5 to 10% according to the ensemble mean, with decreases amplifying with increased temperatures. The exception is in the north, particularly over the Bahamas, where the projections suggest hurricane-season rainfall will increase and rainfall will recover slightly by the 2.0°C as compared to the 1.5°C threshold, although there remains a net annual reduction of perhaps 5% given a 2.0°C threshold. However, examination of standard deviations (Figure 4) indicates that, while the majority of projections simulate rainfall decreases, some projections simulate rainfall increases of up to perhaps 30% over the year.

No definitive value for rainfall changes can be provided in this Report. The most probable outcome is that rainfall will decrease over the CARICOM countries as the warming increases, but there remains a realistic probability that increases will occur based on current information. It is not unknown for later generations of climate models to adjust

23 Note that the temperature scales differ between Figure 1 and 2. (charts for minimum temperatures, not illustrated, provide full confirmation).

precipitation projections (as indeed occurred between the third and fourth IPCC assessments) and thus rainfall projections should be kept under review as newer GCM outputs become available.

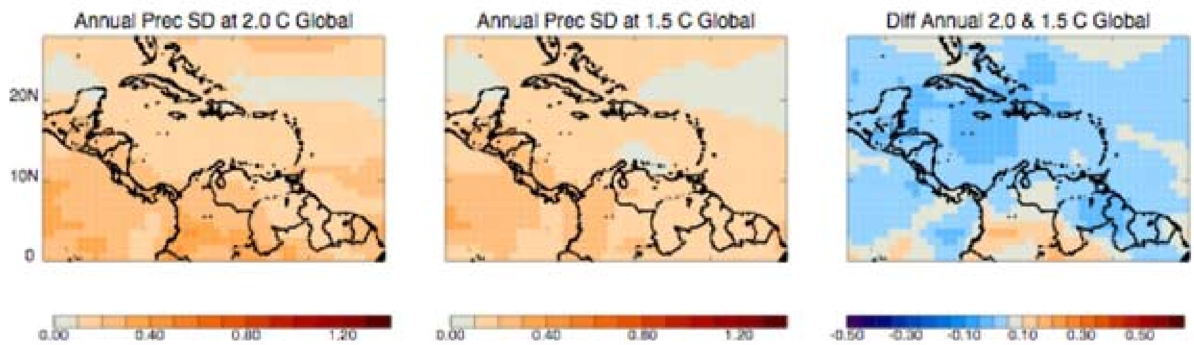


Figure 4: Standard deviations of the fractional change in precipitation on an annual basis, with layout as in Figures 1 to 3.

Table 2 summarizes the projected range of temperature and precipitation changes under each of the threshold global temperature changes. Note that at the 2.0°C threshold temperature, change represents additional change relative to the 1.5°C global warming threshold.

Table 2: Range of Climatic Change in the Caribbean at Global Threshold Temperatures

Climate change effect	Change at 1.5°C global warming	Additional change at 2.0°C global warming
Temperature	~-0.9°C to ~1.7°C	~0.3°C to ~0.6°C
Precipitation	~+15% to ~-35%	~+12.5% to ~-15%
SST	~-0.9°C to ~1.3°C	~0.3°C to ~0.5°C

In order to provide improved spatial detail and to develop more specific information regarding the uncertainties associated with the results presented here, in particular those related to rainfall, it is recommended that a more detailed analysis of the projections employed here, together with research to downscale the information from the global models, be undertaken. This future research should also examine changes in the most intense climate events, such as those that produce heavy rainfall. Such research would support climate change impact assessments and development planning tasks at national and regional levels and provide important support to the UNFCCC Nairobi Work Programme.

2. Implications of Sea Level Rise for the Caribbean Region

2.1 GLOBAL SEA LEVEL RISE (SLR) PROJECTIONS

Continued global warming for the rest of the century and into the 22nd century under some GHG emission scenarios poses a major threat to the stability of the world's ice sheets. The extent and speed of ice sheet melt caused by air and ocean warming will largely determine the magnitude and timing of global sea level rise (SLR) in the future. This report assesses the evidence for the contemporary behaviour of the high latitude ice sheets, and reviews the evidence for polar amplification, a characteristic of the climate system which will help drive changes in the polar ice sheets. The next section discusses past evolution for high latitude ice sheets, the future dynamics in global SLR as the ice sheets melt.

2.1.1 HIGH LATITUDE ICE SHEET DYNAMICS

Multiple lines of evidence have been used to assess the present behavior of the GIS and WAIS. These include ground observations, satellite data and remote sensing from airborne platforms. In the Arctic the total volume of land ice is just over 3 million km^3 (Dowdeswell and Hagen 2004), which they estimated to result in a global sea level rise of around 8m if this melted. As the ACIA (2005) argued glaciers, ice caps, and ice sheets respond to climate changes over very different timescales depending on their size, shape, and temperature condition. The smaller glaciers are likely to respond quickly, with shape, flow, and front position changing over a few years or a few decades, while the GIS and larger WAIS respond to climate changes over timescales of up to millennia. The small ice caps of Svalbard, Franz Josef

Land, Novaya Zemlya, Severnaya Zemlya, Iceland and Arctic Canada are highly sensitive to future warming and polar amplification as a result of their small size, and relatively low elevation. Similar, small ice masses exist in the Antarctic Peninsula and rather larger ones in Patagonia. Such ice masses contributed around 0.77±0.22 mm per year of sea level rise from 1993-2003, out of a total of 3.1±0.7 mm per year of sea level change over that time period (IPCC).

However, it is the stability of the major ice sheets (GIS and WAIS in particular) that potentially will have the greatest impact on global sea levels. The response of the major ice sheets on earth to continued warming is a major uncertainty, but it has the potential to create rapid and catastrophic sea level change and interrupt major oceanic and atmospheric circulations (Oppenheimer 1998). In the last few years there have been a number of attempts to assess the future stability of the ice sheets (e.g. Gregory et al. 2004; Hansen 2005; Oppenheimer and Alley 2005; Dowdeswell 2006; Overpeck et al. 2006). All suggest that melting will occur with a rise in global mean surface temperatures of between 1°C and 3°C or polar warming of less than 5°C. The IPCC AR4 (2007) indicated that such temperatures might be reached during this century.

Over the past decade our understanding of the dynamic evolution of the ice sheets under conditions of present and future anthropogenic global warming is limited by the low level of sophistication of numerical ice sheet models (Alley et al. 2005). These models are inadequate largely because the empirical data with which to develop them are limited, and our physical understanding of the processes operating at the junction between ice sheets and the ocean (the grounding line) are low (Vieli and Payne 2005). We also have limited understanding of basal conditions under large parts of the ice sheets and under the outlet glaciers and ice streams that drain them (e.g. De Angelis and Skvarca 2003). More research on subglacial theology, debris concentrations and basal temperature gradients are required as these affect basal shear stresses, basal sliding, water availability and the likelihood of rapid sediment deformation. All of these variables have the potential to affect the dynamic response of the ice sheets to warming.

2.1.1.1 POLAR AMPLIFICATION

Polar amplification is the term given to increased surface air temperatures (SAT) in the Arctic and Antarctic compared with lower latitudes, in response to a change in global climate forcing. The term was originally introduced by Manabe and Stouffer (1980) who used it to describe the amplification of surface warming identified in their climate model following increased GHG levels. Their model suggested that polar amplification occurred in both hemispheres, although over Antarctica polar amplification was seen to be generally reduced, in part because of the thickness of the ice sheet and the lower temperatures compared with the Arctic. Polar amplification was also restricted to the troposphere in their model (below about 300mb).

Since then, nearly all climate simulations have identified rises in SAT in response to increasing atmospheric GHG concentrations and this will be larger in the Arctic compared to the Northern Hemisphere as a whole (Holland and Bitz 2003; Serreze et al. 2009).

The process of Polar Amplification is related mainly to the changes in albedo associated with ice melting. With warming climate the summer melt season lengthens and warms, allowing enhanced absorption of solar energy in open water which increases the sensible heat content of the ocean. This leads to a delay in autumn sea ice development, increasing upward heat fluxes and allows enhanced surface and lower troposphere warming. Strong lower troposphere atmospheric stability inhibits vertical air mixing and this increases the impact of amplification.

In essence, then, polar amplification is the result of positive feedbacks from the melting of ice and snow, which have high albedo, (i.e., reflective of solar energy), with a less important response to feedbacks to water vapour fluxes. All modelling and observational data suggests that the immediate impact of polar amplification is an increase in surface temperatures by a factor of 2-3 above the global mean surface temperature rise. Clearly this has implications for the stability of the Greenland Ice Sheet (GIS) and the ice sheets of Antarctica, especially the West Antarctic Ice sheet (WAIS).

The 2005 Arctic Climate Impact Assessment argued that (p 22), "Based on the analysis of the climate of the 20th century, it is very probable that the Arctic has warmed over the past century, although the warming has not been uniform. Land stations north of 60ºN indicate that the average surface temperature increased by approximately 0.09°C/decade during the past century, which is greater than the 0.06°C/decade increase averaged over the Northern Hemisphere. It is not possible to be certain of the variation in mean land-station temperature over the first half of the 20th century because of a scarcity of observations across the Arctic before about 1950. However, it is probable that the past decade was warmer than any other in the period of the instrumental record". More recent studies (e.g. Serreze et al 2009) shows that Polar Amplification is now clearly evident, especially in the Arctic regions and this finding is supported by Kaufman et al. (2009) who show that a long-term cooling trend (driven by reduced insulation) was reversed during the 20th century, with four of the five warmest decades of our 2000-year-long reconstruction occurring between 1950 and 2000.

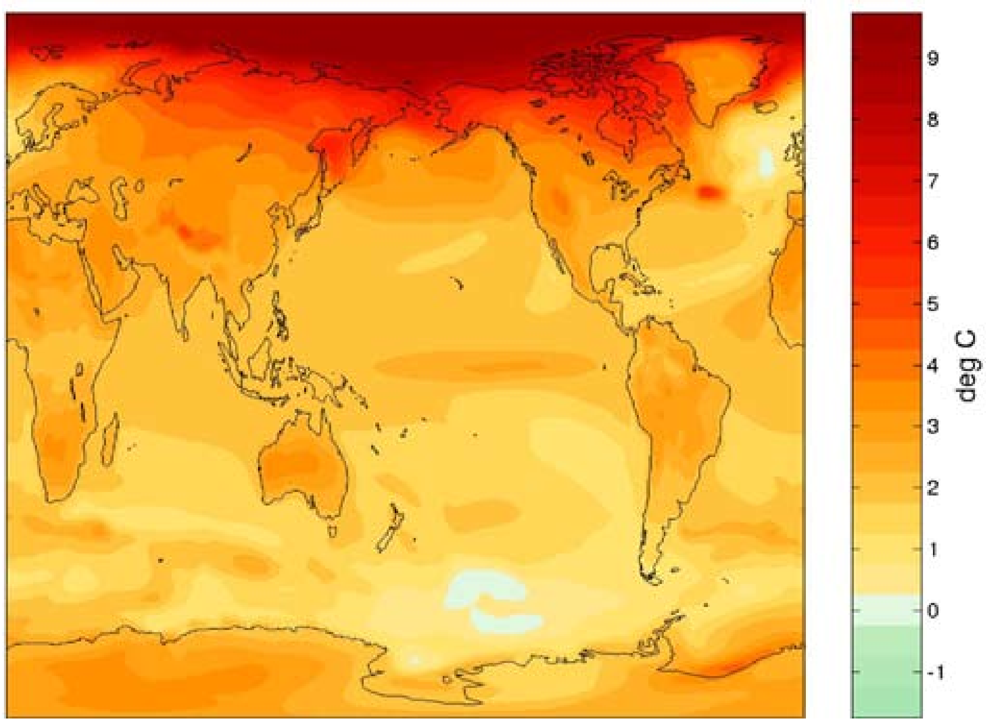


Figure 5: Linear surface warming trend in °C per century from NCAR CCSM3 averaged from 9 ensemble members using the SRES A1B scenario (From www.esrl.noaa.gov/csd//2002/index.html)

Until recently, observations of Polar amplification were asymmetric with significant Antarctic warming only occurring along the Antarctic Peninsula. The Antarctic climate is different from the Arctic climate because of the influence of deep circumpolar ocean currents that serve to isolate the continent from low-latitude climate influences. Despite this, climate models show that amplification in the Antarctic exists to the same extent as in the Arctic and this pattern exists when climate models are run to equilibrium. New research (Steig et al. 2009) shows that the WAIS is also warming considerably, although the higher East Antarctic Ice Sheet (EAIS) does not show this trend as clearly.

2.1.1.2 GLACIOLOGICAL PROCESSES AFFECTING SEA LEVEL RISE

The velocities of glaciers draining the GIS and WAIS have been observed to increase in recent decades. There are two processes that have been identified to explain this. The first is the 'Zwally Effect' that was seen to contribute to the increase in velocity of Jacobshavns Isbrae of around 20% in 1998 and 1999 (Zwally et al 2002). This concerns the increase in meltwater from the surface, which enters the subglacial zone via moulin crevasses. This meltwater increases the subglacial hydrological pressure and reduces the friction between the glacier bed and the underlying bedrock. Recent work (e.g. Das et al 2008) has shown that this effect may increase the seasonal flow of the glacier, but it probably does not contribute to long-term (annual or decadal) variations in flow velocity of such outlet glaciers (van der Wal 2008). The second proposed process is the so-called 'Jacobshavns Effect' where thinning of the frontal zone of the outlet glacier leads to flow acceleration by a reduction in effective bed pressure. It is suggested (Hughes 1986; Thomas 2004) that the effect is propagated up the glacier as the calving terminus undergoes enhanced flotation and is therefore unable to maintain resistive forces. Rapid ice discharge is maintained by positive feedback via high levels of surface crevasses, extending creep flow, enhanced iceberg calving fluxes and uncoupling of the bed and sides from underlying bedrock. Clearly, if this process dominates then its effects will be continuous, without the seasonal variation seen in the Zwally Effect.

In essence, outlet glaciers that are coupled to the ocean and grounded below sea level are most vulnerable to rapid collapse, caused by enhanced submarine melting, calving fluxes and iceberg production. Thinning of outlet glaciers also increases their flow and results in increased drainage of interior ice sheets.

2.1.2 PAST EVOLUTION OF THE HIGH LATITUDE ICE SHEETS

Understanding the past dynamic evolution of the high latitude ice sheets gives insight into likely future response to warming global average air and ocean temperatures. Thanks to recent advances in Quaternary science there is now detailed information on the nature and timing of deglacial events at the end of the Pleistocene (circa two million years ago), and from palaeoglaciological investigations, it can be shown that the ice sheets with major terrestrial margins, such as large parts of the Laurentide and Fenno-Scandian ice sheet, were largely stable and melted slowly following the Last Glacial Maximum. Those ice margins that were significantly coupled to the ocean, such as those that drained through the Hudson Strait in central Canada, disintegrated rapidly and this resulted in rapid discharge of icebergs and significant sea level rise from displacement (Overpeck et al. 2006, Andrews et al. 2005).

During the deglaciation between the last glacial maximum and the early Holocene, large sections of the Northern Hemisphere ice sheets underwent periods of dynamic change and at this time sea levels rose rapidly. Two elements of this change were Dansgaard-Oeschger (D-O) events and Heinrich events. D-O events were periods of repeated regional rapid warming and gradual cooling which occurred with an underlying periodicity of 1,500 years or so (Rahmstorf 2003). At least 20 D-O events occurred during the last glaciation and, although evidence for these is found in many regions of the world (Voelker 2002), their strongest effect is seen in the Greenland ice cores where annual temperatures rose abruptly between 10 and 15°C. While these events are therefore more rapid and of higher magnitude than anything predicted by GCMs over the next century, Rial et al. (2004) ask: "Could present global warming be just the beginning of one of those natural, abrupt warming episodes, perhaps exacerbated (or triggered) by anthropogenic CO_2 emissions? Since there is no reliable mechanism that explains or predicts the D-O events, it is not clear whether the warming events occur only during an ice age or can also occur during an interglacial, such as the present".

Concurrent with this increased understanding of past ice sheet changes, has been the recent revolution in our understanding of ice sheet dynamics which suggests that considerable ice sheet change can occur over centennial timescales. Before this, the consensus was that ice sheets underwent dynamic change over periods of 1000s to 10000s of years, but this understanding was based on numerical ice sheet models with limited resolution (around 40km grid squares) that could not resolve important characteristics of ice sheets, such as individual ice streams. Consequently, the physics driving these models appeared to be reasonable at the scale then resolved. However, since 2000 satellite-based repeat pass synthetic aperture radar interferometry (InSAR) has allowed a reassessment of ice sheet behaviour to be made, and this has radically altered our understanding of the rate and amount of sea level change which may be expected from the dynamic response of ice sheets to continued global warming.

West Antarctic Ice Sheet: Much of the WAIS is at or below sea level, as are parts of the EAIS, and are therefore vulnerable to SLR and hence rapid collapse. Originally, the low temperatures of Antarctica were assumed to preclude melting during global warming episodes; however, it has become clear that submarine melting is occurring where outlet glaciers come into contact with the ocean. Recent estimates show that annual ice losses from Antarctica approach 220 gigatonnes and this figure appears to be accelerating (Velicogna et al. 2006).

Being marine-based and with large parts below sea level (Bamber et al. 2007), the stability of the WAIS is seen as one of the key issues in deciding whether 'dangerous climate change' (Oppenheimer and Alley 2004; 2005) is occurring or likely. Until recently, there has been little evidence to show the nature of climate change from the centre of the Antarctic continent, and the data sets that did exist are of short duration. More recently, however, gravitational studies by Velicogna and Wahr (2006) have shown that the Antarctic ice sheet decreased its mass at a rate of 152 $\pm$ 80km^3/year of ice (equivalent to 0.4 $\pm$ 0.2 mm/year of global sea level rise) between 2002 and 2005, and most of this ice loss came from the WAIS.

From the Antarctic peninsula and ice shelves around the margins of the West Antarctic ice sheet we now have evidence that significant warming is occurring (e.g. Turner et al. 2005). The Amundsen Sea region of West Antarctica is currently the largest contributor to global sea level rise in Antarctica and contains enough ice to raise global sea levels by around 1m. In this region, much work has concentrated on the ice shelves, which buttress the ice sheet, and on the behaviour of its outlet glaciers, especially Thwaites and Pine Island Glaciers. These large glaciers drain the WAIS into the Amundsen Sea and their behaviour is closely linked with the overall stability of the WAIS (Shepherd et al 2004). In 2001, Rignot showed that the grounding line on Thwaites Glacier had retreated 1.4km between 1992 and 1996, and the lower part of the glacier had downwasted at 1.4m/year. Rignot et al. (2002) further reported that Pine Island Glacier had increased its velocity over 150km of the glacier by 18% between 1992 and 2000, downwasted at 1.6m/year and seen a 5km grounding line retreat between 1992 and 1996. We can suggest that the recent behaviour of Pine Island Glacier may be the initiation of a shift in the long-term stability of the WAIS (e.g. Payne et al. 2004) and this leads glaciologists to suggest that there is a strong coupling between the interior of the ice sheet and the surrounding ocean. Recent work suggests that acceleration of Pine glacier will continue.

Antarctic Ice Shelves: The large ice shelves that buttress the Antarctic outlet glaciers have also undergone recent change. Ice shelves are important components of the current and future global Earth-system for three main reasons (Glasser and Scambos 2009): (1) ice shelves play a significant role in the global ice-volume/sea-level system because the calving of icebergs from their termini accounts for about 90% of Antarctic ice loss; (2) ice shelves influence the dynamics, and therefore the system response time, of upstream inland Antarctic ice; (3) rapid heat exchange in sub-ice-shelf cavities has a significant impact on the global ocean heat budget. Ice shelves fringe around 45% of the Antarctic continent and are sensitive elements of the climate system (Braun et al. 2009). In Antarctica a number of these have recently undergone considerable recession or collapse. This includes the Wordie, Mueller, Jones and Larsen A and B ice shelves. Ice shelf collapse removes horizontal compressive forces and, as a result, the glaciers draining the Antarctic Peninsula have increased their velocities by factors of two to eight with downwasting rates in the order of 10s metres/year. Consequently, overall ice loss in the region is now greater than 27 cubic km/year (Rignot et al. 2004). As the buttressing affect of ice shelves decays, the flow of ice streams from ice sheets become more rapid. This fact points to a rapid decay in the future.

Ice shelf collapse appears to be caused primarily by submarine bottom melting as the ice shelf base encounters warm ocean water. Surface melting also plays a role, as does the development of structural weaknesses in the shelf caused by variable flow velocities of inland glaciers. Once the shelf thins, this allows increased calving and ultimate recession of the shelf; debuttressing of the termini of outlet glaciers also allows these to increase their velocity, thin and initiate rapid calving and collapse of the frontal zone. The ice shelf thins and this weakens the structure of the shelf where it possesses pinning points at the grounding line. In 2002, the Larsen B ice shelf collapsed and this is probably the first time that this ice shelf has collapsed during the Holocene (Domack et al. 2005). More recent work by Glasser and Scambos (2009) on the failure of the Larsen B ice shelf shows that the shelf became buoyant and an increase in crevasses and rifts in the shelf were observed in the decade before collapse. After collapse the ice terminus receded to the position of existing rifts; these therefore determined the pattern of ice shelf recession and formed structural controls on shelf behaviour. Glacier and ice shelf thinning is a precursor for collapse and rapid recession of these ice masses.

The Wilkins Ice Shelf on the Antarctic Peninsula was examined by Braun et al. (2009) and is buttressed by Alexander, Latady, Charcot and Rothschild islands, suggesting that parts of the ice shelf are grounded and therefore likely to be stable. The work by Braun et al. (2009) showed that in this area seven ice shelves disintegrated or retreated between 1995 and 2002. They showed that ice front retreat rates from 1986 to 2008 showed several distinct break-up events, including one in February 2008, when 40% of a part of the ice shelf that connected two islands broke off. By February 2009 research shows that about 3100km^2 of the Northern Wilkins Ice Shelf are endangered, although the remainder of the ice shelf (around 8000km^2) to be stable at present.

With the removal of horizontal compressive forces by ice shelf collapse, the glaciers draining the Antarctic Peninsula have increased their velocities by factors of two to eight with downwasting rates in the order of 10s metres/year (Scambos et al. 2004). Consequently, overall ice loss is now greater than 27 cubic km/year (Rignot et al. 2004). Understanding and assessing the future behaviour of these ice masses is difficult, but their dynamic evolution is likely to be sensitively dependent upon the configuration of their subglacial bedrock channels through which they flow, and it appears that the glaciers flow into ice shelves several hundreds of metres thicker than was previously believed (Thomas et al. 2004). These sub-glacial conduits are thus the routes by which ice can be discharged from the central parts of the WAIS if ice sheet collapse is initiated. This idea was suggested by Mercer (1978).

Greenland Ice Sheet: Unlike the WAIS, the GIS is not at or below sea level and, as a result, is unlikely to collapse quickly. However, parts of the ice sheet are clearly unstable; over the past decade a number of the large outlet glaciers draining the ice sheet have increased their velocities and ice discharge rates and this is helping to drain large areas of inland ice.

Rignot et al. (2008) estimated the surface mass balance of the GIS from 1958-2007 and estimated discharge variations to obtain an estimate of the mass balance of the ice sheet. From this, they showed that the ice sheet had a negative mass balance of 110 ± 70 Gt/yr in the 1960s, 30 ± 50 Gt/yr or near balance in the 1970s–1980s, and 97 ± 47 Gt/yr in 1996 increasing rapidly to 267 ± 38 Gt/yr in 2007. The increased discharge from outlet glaciers dominated the ice sheet mass budget. These data show that the mass of the GIS was in balance in the 1970s and 1980s but since then has been in negative mass balance of around 20 gigatonnes per year and recent work shows that the ice sheet lost around 280 gigatonnes of ice in 2008. About 30% of the ice loss is accounted for by increased melt and runoff and this has increased by 50% since the early 1990s. The rest of the negative mass balance occurs due to increased calving and ice flux from marine-terminating outlet glaciers.

Modeled sea level projections by IPCC AR4 (2007) failed to account for the recent recession and velocity changes of some of the Greenland outlet glaciers because the physical behavior of ice mass calving, crevasse development and terminus destabilization caused by ice thinning is insufficiently understood to incorporate into models. In addition, many of the processes implicated in the behavior of outlet glaciers occur at smaller scales than the model grids and have to be parameterized; without a better understanding of these processes, parameterization is difficult.

The most dynamic of the outlet glaciers draining the GIS is the tidewater Jakobshavn Isbrae that is the fastest moving glacier in the world. The glacier has doubled its velocity (up to 40m/day) and has undergone a 4km terminus recession over the past decade (Dietrich et al. 2005; Mayer and Herzfeld 2005). Glaciological work shows that downwasting and acceleration of the glacier are linked and self-sustaining, at least on seasonal timescales, and is caused by positive feedback mechanisms triggering rapid ice discharge, deep crevassing and basal uncoupling to produce high calving fluxes (see Zwally et al. 2002). In support of this contention, it was observed that thinning of the glacier terminus and acceleration followed a period of calving.

Similar work was reported by Chen et al. (2006) who showed a five times increase in melting from southeast Greenland over the last two years of the study (between April 2002 and November 2005) compared to the first 18 months with estimated total ice melting rate over Greenland as 239 ± 23 cubic kilometres per year. This increase in melting is likely to add over 0.5mm per year of global sea level rise and may affect North Atlantic oceanic currents and climates. One of the authors, (B.D. Tapley) said "This melting process may be approaching a point where it won't be centuries before Greenland's ice melts, but a much shorter time-frame," but also noted that it is not possible to suggest a timetable for this.

The most recent work from Greenland shows that the pattern of glacier thinning enhanced calving and flow acceleration observed from marine-calving outlet a glacier over the past decade has continued (Sole et al 2008). Recently, Box et al. (2008) observed that Jakobhavns Isbrae has undergone further recession of around 15km^2 and accelerated its output (Box et al. 2008).

Sole et al (2008) have demonstrated that the thinning and acceleration is greatest for marine terminating outlet glaciers. They supported earlier conclusions that certain marine-terminating outlet glaciers have thinned much more than land-terminating outlet glaciers over recent years, and that these differences are seen in almost all of the marine-terminating outlet glaciers, with a four-fold increase in mean marine terminating outlet glacier thinning rates below 1000 m elevation between the periods 1993 to 1998 and 1998 to 2006, while thinning rates of land-terminating outlet glaciers remained statistically unchanged. For instance, in 2008 Sermeq Avannarleq glacier to the north of Jacobshavns Isbrae underwent its second year of frontal recession (Box et al. 2008); since 2001 the glacier has lost almost 18km^2 in area.

Work by de Lange et al. (2005) on the Helheim Glacier showed that it increased its velocity significantly in 2002-3 compared with its behaviour in the 1990s. Their observations suggest that this behaviour is largely unrelated to changes in runoff and therefore make no explicit link to the 'Zwally Effect'. In addition, Sterns and Hamilton (2005) observed the tidewater Kangerdlugssuaq and Helheim Glaciers (that drain around 10% of the Greenland ice sheet). Increased their flow velocity between 2001 and 2005 and underwent recession of 3-5km since July 2003. In

1995 the flow velocity of Helheim Glacier was ~8km/yr; by 2005 this had increased by about 40% to ~11.7km/yr. Kangerdlugssuaq Glacier underwent a similar increase in flow velocity; between 2001and 2005 this had increased from ~5km/yr to ~14km/yr.

More recent work by Sole et al. (2008) investigated the behaviour of Helheim Glacier as well as others including Jakobshavn, Kangderlugssuaq, Cristian IV, Equaluit and Rinks Isbrae, and showed that all had undergone recent acceleration and thinning. In all cases, increased flow velocities of these glaciers occurred in combination with significant ice thinning of around 100m and recession of calving termini and the correlation of these variables is suggestive of a common triggering process.

Most of the glaciers mentioned above drain to the southeast or southwest of Greenland. However, in northwest Greenland, the Petermann Glacier has shown similar behaviour, although its glaciological characteristics are different from many of the other glaciers studied. Studies by Higgins (1990) shows that the glacier is the largest floating glacier in the Northern Hemisphere, making it highly vulnerable to rising sea level. The floating portion of the glacier is some 80km long and 1300km^2 in area. Box (2008c) showed that the glacier lost 29km^2 in area over the last decade and crevasse patterns suggest that it may well lose a further 150km^2 in the near future.

2.1.3 FUTURE GLOBAL SEA LEVEL RISE PROJECTIONS

Until recently, estimates of changes in the global sea surface have taken little account of the implications of the recently observed changes in the GIS and WAIS. Recent studies (Chen et al., 2006, Monaghan et al., 2006; Rignot et al. 2008) indicate a marked increase in the ablation (melting) rate of the GIS, while the WAIS accumulation rate is not now believed to exceed its ablation rate and since the base of this ice sheet is largely below sea level it is thought inherently unstable and susceptible to rapid retreat. The amount of sea level rise expected from melting of these ice masses is currently uncertain, Table 3 depicts observed changes from which estimations can be made. Early assessments suggested that if the GIS melted, it would raise the global sea surface by circa 7m and the WAIS by circa 5m. However, new work by Bamber et al. (2009) used elevation and topographic data to estimate the amount of ice below sea level under the WAIS and its likely vulnerability to rapid collapse. They used these assessments to obtain a revised global figure of around 3.3m of sea level rise if the WAIS collapsed over a 100-year period.

Table 3: Observed rate of mean global sea level rise and estimated contribution from different sources, IPCC Fourth Assessment Report, 2007.

Source of sea level rise	Rate, mm/yr, 1961-2003	Rate, mm/yr, 1993-2003
Thermal expansion	0.42±0.12	1.6±0.5
Glaciers and ice caps	0.50±0.18	0.77±0.22
Greenland ice sheet	0.05±0.12	0.21±0.07
Antarctic ice sheet	0.14±0.41	0.21±0.35
Sum of individual climate contributions to sea level rise	1.1±0.5	2.8±0.7
Observed rate of global mean sea surface rise	**1.8±0.5**	**3.1±0.7**

Prediction of future SLR is severely compromised by the inability of climate models to incorporate the rapid likely behavior of ice sheets. IPCC AR4 projected that sea levels could rise by up to 59cm higher than present by the end of this century. This figure was based upon the emissions scenario (A1F1) where rapid economic growth occurs, population growth reaches 9 billion by 2050 and then gradually declines and fossil fuel use is intensive. However, it is clear that this figure for future sea level change forms a likely lower bound as it only accounts for sea level rises in response to thermal expansion of the oceans and the melting of glaciers and ice caps; both of the latter make up only a very small proportion of the ice on earth. This projection specifically excluded the rapid increase in calving and melting from ice sheets as the scientific data from these was largely incomplete and partial.

The research summarized here from modeling and observational studies on both the GIS and WAIS shows that ice sheet losses are currently increasing faster than any other system contributing to sea-level rise, and it is likely that ice sheets will be the primary contributor to sea-level rise during this century.

To increase our ability to understand future sea level change we will need a suite of more advanced numerical models and more detailed and complete observations on key physical processes. It is also clear that sea level rise will continue after 2100 and the dynamical breakup of parts of the GIS and WAIS will continue for centuries. The behavior of ice sheets and sea level are therefore irreversible on human timescales.

Alternative methods of estimating sea level rise are to base projections on the observed covariance of sea levels and temperature during the period of instrumental observations. If this relationship continues, IOP (2009) suggests that sea level rise will average around 1m by 2100.

However, we can also use the past behavior of sea levels in response to changing temperatures to assess the likely rate and amount of future change. Archer and Brovkin (2008, 290) have shown that "There is a clear and strong correlation between long-term global average temperature and sea level in the geologic record. Sea level has the potential to change much more than is forecast for the coming century, and it has done so in the past". There are major uncertainties in this view of course. For instance, the response of individual ice sheets depends upon their relationship to the oceans and the detailed response depends upon the physics operating at submarine grounding lines. In addition, the growth and decay of ice sheets is clearly non-linear, with rapid collapse seen in the past often with no corresponding climate forcing to act as a trigger. Figure 6 shows that the geological record gives us clear indications that global temperatures and sea level are highly correlated. For instance, during the Eemian period, global temperatures were around 1°C warmer than those in the Late Holocene and sea levels were 4-5m higher than now (see Kubatzki et al. 2000). Sea level forecasts by 2100 are in the region of 2-50cm in response to warming of around 3°C and this is about 100 times less than the covariation of temperature to sea level seen in the past record. As Archer and Brovkin (2008, 290) argue: "The contrast between the past and the forecast for the future is the implicit assumption in the forecast that it takes longer than a century to melt a major ice sheet".

Several recent papers have attempted to assess sea level sensitivity and derive a likely bound on global sea level rise by the end of this century. Siddall et al. (2009) derive a low estimate for global sea level rise of between 7 and 82cm by 2100. However, it appears that their model parameters were fitted to the slow changes of the ice sheets (their model time scale τ =2900 years) and not to the early response caused by thermal expansion and mountain glaciers, which makes up most of the 20th century sea level rise. Their model appears to under-estimate 20th century sea level rise and hence their projections are likely to underestimate 21st century rises.

Several of these modelling approaches assume that the sea level response and future temperature drivers behave in a linear way. Evidence from the paleo-record of temperature, ice sheet and sea level response shows that non-linearity is a characteristic of these coupled systems. As a result, while some authors have used linearity to assess future sea level rise, it is not clear over what timescales this is an appropriate methodology.

As a result, while most studies predict sea level rises in the order of around 1m this century, any departure from the current and projected rate of rise or ice sheet response would make such a prediction an underestimate (Milne et al. 2009). Therefore, it might be prudent to plan for several metres of sea level rise by the end of the century. However, the regional and temporal pattern of sea level rise is likely to be highly variable, and this aspect is incompletely modeled.

Available data from satellite altimetry show that sea level rise is currently not uniform, with some regions of the world experiencing higher than average sea level increases. For instance, in parts of the western Pacific sea level rises are around 3 times the globally averaged rate. Although the contribution of the WAIS and GIS to overall sea level rises is expected to increase markedly over this century, present rises are the result largely of thermal expansion of the oceans, and this is spatially variable. In addition, other factors influence regional sea level rise including isostatic adjustment of the crust (often associated with unloading following the melting of Pleistocene mid-latitude ice sheets) and changes in water salinity. Such regional variations also change over time in response to decadal and shorter fluctuations in ocean and wind currents such as El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO).

The prospects for future global sea level changes are ten times the rate observed a century ago and predicted to increase by 1.5m to 2m by the end of the century. This is very likely to be much greater if the potential, large-scale changes described here for both the Greenland and Antarctic ice sheets were to take place. Considered together with known crustal movements, the risks of SLR for some coastal communities, especially in the developing world, are a legitimate concern for the global community.

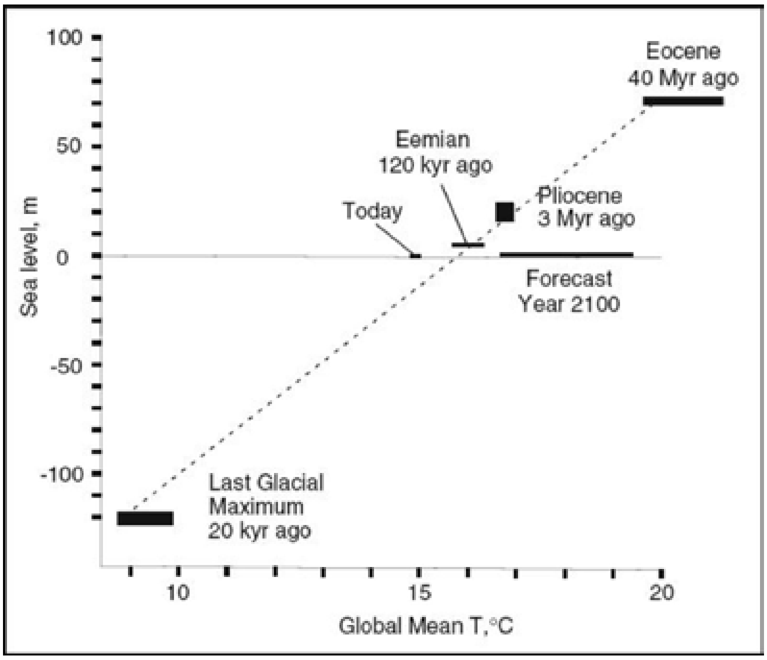


Figure 6: The relationship between temperature and sea levels over recent geological timescales (Archer and Brovkin 2008).

2.2 SEA LEVEL RISE PROJECTIONS FOR THE CARIBBEAN REGION

The coastlines of the Caribbean, which include many low lying and highly erodible shore areas, are particularly susceptible to sea level rise (SLR). Studies of both coral reefs and mangroves have established that the level of the sea surface has risen since the end of the last glacial maximum, around 25,000 years ago, by as much as 120 metres, and by around 45 metres over the last 11,500 years (e.g. Fairbanks, 1989). The rise in sea surface levels was marked by at least two and possibly three periods of acceleration before decreasing around 7,000 years ago and reaching present levels very recently. Figure 7 depicts sea level change in the Caribbean for the last 10000 years according to Toscano and Macintyre (2003). The graph shows sea levels rising rapidly until circa 7-8000 years before present, then slowing, but still rising during the last 2000 years. There is no evidence that sea surface levels in the Caribbean have been above present levels at any time since the last glaciation.

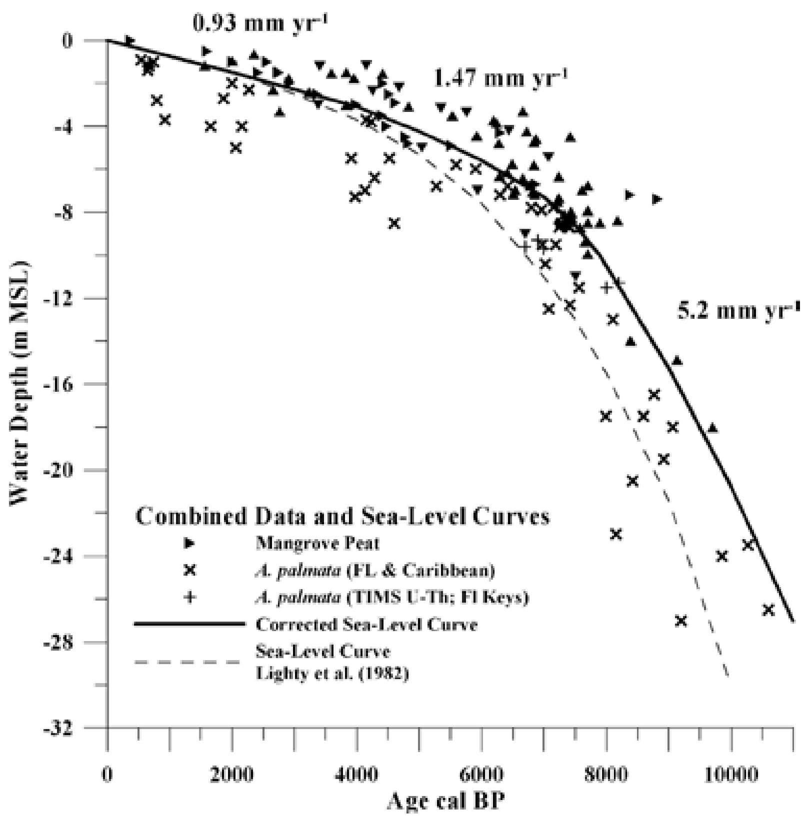


Figure 7: Sea level graph (solid line) for the Caribbean area from Toscano and Mackintyre (2003), showing the data upon which it is based, rates of rise, and the curve (dashed line) of Lighty et al (1982). The rate of 5.2mm/yr refers to the period 10600 – 7700 BP (before present); that of 1.47mm/yr refers to 7,700 – 2000BP and that of 0.93mm/yr to 2,000-400 BP.

As indicated, the IPCC AR4 in 2007 reported that the mean global sea surface rose by 1.8mm/year over the period 1961 – 1993, and by 3.1mm/year between 1993 and 2003. There are few records of sea level change at the present time in the Caribbean (detailed information from tide gauges is lacking), but it is likely that a similar rate of rise to that estimated for 1961 – 1993 occurred in the area at the end of the last century. If sea level in the region generally followed global changes, there is no reason to suppose that the greater rate of rise for 1993 – 2003 did not take place. This is in agreement with observed trends in sea level rise globally from 1950 to 2000, when the rise in the Caribbean appeared to be near the global mean (Church et al., 2004). Land movement is only imperfectly recorded in the Caribbean, and it is therefore assumed that SLR of about +3.1mm/year applies to all areas. Given the most recent information on the Greenland and Antarctic ice sheets (see Sections 2.1.2 and 2.1.3) and on the effect of global warming on the oceans (i.e., thermal expansion of ocean waters), it seems increasingly likely based on scientific evidence published in the last two years that the rate of mean global sea level rise identified by the IPCC[24] will actually increase in the years ahead, and that the total SLR by the end of the century will be exceeded, perhaps reaching as much as 1.5m to 2m above present levels (Mann et al., 2009) (see also Section 2.1.3). With a 1.5°C increase in mean global temperatures by 2100, this increase in SLR may slow compared to recent observations. Whereas with a 2°C global temperature rise, the recent observed increases in SLR will continue (Nyberg et al. 2007).

Furthermore, it is important to note that projected increases in global sea surface levels of 1.5m to 2m may be even greater in the Caribbean region because of gravitational and geophysical factors. Recent modelling indicates that in the event that the GIS and WAIS melt quickly (over 100 years) the greatest rises in sea level will be experienced along the Western and Eastern coasts of North America and result in greater rises (up to 25% more than the global average) in the sea surface in the Caribbean (Bamber et al. 2009). Even partial melting of the ice sheets will result in greater rises in sea surface levels in the Caribbean region than in most other areas of the Earth.

Set against the rises in sea surface levels, the extreme events to which the Caribbean is subjected will result in impacts of even greater prominence. Although there is no consensus on trends in either intensity or frequency of hurricanes and tropical storms, their range of inundation and capacity for coastal erosion will increase as the sea level rises. The same will be true for tsunamis.

Hurricanes are a well-known feature of Caribbean meteorology; although they are do not normally affect the most southerly countries of CARICOM, Guyana and Suriname. All countries of CARICOM are, however, affected by tropical storms. The hurricane season is June to November, with the peak season mid-August to October. The statistical peak occurs on 10th September. Table 4 provides a statistical analysis of Hurricanes and tropical storms by month.

Table 4: Recorded Tropical Storms and Hurricanes by month since 1851 (Source: NOAA)

Month	Total	Mean

24 IPCC mean global sea SLR being a maximum of 0.79 m by 2100 using the A1F1 scenario (95% confidence limit) with scale up ice sheet factors

January - April	5	0.03
May	19	0.1
June	80	0.5
July	102	0.7
August	347	2.2
September	466	3.0
October	281	1.8
November	61	0.4
December	11	0.07
Total	1,372	8.8

Hurricane activity in the Caribbean has been the subject of many studies. Hurricanes depend upon a warm SST amongst other factors, and studies indicate that SSTs are increasing. However, they are related to the El Niño/La Niña (El Niño Southern Oscillation -ENSO) cycle in the Pacific Ocean. The number of hurricanes in a given season, in the Caribbean, is influenced by ENSO. There may be an increasing number of hurricanes, but that is uncertain. However, there appears to be an increase in hurricane intensity. The intensity of some recent hurricanes can be seen from the statistics in Table 5.

Table 5: The most intense Atlantic Hurricanes*

Rank	Hurricane	Season	Minimum Pressure
1	Wilma	2005	882mb
2	Gilbert	1988	888mb
3	"Labor Day"	1935	892mb
4	Rita	2005	895mb
5	Allen	1980	899mb
6	Katrina	2005	902mb
7=	Camille	1969	905mb
7=	Mitch	1998	905mb
9	Ivan	2004	910mb
10	Janet	1955	914mb

*Note: All of these storms impacted at least one country while at a Category 5 intensity on the Saffir-Simpson Hurricane Scale.

The storm surges associated with hurricanes may cause considerable damage and flooding. Storm surges precede the arrival of hurricanes, and then continue during the hurricane with their effects sometimes involving larger areas. Storm surge height is related to the reduction in pressure in the hurricane, so that the lower the pressure the stronger the surge. Since pressures in the strongest hurricanes appear to be getting lower, storm surges associated with these hurricanes will be getting higher, and on top of this when winds become stronger storm-driven waves become larger, so it seems likely that if intensity of the strongest hurricanes is increasing, storm surges will increase. Table 6 gives hurricane wind speeds associated with each category of storm, along with the corresponding storm surge value.

Table 6: Saffir – Simpson Hurricane Scale (US National Hurricane Center)

Category	Wind Speed (mph)	Storm Surge (metres)
1	74-95	1.2-1.5
2	96-110	1.8-2.4
3	111-130	2.7-3.7
4	131-155	4-5.5
5	>155	>5.5

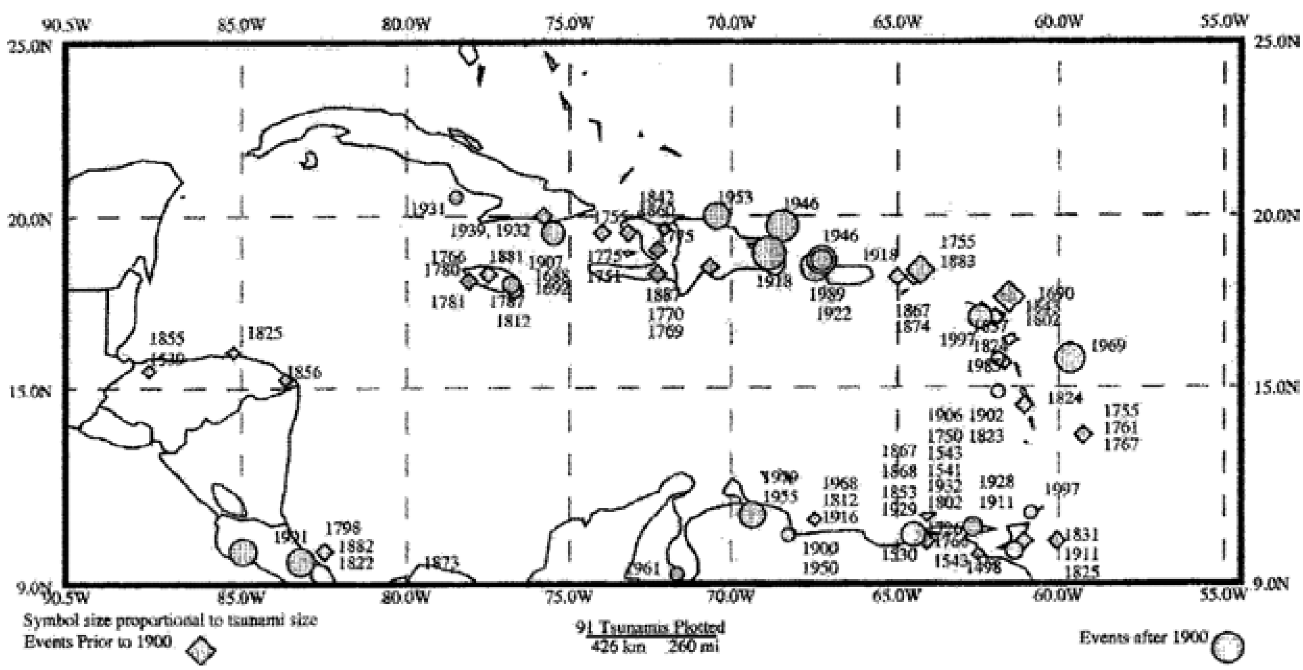


Figure 8: Tsunamis in the Caribbean since the sixteenth century, taken from Lander et al. (2002). Events prior to 1900 are shown with a diamond; events post 1900 with a circle.

The combination of sea level rise, increased intensity of hurricanes, and occasional tsunamis presents a considerable threat to the coastlines of CARICOM countries. The impact of these events will greatly depend upon the topography.

In the following country-by-country account, the topography of each country has been provided. The discussion then passes to the specific impacts that sea level rise (SLR) will have for each country because of their infrastructure developments and topography.

2.3 IMPACTS OF SEA LEVEL RISE IN CARICOM MEMBER STATES

There is overwhelming scientific evidence that SLR associated with climate change projected to occur in the 21st century and beyond represents a serious and chronic threat to the sustainable management of the coastal zone in CARICOM nations. Adaptations to future sea level rise will frequently involve revisions to development plans and major investment decisions, which must be based on the best available information about the relative vulnerability of specific coastal areas and the economic and non-market impacts on infrastructure as well as environmental and heritage resources. This report provides the first comprehensive assessment of the consequences of projected SLR for the people and economies of the 15 CARICOM nations.[25]

The impact of coastal flooding due to climate change along the coastlines of CARICOM countries is greatly dependent upon topography. Where the coastline is steep and low lying areas are narrow, rises in sea levels will consume less land and here the main concerns will be loss of beaches and damage to developed areas concentrated in relatively flat lands. Where the coastline is low-lying the main concerns will be the loss of agricultural land, damage to infrastructure, and salinisation of the water table. Much will depend upon the rate at which the sea level rises and the frequency and magnitude of storms. It is uncertain at present whether hurricanes, which impact the region widely, are increasing in number; however, it is very likely that their intensity is increasing. It is also possible that other storms are increasing in number and intensity, and with a rising sea level the impact of hurricanes and other storms on the countries of the Caribbean will increase.

The CARICOM countries can be broadly categorized into four groups in terms of their relative vulnerability to coastal flooding. The first group are the small islands and cays, largely comprised of coral reefs: The Bahamas, most of The

25 To ensure comparability of SLR vulnerability results between the CARICOM nations and developing nations in other regions, some of the impact indicators selected for this study were common to a previous study by the World Bank (Dasgupta et al. 2007), which examined 84 developing nations, including six CARICOM nations. The results for the six CARICOM nations included in the World Bank study and this analysis were highly consistent for all common indicators (±2%).

Grenadines, Barbuda and a few small islands lying offshore from other countries. These islands, lying mostly below 10m, are highly vulnerable to sea level rise and hurricane storm surge. They will likely experience periodic flooding, erosion and retreat of mangroves and seagrass beds together with saltwater intrusion into the small lenses of fresh groundwater upon which they depend. Additional biophysical impacts to the land masses will very likely be experienced from other climate change drivers such as ocean acidification, increased coastal water temperatures and changes to currents and wave climates.

The second group are the mainly volcanic islands of St Christopher (Kitts) and Nevis, St Lucia, St Vincent, Grenada, Dominica and Montserrat. These islands, with only narrow coastal areas, are vulnerable to beach erosion and local coastal landslides. In some of these islands, mangroves and seagrass beds are also threatened. In addition, it can be seen that coastal roads are vulnerable, as well as homes and infrastructure, especially in the tourism industry. Saltwater intrusion is less of a problem in this group, but isolated areas of mangroves and seagrass beds are vulnerable, as are coral reefs. These islands, being tectonically active, may be experiencing land movement, which could mitigate against or exacerbate SLR, although generally these rates of uplift are much less than the probable rate of SLR.

The third group of countries are those where there are large coastal plains, which lie near the sea level, exemplified in Belize, Guyana and Suriname. These topographic conditions make them highly vulnerable to SLR. In the case of Belize, hurricanes are also of great concern; less so in the case of Guyana and Suriname, although other storms may affect all three countries. Saltwater penetration of the groundwater reservoirs is of concern in Guyana and Suriname, because they are part of continental landmasses that generally receive fresh water resources from over land stream flow and the threat of SLR will cause brackish water to require further processing than is currently necessary before drinking and other uses. Mangroves are more extensive in these nations as compared to other CARICOM countries, and deterioration in the mangroves will lead to accelerated coastal erosion as the stabilizing root systems are lost.

The final group of CARICOM countries are Antigua, Barbados, Haiti, Jamaica and Trinidad and Tobago. The coastlines of these countries are varied and include both steep, sometimes volcanic coastlines and coastal plains, sometimes with mangroves and seagrass beds along the shore. Flooding of the coastal plains due to SLR is a considerable threat, as is coastal erosion and flooding caused by storms (including hurricanes in the case of Antigua, Barbados, Haiti and Jamaica, and tropical storms in all areas). These nations lie in tectonically active, and as with the volcanic islands, tectonic activity may cause rises or falls in land level (which would alter SLR projections slightly).

2.3.1 GEOGRAPHIC INFORMATION SYSTEM ANALYSIS OF SLR IMPACTS

A Geographic Information System was constructed using the best available geospatial data to examine the vulnerability of multiple key natural and economic indicators (total land area, population, urban areas, wetland area, agricultural land, major tourism resorts, and transportation infrastructure-airports/roads) to inundation from scenarios of 1 to 6 meters of SLR and storm surge in each CARICOM nation (at 1m intervals). The analysis was designed to be consistent with the methods use in a World Bank study of SLE vulnerability of selected developing countries worldwide (Dasgupta et al. 2007), so as to facilitate comparisons of vulnerability of CARICOM nations with SIDS and other developing countries. The geospatial data sets used in this analysis were updated where new data were available and additional impact indicators (e.g., key tourism and transport infrastructure) were added. The major methodological procedures are outlined below along with the sources of the geospatial data sets used in the analysis (Table 7)

2.3.1.1 STUDY AREA AND COUNTRY BOUNDARY PREPARATION

A study area polygon was created for the greater Caribbean region. The study area polygon was used to clip large global datasets to improve processing time and reduce data redundancy. CARICOM country boundaries were derived from the National Geospatial Intelligence Agency's World Vector Shoreline data set. All inland lakes, wetlands and ponds were masked out using geospatial data obtained from version 2 of the Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GHHS).

2.3.1.2 DATA INSPECTION AND MAPPING PROJECTION

Due to the small area of many of the CARICOM nations, careful inspection for data completeness was performed for all of the geospatial data files listed in Table 7. All of the vulnerability indicator datasets were collected from public sources (all sources are identified in Table 7). Approximately 5,000 unnamed country boundary polygons (mainly small islands) were inspected and subsequently updated with corrected country identifications. Similarly, all airport runways and urban extent polygons were inspected by overlaying data over aerial imagery as well as GAE-2 urban extent data to ensure correct boundary assignment. Finally, airport and seaports inspected by cross-referencing data with Google Earth Pro © to ensure correct locations of all point features.

After inspection, all of the geospatial data was projected using the World Equal Area projection. The horizontal datum used for the study was the World Geodetic System 1984. Latitude and longitude geographic coordinates are presented in decimal degrees unless otherwise noted.

Table 7: GIS Data Sets Utilized in SLR Analysis

Dimension	Dataset Name	Unit	Resolution	Source(s)
Coastline and country Boundary	WVS	km^2	1:250,000	NOAA/NASA
Elevation	SRTM 90m DEM V4 (sinks filled)	km^2	90m	CIAT
Population Data (2010 Projections)	glp10ag	Population Counts (millions)	5km	CIESIN
Economic Activity	GPD2000	Million US Dollars	5km	World Bank, based on Sachs et al. (2001).
Urban extent	Global Rural-Urban Mapping Project – 1	km^2	1km	CIESIN
Agricultural Extent	GAE-2	km^2	1km	International Food Policy Research Institute
Wetlands	GLWD-3	km^2	1km	Bernhard Lehner, World Wildlife Fund US
Lakes, and Water Bodies	GHHS	km^2	1:250,000	Global Self-consistent, Hierarchical, High-resolution Shoreline Database
Global Airports	Digital Aeronautical Flight Information File)	Count	n/a	National Imagery and Mapping Agency
Global Airport Runways	DIAFF	km^2	1:250,000	National Imagery and Mapping Agency
Roads	VMap Worldwide Vector Data (v5)	Km (length)	1:250,000	LandInfo Worldwide Mapping
City areas	VMap Worldwide Vector Data (v5)	km^2	1:250,000	LandInfo Worldwide Mapping
Major Tourism Resorts	UW SLR Data	Count	n/a	University of Waterloo
Ports of the Wider Caribbean	NIMA World Port Index	Count	n/a	World Resources Institute (Burke et al. 2004)
Aerial Imagery	UW SLR Data	n/a	Varying Scales	Google Earth Pro©

2.3.1.3 CREATING THE COASTAL DIGITAL TERRAIN MODEL (DTM)

The coastal digital terrain model was derived using tiles from the current (version 4) CIAT SRTM 90 metre grid cell digital elevation model (DEM). A continuous sink filled DTM was established by creating a mosaic of all required tiles in ArcGIS.

2.3.1.4 CREATING SLR FLOOD SCENARIOS

Six flood scenarios (1 to 6 metres) were created by converting the sink filled DTM into a series of binary raster files. Within each flood scenario, all inland elevation pixels were manually masked out to ensure that only contiguous coastal pixels were included in the analysis. Inland pixels that could be flooded through riverine connections to the sea were not included in this analysis, contributing to the conservative nature of the impacts estimated by this analysis.

2.3.1.5 CALCULATING VULNERABILITY ESTIMATES

Vulnerability estimates were calculated by overlaying the DTM on the applicable surface datasets. Four GIS models were built to calculate the total effected values for each type of surface dataset. For the purpose of this study, an assumption was made that raster cell values contained an evenly distributed relation.

i) Polygon area (land area, city areas, airport runways, agriculture, wetlands)

Polygon features (within the study area) are overlaid with the DTM using Hawth's Analysis Tools for ArcGIS (Beyer 2004). Using the results from the Hawth's tool analysis affected cells counts are converted into square kilometers to estimate the total area affected by sea level rise for each polygon. The total affected area for each scenario is then summarized by country using ArcGIS.

ii) Polygon percentage (Economic Activity, Population)

A separate GIS model was created for gridded data with non-spatial pixel values (millions of dollars and people). Raster cells were converted to polygon features and rounded to the closet value. An overlay and Hawth's analysis was used to determine the amount of impacted DTM cells within each polygon. Population and economic estimates were then calculated using the following formula:

$$P / T * 100$$

P = The amount of affected cells in a polygon for a given flood scenario.
T = The total amount of cells within the polygon.

iii) Lines (Road network)

A GIS model was created which identified road segments affected by flooded DTM cells. The lengths of each road segment was then calculated and summarized by country for each scenario in ArcGIS.

iv) Points (Major Tourism Resorts, Seaports, Airports)

A 50 metre buffer was applied to all surface point features. Point features that intersected with at least one flooded DTM cell were identified as vulnerable.

2.3.1.6 ADJUSTING VULNERABILITY ESTIMATES

In some instances, countries had accurate data pertaining to land area, economic activity (GDP) and population. The methods used in this study to adjust estimated values to known country totals were based on Dasgupta et al. (2007) to facilitate international comparisons. The following formula was used:

Vadj = CTmea/ CTcal* Vcal

Where:

Vadj = Exposed value adjusted;
Vcal = Exposed value calculated from vulnerability estimates;
CTmea = Country total obtained based on statistics;
CTcal = Country total calculated from surface datasets.

While there remains considerable uncertainty related to the magnitude and timing of both climate change and SLR, the previous discussion indicated that the most recent studies on SLR project a range of 1-2m over the 21st century. The impacts of both a 1m and 2m SLR scenario are discussed in detail below. To examine vulnerabilities associated with the combination of SLR and storm surge, the potential impact of a 3m storm surge (recorded in several parts of the Caribbean during category 4-5 hurricanes) superimposed on a 2m SLR is also discussed. The impact of greater SLR and storm surge (3m to 6m) associated with long-term equilibrium response of sea levels to climate change under higher GHG emissions is also explored below.

2.3.2 CARICOM NATIONS MOST VULNERABLE TO SLR

The analysis revealed that the impacts of SLR would not be uniform among the CARICOM nations, with some projected to experience severe impacts from even a 1m SLR. The differential vulnerability can be largely explained by the geophysical characteristics of the islands and their different coastal topographic settings, which are briefly summarized below and in Table 8. A more detailed examination of the individual impacts to various industries and land classifications is provided for the six most vulnerable countries (Antigua and Barbuda, The Bahamas, Belize, Guyana, Suriname, and Jamaica).

Table 8: Summary of the vulnerability of islands with different topographical characteristics

Topographic Setting	Key Vulnerabilities	CARICOM Members
Coastal plain below 10m and low lying islands	1.Flooding from storms and tsunamis 2.Inundation from high tidal levels 3.Salt water penetration of ground water reservoir	Guyana, Suriname, Belize, Jamaica (locally), Haiti (locally), Barbuda, Bahamas
Coastal mangrove swamp	1.Erosion by storms 2.Erosion by waves during high tides	Guyana, Suriname, Belize, localised areas in other countries, e.g. Antigua, Barbados, Trinidad
Coastal dunes	1.Erosion by storms and tsunamis	Bahamas, Barbuda
Coral reefs	1.Erosion by storms and tsunamis 2.Bleaching	Bahamas, The Grenadines, local areas in Barbados, St Lucia, The Grenadines, Belize
Volcanic island coasts	1.Beach erosion 2.Landslides (locally)	Dominica, Grenada, St Kitts and Nevis, St Lucia, St Vincent, Montserrat

Antigua and Barbuda: Antigua is an island of approximately 280km^2 and Barbuda occupies an additional 160km^2. The islands contrast markedly in topography, Antigua being hilly, rising to 402m and with a rugged coastline, whilst Barbuda is much lower, reaching only 44m, and with a coastline marked by lagoons and dunes. The total population for islands is 70,000.

Both islands are vulnerable to coastal flooding from sea level rise and storms, and in recent years have seen increases in both sea levels and hurricanes. Peltier and Fairbanks (2006) have observed that this north-eastern part of the Caribbean lies close to the mean for global sea surface rise, so that the present mean global figure of +3.1mm/year (IPCC, 2007) is probably close to reality for Antigua and Barbuda. Given that many authorities estimate a significant increase in the rate of SLR by the end of the present century, to +4mm/year or perhaps as much as +6mm/year, it can be inferred that this increase will also apply to Antigua and Barbuda. In addition, hurricane activity in the Caribbean has increased in recent years, and although this trend may not continue in future years. With increased SLR and increased hurricane activity, Antigua and Barbuda will face increasing frequency of coastal inundation in future years.

Many areas of the coast are backed by mangroves and sea-grass beds: these habitats will retreat landward in the face of SLR, but if there is no space for them to retreat to, they will become narrower and therefore in danger of disappearing in some areas. Mangroves in particular can provide protection against inundation by storms and tsunamis. If they are degraded the consequences in some areas may be significant. Furthermore, with increasing hurricane activity further degradation of reefs may occur. Corals and coral reefs are likely to keep up with sea level rise if they remain healthy, but this growth will be challenged by local pollution and acidification.

In Antigua and Barbuda, areas of low-lying coast under threat of inundation include Parham, around Fitches Creek Bay and Parham harbour. Also, substantial areas around the capital St. John's, where large areas of reclaimed land exist, are vulnerable (See Figure 9).

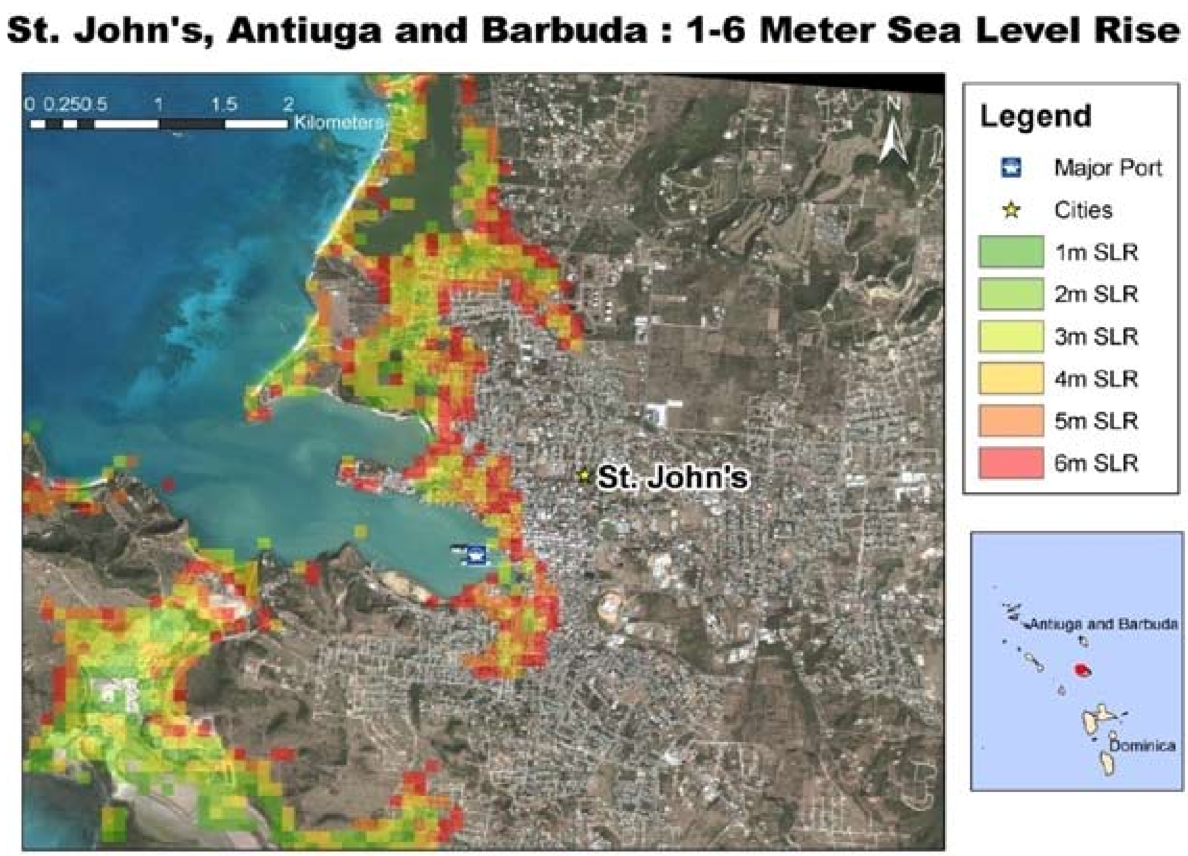


Figure 9: Map of St. John's, Antigua showing areas impacted by sea level rise

Table 9: Impacts of Sea Level Rise for Antigua and Barbuda

Antigua & Barbuda	1 m SLR	2 m SLR	3 m SLR	4 m SLR	5 m SLR	6 m SLR
Land Area	1%	2%	4%	7%	11%	16%
Population (2010 est.)	2%	3%	5%	8%	11%	13%
Urban Area	1%	2%	%	%	%	%
Wetland Area	1%	2%	5%	6%	7%	9%
Agricultural Land	1%	1%	2%	5%	7%	11%
Crop and Plantation Land	0%	1%	2%	5%	8%	11%
Major Tourism Resorts**	9%	27%	36%	63%	82%	91%
Airports	0%	0%	100%	100%	100%	100%
Road Network	1%	1%	1%	3%	6%	8%
GDP(2008 est.)	2%	3%	4%	6%	9%	11%

** Please note that these are "major" tourism resorts, and not ALL tourism resorts.

Table 9 provides a summary of the specific impacts of SLR by economic sector and land classification at one metre increments of SLR. With a 1m increase in sea level, Antigua and Barbuda remains relatively safe in all examined industries except tourism, where 9% of the major tourism resorts will be severely affected. The impact of rising sea levels may be greatly felt in tourist areas, notably at Dickinson Bay, Elys Bay, and Winthorpes Bay. Many hotels in these areas are low-lying and will be affected by increased flooding. Tourism resorts remain the most highly affected sector with a 2m increase in sea level. With a 3m increase in sea levels or storm surge, the Antigua International Airport will have 100% of its function affected. The loss of this important infrastructure will have ripple effects on the economy and international trade for Antigua and Barbuda.

Although, very few urban areas will be impacted by sea level rise, the primarily rural nature of habitation on these islands will affect all people; whether directly in loss of property or indirectly in reduction in food supply and international trade. Although the loss to GDP is just over 1%, that results in a loss of US $24,291,040.00, which is quite significant for a small island nation that is dependent on its natural resources.

The Bahamas: The Bahamas is an archipelago that consists of 700 islands and 2300 cays and rock outcrops, with a total area of 13,939km^2. The islands are low and flat, rising to the greatest elevation at Mount Alvernia on Cat Island (63m). The total population was 306,000 according to the 2000 census. Ninety percent of the population lives on just three of the islands: New Providence, Grand Bahama and Abaco. As sea levels raise an increasing percentage of the populations will be at risk to flooding and coastal erosion. With a 1m increase in the sea levels will affect 5% of people, a figure that drastically increases up to 42% in the ranges beyond 3m (see Table 10).

In his Earth Day message, in April 2009, the Hon. Earl D. Deveaux, Minister for the Environment in the Bahamian Government, observed that The Bahamas are vulnerable to global warming, citing the low lying topography. With a coastline of 3542km in length, the islands will be severely affected by increases in sea level and hurricane activity. Eighty percent of the land surface is 1m or less above sea level. Fresh water on the islands is obtained from shallow lenses of water, which will suffer increasing salinisation with a rising salt water table as sea level rises. Additionally, the impact of hurricanes will increase as sea level rises. Coastal mangrove areas, which provide protection against storms and hurricanes, may decrease as sea level rises, leaving the primary landmass of the islands more exposed. Storminess and bleaching may degrade fringing coral reefs, further increasing the vulnerability of the coastline.

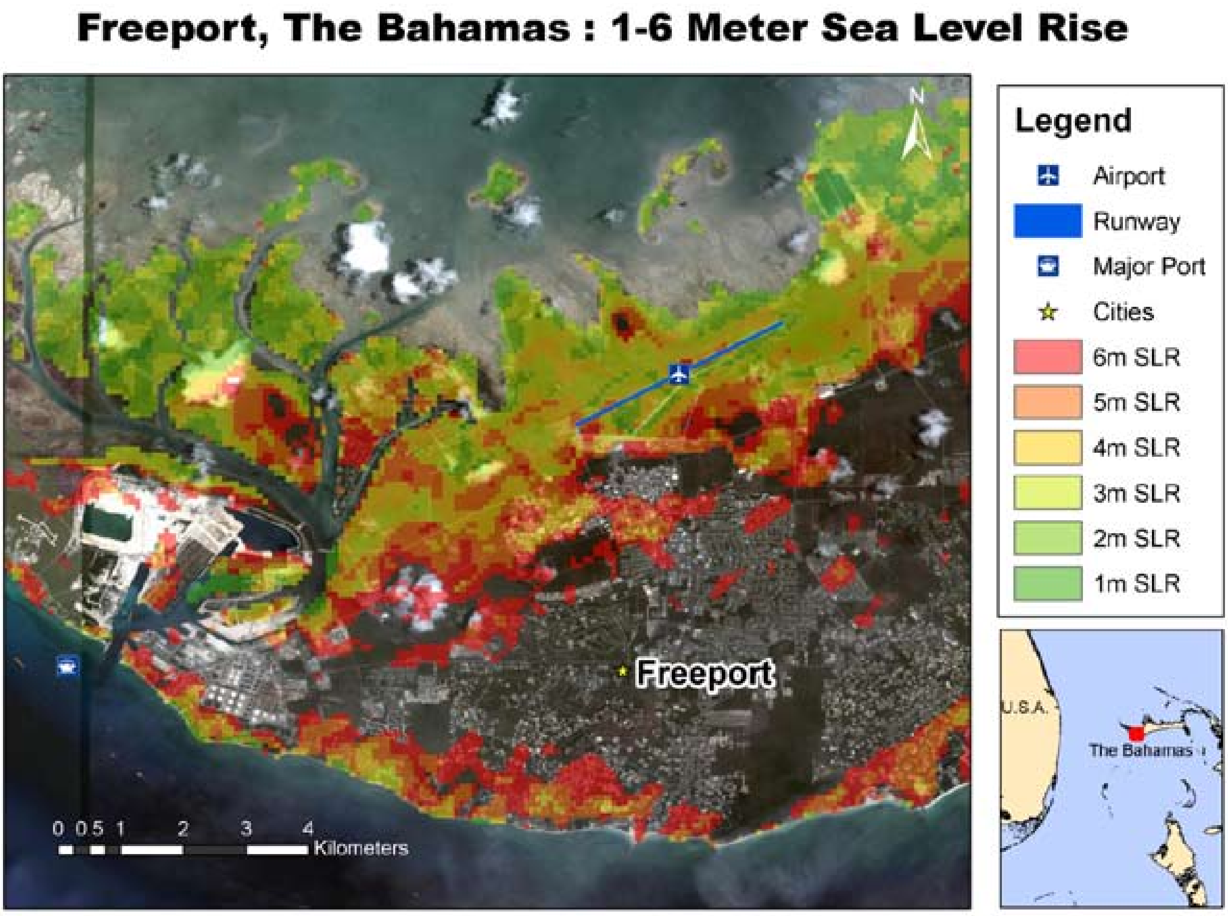


Figure 10: Map of The Bahamas showing areas impacted by sea level rise

The islands are formed from a carbonate platform as a result of historical upward land movements of coral reefs. The Bahamas has five percent of the world's coral reefs surrounding its islands which makes for shallow, clear water, ideal for snorkelling and fishing. This sub-surface topography affects ocean habitats and is also an important yet vulnerable feature in the tourism industry for the islands. Corals and coral reefs are likely to keep up with sea level rise if they remain healthy, but this health will be challenged by local pollution and acidification.

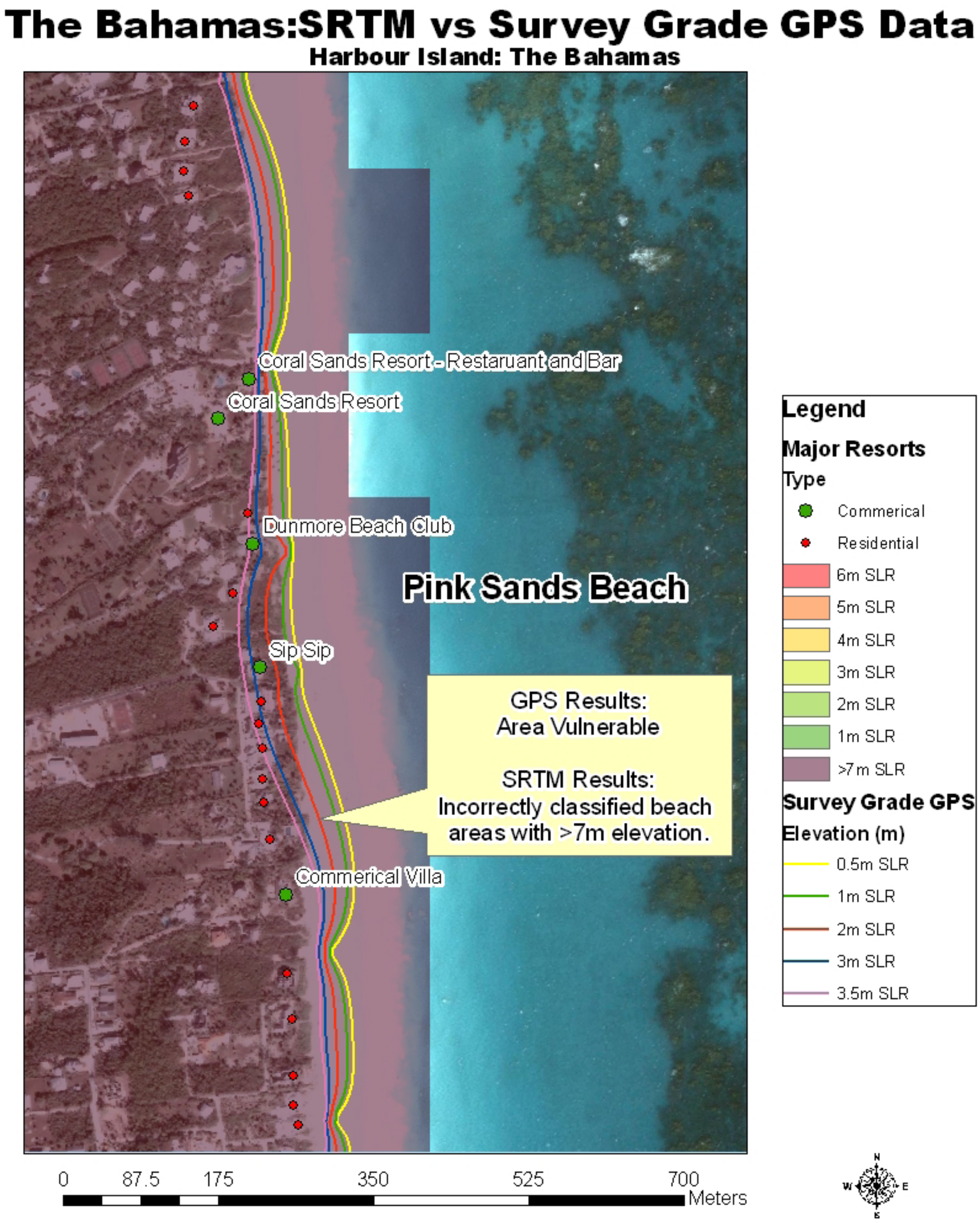


Figure 11: A Comparison of SLR and Storm Surge Vulnerability Using both Satellite-based DEM ($90m^2$) and High-Resolution GPS-based Elevation Data (Harbour Island, The Bahamas)

Table 10: Impacts of Sea Level Rise for The Bahamas

The Bahamas	1 m SLR	2 m SLR	3 m SLR	4 m SLR	5 m SLR	6 m SLR
Land Area	10%	17%	30%	50%	68%	81%
Population (2010 est.)	5%	8%	12%	19%	29%	42%
Urban Area	3%	7%	13%	23%	33%	44%
Wetland Area	15%	23%	41%	65%	78%	84%
Agricultural Land	3%	7%	14%	34%	38%	51%
Crop and Plantation Land	2%	6%	11%	21%	36%	53%
Major Tourism Resorts**	9%	11%	24%	26%	35%	50%
Airports	13%	25%	38%	69%	81%	91%
Road Network	2%	6%	11%	19%	30%	43%
GDP (2008 est.)	4%	8%	12%	19%	29%	42%

** Please note that these are "major" tourism resorts, and not ALL tourism resorts.

Table 10 provides a summary of the specific impacts of SLR by economic sector and land classification at one metre increments of SLR. Because of their topography and the location of vital infrastructure, The Bahamas is vulnerable to even a 1m increase in sea level. The location of Grand Bahamas International Airport and other airports, near the coast, means that 25% of airports would be affected by SLR of 2m and a massive 91% is at risk to storm surge of 6m. Road networks are less vulnerable but will still be affected by SLR. Eleven percent of the road networks across the island chain will be affected by 3m increases in sea surface levels and a further eight percent is affected by an additional 1m increase.

The natural environmental features in this island chain are at risk to SLR. The shallow nature of the shores of the Bahamas archipelago means that mangroves and grasslands will have to move inland with even small rises in sea levels. Fifteen percent of wetlands are at risk to a 1m rise in sea level. Agricultural activities in The Bahamas face challenges from SLR as well, although they are relatively well protected to 3m increases. Crop and plantation lands are most at risk in the range of 4 to 6 metre increases. Finally, impacts to GDP are also important to note. The impacts of 1m of SLR will lead to a 4% loss in GDP, or US $ 421,488,795.00, primarily this will be from lost agricultural productivity and from lost tourism, however the impacts will likely be felt in all parts of The Bahamian economy.

As described above, the Bahamas are particularly vulnerable to SLR, and although increases in hurricane frequency are uncertain, the impact of both hurricanes and tropical storms will be exacerbated as sea level rises because of the topography of this island chain and the surrounding bathymetry.

Belize: Belize occupies an area of some 21,400km^2 on the eastern coast of Central America. The coastline is flat with mangrove swamp and many lagoons, especially in the northern and central parts of this continental country. A coastal plain 40km wide stretches as far as the Maya Mountains, where the highest peak of Doyle's Delight (1124m) is found in the Cockscomb Ridge. The underlying solid geology of Belize is limestone. The population of Belize was 297,651 according to 2007 estimates.

The extensive coastal plain of Belize lies largely below 20m above sea level, with substantial areas below 10m and many denoted "subject to inundation" on hazard maps. Along the river valleys, notably the Belize River, there are vast areas below 10m which are also subject to inundation. Major roads are likely to be affected by inundation from sea level rise, including the New Northern Highway and the Old Northern Highway. Moreover, much of the northern part of the capital, Belize City, is on land below 10m, and thus will potentially be affected by SLR.

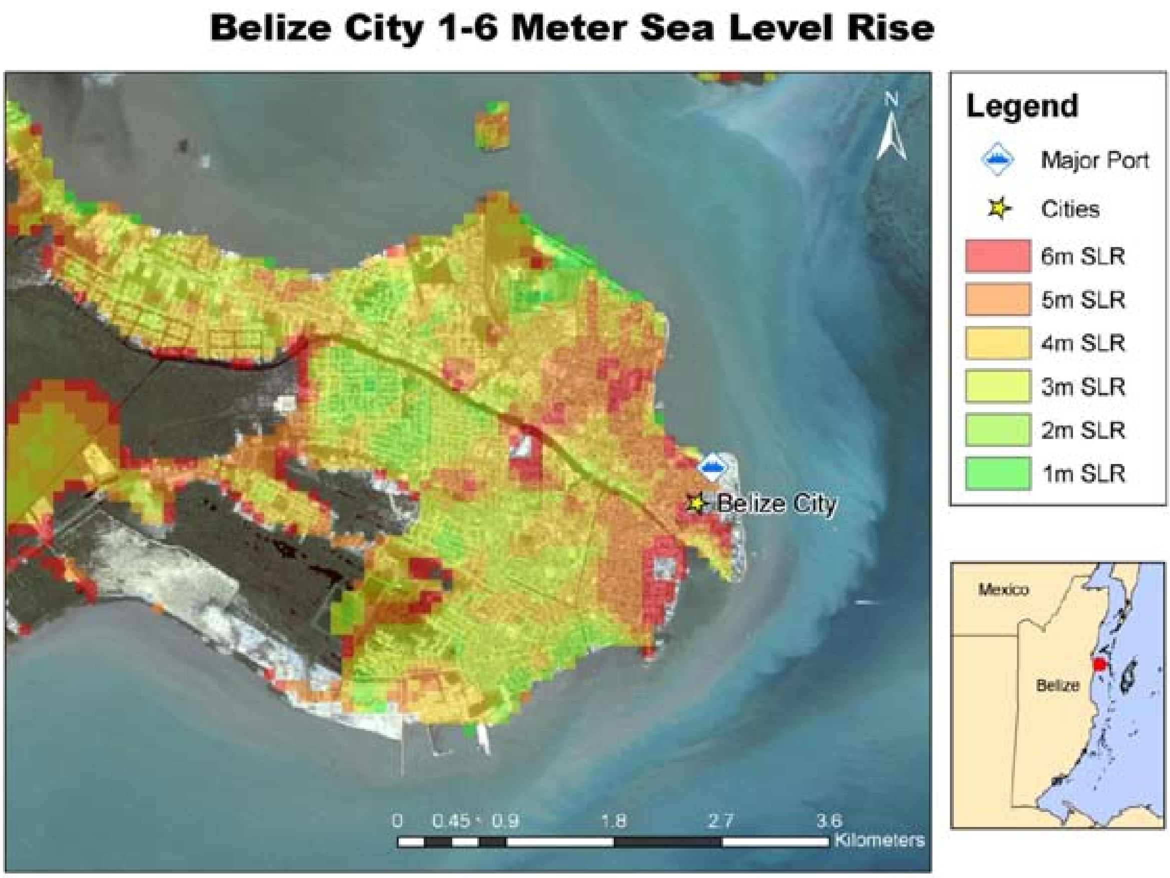


Figure 12: Map of Belize showing areas impacted by sea level rise

As a result of its topography, notably the large coastal plain, Belize is extremely vulnerable to SLR. It is also vulnerable to hurricanes and tropical storms originating in both the Pacific Ocean and the Caribbean Sea. A study of sea level change over the last 20,000 years by Toscano and Mackintyre (2003), using both coral and mangrove peat data, indicates that sea levels are rising at a present estimate of around 3.1mm/year globally. Given the past and present records of sea level change for Belize, the wide coastal plain, with its mangrove areas, is vulnerable to a changing climate that is likely to produce rising sea levels.

Belize has not been affected by hurricanes as much as some other areas of the Caribbean, but when hurricanes have struck, they have often been devastating. This is probably due to the size of the low-lying coastal plain. A study of hurricane activity by Naquivi and Alexander (2009) indicates that hurricane activity increases during La Niña years and decreases during El Niño, and that it is related to changes in SST. As sea level rises, the impact of hurricanes will increase, peaking during La Niña years then decreasing during the El Niño part of the ENSO cycle. Given its coastal topography, Belize will be affected more severely than many countries of the Caribbean. There are also "Northers", which although less extreme than hurricanes, may also lead to increases in precipitation and flooding. Tropical Storms may also cause increased coastal erosion.

Several studies have drawn attention to the impact of beach erosion during hurricanes and tropical storms, as well as to the effect of these storms on coastal mangrove areas (Coastal Zone Management Authority and Institute, Belize). Degradation of mangroves is particularly disconcerting since this fragile ecosystem acts as a protective area along the coast.

Table 11: Impacts of Sea Level Rise for Belize

Belize	1 m SLR	2 m SLR	3 m SLR	4 m SLR	5 m SLR	6 m SLR
Land Area	1%	3%	4%	5%	7%	8%
Population (2010 est.)	3%	6%	9%	11%	13%	15%
Urban Area	1%	4%	8%	12%	18%	22%
Wetland Area	17%	40%	45%	49%	66%	69%
Agricultural Land	1%	3%	5%	8%	10%	13%
Crop and Plantation Land	0%	2%	4%	5%	6%	13%
Major Tourism Resorts**	33%	33%	50%	67%	67%	83%
Airports	0%	0%	100%	100%	100%	100%
Road Network	0%	1%	3%	5%	7%	10%
GDP (2008 est.)	2%	5%	7%	10%	11%	13%

** Please note that these are "major" tourism resorts, and not ALL tourism resorts.

Table 11 provides a summary of the specific impacts of SLR by economic sector and land classification at one metre increments of SLR. Because of its topography and the location of vital infrastructure, Belize is vulnerable to even a 1m increase in sea level. The location of major tourism resorts near the coast, means that 33% would be affected by SLR of 1m and a massive 83% is at risk to SLR of 6m. Urban areas, road networks and the population are less vulnerable but will still be affected by SLR. Nine percent of the population will be affected by 3m increases in sea surface levels and a further six percent is affected by an additional 3m increase in sea levels.

The natural environmental features in Belize are also at risk to SLR. The shallow nature of the shores and the large coastal plain make 17% of wetlands vulnerable to a 1m rise in sea level. Agricultural activities in Belize will face the challenges of SLR as well, although they are relatively well protected to the threat of a 2m increase in sea level. Crop and plantation lands are most at risk in the range of 4 to 6 metre increases with 13% being at risk in this range. Finally, impacts to GDP are also important to note. The impacts of 1m of SLR will lead to just over a 2% loss in GDP, or US $ 61,373,301.00, primarily this will be from lost tourism, however the impacts will likely be felt in all parts of Belize's economy.

Thus, although less publicised than many countries, Belize is extremely vulnerable to sea level rise and hurricane activity. Climate change will undoubtedly have a serious impact upon coastal Belize.

Guyana: Guyana occupies an area of 214,970km^2, including has a coastline of 459km. Its highest point is Mount Roraima, at 2835m. Its population was estimated to be 765,263 in 2008. Geologically, the country consists of Precambrian shield rocks and along the coast it is overlaid with sedimentary rocks from the Cretaceous period and some more recently formed. The coastal plain, which occupies about 5% of the country's area, is home to over 90% of Guyana's inhabitants. The coastal plain ranges from 5 to 6km in width, occupying several thousand km^2 and comprised largely of silts and clays with thin layers of peat, overlying white sands derived from erosion of the bedrock. South of the coastal plain, the white sand belt is 150-250km wide and consists of low sandy hills interspersed with rocky outcrops.

Guyana is particularly susceptible to sea level rise, since the coastal plain is near sea level and much of this region becomes flooded during high tide. Toward the sea the clays and silts of the coastal plain transition into areas of marsh and swamp and further into the sea is a region of inter-tidal mudflats and sandbars. Offshore from the city of New Amsterdam, the mud flats extend for almost 25km. Much of the coastal plain was reclaimed by the Dutch, beginning in the eighteenth century. These areas are particularly vulnerable to sea level rise, a risk exacerbated by storms associated. Guyana lies south of the hurricane belt and thus is less vulnerable to erosion and beach loss, however, it's vulnerability to SLR is severe because of its elevation.

From nearby Suriname, Roeleveld and van Loon (1979) showed that sea levels reached their present height around 7000 years ago and have changed little since. A similar record is probable for Guyana. However, it is very likely that Guyana is already, and will in the future, experience a rise in sea level greater than anything experienced in the last 7000 years. The coastline lies in an area where the level of the sea surface is close to the global mean. The IPCC 2007 report showed that, in the then latest figures available, for 1993-2003, the mean global sea surface was rising by 3.1mm/year. This figure is likely to be close to that for the Guyana coast. Further, the rise is likely to increase in the future according to many authorities (see Section 2.1) and any rise would be very serious for the Guyana coastal plain.

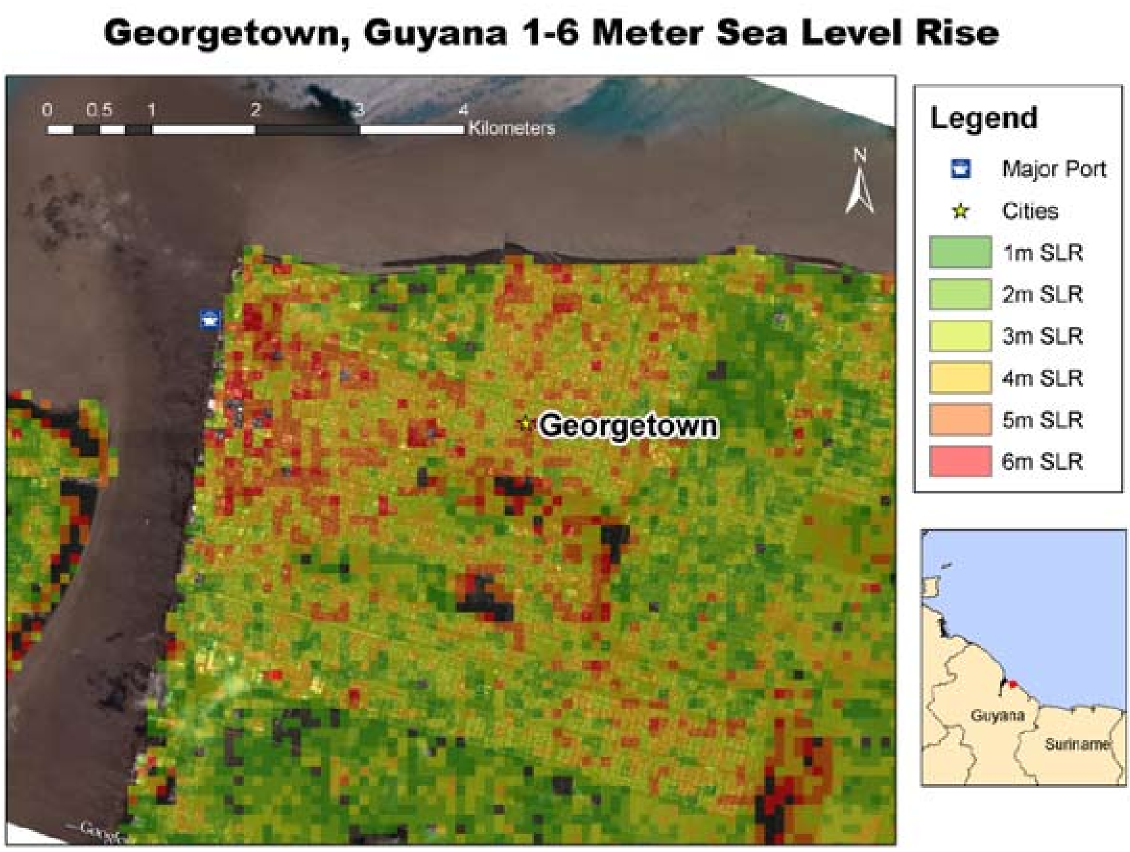


Figure 13: Map of Guyana showing areas impacted by sea level rise

Further, if expectations of increased storminess were realised, the already vulnerable coast would be threatened. Sea level rise and increased storminess may cause changes in currents in the near shore environment, affecting the deposition of sediment, presenting hazards for shipping.

Table 12: Impacts of Sea Level Rise for Guyana

Guyana	1 m SLR	2 m SLR	3 m SLR	4 m SLR	5 m SLR	6 m SLR
Land Area	0%	1%	1%	2%	2%	3%
Population (2010 est.)	3%	8%	17%	25%	30%	32%
Urban Area	8%	21%	38%	48%	56%	60%
Wetland Area	1%	3%	6%	9%	11%	14%
Agricultural Land	1%	2%	4%	5%	6%	7%
Crop and Plantation Land	0%	0%	0%	0%	0%	0%
Major Tourism Resorts**	50%	50%	75%	100%	100%	100%
Airports	0%	0%	0%	0%	0%	0%
Road Network	6%	14%	24%	30%	33%	35%
GDP (2008 est.)	3%	8%	17%	25%	30%	32%

** Please note that these are "major" tourism resorts, and not ALL tourism resorts.

Table 12 provides a summary of the specific impacts of SLR by economic sector and land classification at one metre increments of SLR. Because of their topography and the location of vital infrastructure, Guyana is vulnerable to even a 1m increase in sea level. The location of major tourism resorts in the low-lying coastal plain means that 50% would be affected by SLR of 1m and 100% is at risk to SLR and storm surge of 6m. Urban areas, road networks and the population are less vulnerable but will still be affected by SLR. Six percent of the road networks will be affected by a 1m increase in sea surface levels and a further seven percent is affected by the next 1m increase in sea level. A significant 38% of the urban areas in Guyana will be impacted by an increase of 3m to the level of the sea. The road networks are affected with every incremental rise in sea level but the 3m increase in sea level is the most significant as it will cause the loss of one quarter of roads in the country.

The natural environmental features in Guyana are also at risk to SLR. Because of the low-lying nature of the shoreline and the large coastal plain, agricultural and wetland areas are vulnerable to SLR. Crop and plantation lands and airport infrastructure are the only areas of Guyana that are not at risk to SLR. Finally, impacts on GDP are also important to note. The impacts of 1m of SLR will lead to almost a 3% loss in GDP, or US $ 86,716,167.00, primarily this will be from lost tourism resorts, however the impacts will likely be felt in all parts of the Guyanese economy.

Suriname: Suriname occupies an area of 163,800 sq km and has a coastline of 386km along the northern shore of South America. There is a wide coastal plain, much of it below 5m. The land raises inland to the highest mountain, Juliana Top, which reaches 1230m. Geologically, the country is underlain by rocks of the Guyana Shield, comprising igneous and metamorphic rocks. These rocks are overlain by sands and silts, which form the coastal plain, where 85% of the population lives. The total population in 2009 is 481,267.

Suriname, like Guyana, is vulnerable to coastal flooding on a large scale. The low, swampy coastal plain is up to 16 – 80km wide and covers 10,000 sq km. This plain is the primary location for agriculture; systems of dykes, canals and pumps, originally developed by the Dutch, drain the land and supply water during the wet seasons. Fresh water flowing to the coast is canalised. Toward the sea are wide forests of mangroves. The canalisation of the rivers has caused deterioration of some mangrove areas, and coastal erosion has led to some breaching of the dykes. Changes in the mudflats beyond the reclaimed coastal plain may have played a role in the erosion of the coast.

Suriname is extremely vulnerable to sea level rise and storms. As study by Roeleveld and van Loon (1979) showed that sea levels along the coast reached present levels about 7000 years ago and have not varied greatly since. The mean global estimate for sea level rise is 3.1mm/year based on data from 1993-2003. There is reason to expect that the rate of increase along the coast of Suriname will be close to this estimate, thus Suriname will become increasingly vulnerable to flooding and coastal erosion because of the nature of the topography along the coast. Furthermore, this rise would bring changes to the peri-marine environment, perhaps leading to changes in currents and in tidal parameters which might lead to serious coastal erosion, the further breaching of dykes, and salt water intrusion.

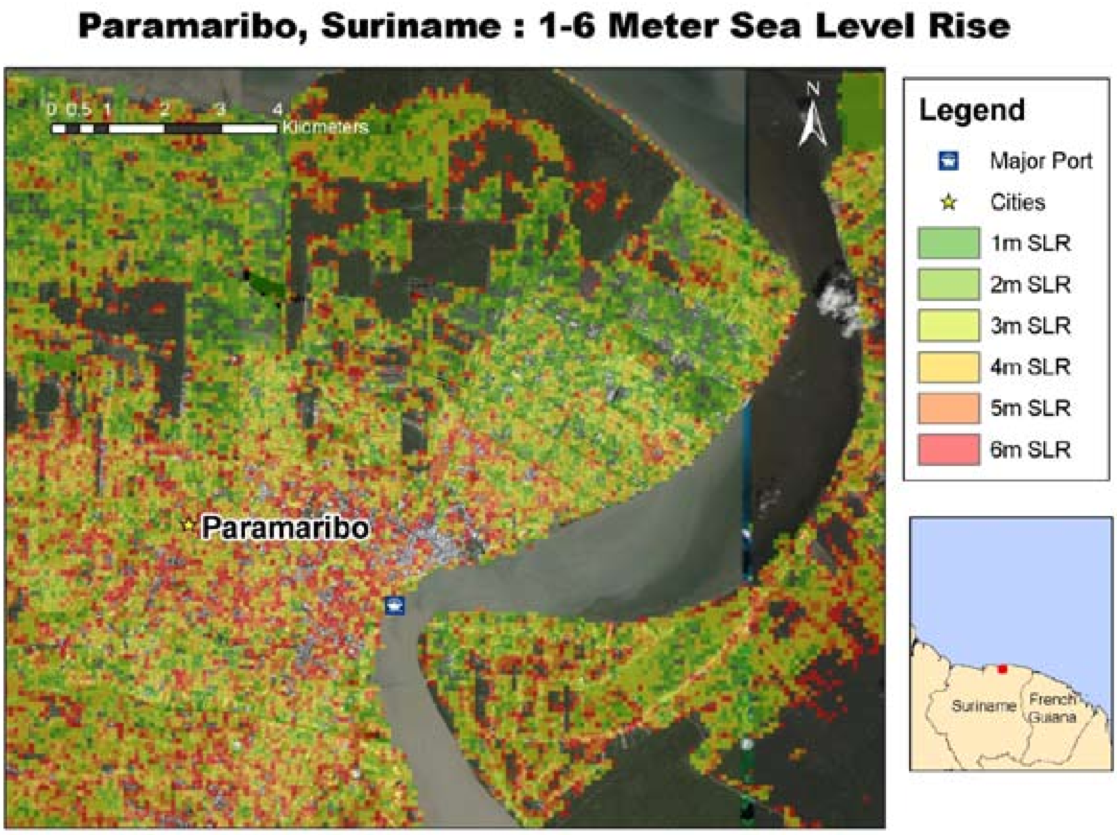


Figure 14: Map of Suriname showing areas impacted by sea level rise

In this context, the offshore mudbanks are relevant. Allison et al. (2000) showed that the mudbanks along the coasts of Guyana, Suriname and French Guyana migrate in a northwesterly direction, probably influenced by variations in trade wind patterns. Finally, given the huge amount of sediment deposited along the coast from the Amazon and other major rivers, the isostatic effect could result in depression of the land surface and a greater relative rise in sea level.

The situation would be exacerbated if storms increase, as has been suggested in a global warming environment. Although the coastline lies south of the hurricane belt, it is not immune to storms.

Table 13: Impacts of Sea Level Rise for Suriname

Suriname	1 m SLR	2 m SLR	3 m SLR	4 m SLR	5 m SLR	6 m SLR
Land Area	0%	1%	2%	2%	3%	3%
Population (2010 est.)	8%	17%	31%	46%	58%	65%
Urban Area	4%	9%	18%	32%	46%	56%
Wetland Area	2%	4%	6%	9%	12%	15%
Agricultural Land	4%	9%	13%	17%	22%	25%
Crop and Plantation Land	0%	0%	0%	0%	0%	0%
Major Tourism Resorts**	0%	0%	0%	100%	100%	100%
Airports	0%	50%	50%	50%	50%	50%
Road Network	4%	9%	14%	18%	21%	24%
GDP (2008 est.)	6%	13%	25%	37%	47%	52%

** Please note that these are "major" tourism resorts, and not ALL tourism resorts.

Table 13 provides a summary of the specific impacts of SLR by economic sector and land classification at one metre increments of SLR. Because of its topography and the location of vital infrastructure, Suriname is vulnerable to even a 1m increase in sea level. Four percent of the road networks will be affected by a 1m increase in sea surface levels and another 10% is affected by the next 2m increase in sea levels. A significant 32% of the urban areas in Suriname will be impacted by increases of 4m in sea level. The road networks are affected with every incremental rise in sea level but the 5m increase in sea level is the most significant as it will cause the loss of one fifth of roads in the country. The impact of sea level rise on the population of this country is also important to note. The population of Suriname will see significant inundation with each incremental rise in sea levels; most notably the 31% that will be affected with a 3m increase.

The natural environmental features in Suriname are also at risk to SLR. Because of the low-lying nature of the shoreline and the large coastal plain, agricultural and wetland areas are vulnerable to SLR. Agricultural land will be continually affected by SLR starting with 4% of cultivated land impacted by +1m and 25% impacted by +6m. Finally, impacts to GDP are also important to note. The impacts of 1m of SLR will lead a 6% loss in GDP, or US $ 278,742,789.00. Primarily this will be from the impact to road infrastructure and affected populations; however, the impacts will likely be felt in all parts of Suriname's economy.

Hence, Suriname, with its wide coastal plain, fundamental in an economic and societal context, is extremely vulnerable to flooding both from rising sea levels and from storms.

Jamaica: Jamaica occupies an area of 10,911km^2 and has a coastline of 1022km (excluding the small cays and islands offshore). The island rises to 2246m at Blue Mountain, and has a population of 2,804,332 as of 2008. The island, part of the Greater Antilles, evolved from an arc of ancient volcanoes, and the volcanic rocks have been overlaid with limestone. The north-eastern coast is rugged, and although there are small inlets, there is no coastal plain. The southern coast has small stretches of plain fronted by black sand beaches, but in the south-west broad plains stretch inland for several kilometres, with swamplands.

Digerfeldt and Hendry (1987) plot the rise of sea level at the coastal wetlands of Negril and Black River, showing that sea level rose rapidly until about 6000 years ago; since then sea levels progressively slowed until present. It is assumed that sea level is rising against the coast of Jamaica, although some tectonic movement of the land upwards is probably taking place (See Sutherland et al., 2009). The total rise is therefore likely to be less than the global mean 3.1mm/year of IPCC 2007.

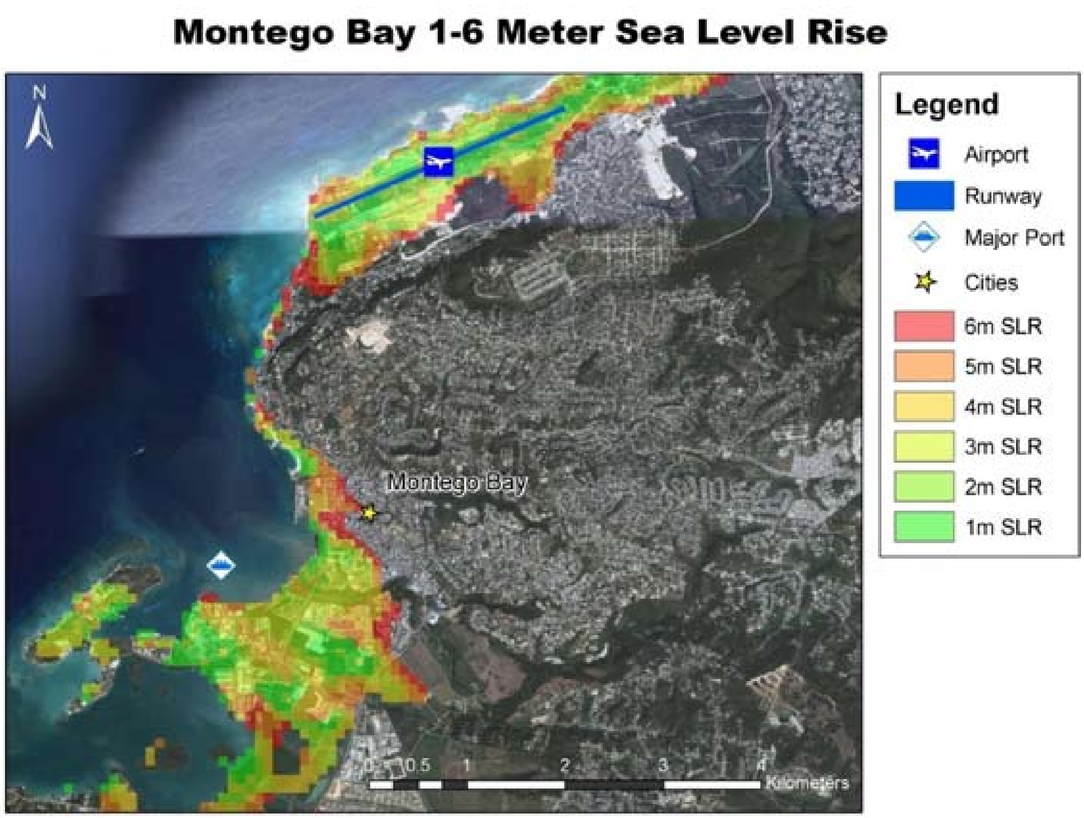


Figure 15: Map of Montego Bay, Jamaica showing areas impacted by sea level rise

Jamaican coasts are vulnerable to the effects of climate change, particularly SLR and increased hurricane activity. Jamaica lies in the Atlantic hurricane belt. Hurricanes are variable in their occurrence both spatially and temporally, but they are thought to be intensifying, so that beaches suffering from erosion are not able to be replenished. An example of this comes from Long Bay Beach, which suffered over 5m of beach loss between Hurricane Ivan, in 2004, and Hurricane Dean in 2007. In addition, coral bleaching and coral reef erosion during increased hurricane activity has both reduced the tourist appeal to some areas and reduced the protective effect of coral reefs. Sea level rise is likely to result in salt water penetration of groundwater locally and increased hurricane and tropical storm activity will result in beach erosion.

Table 14: Impacts of Sea Level Rise for Jamaica

Jamaica	1 m SLR	2 m SLR	3 m SLR	4 m SLR	5 m SLR	6 m SLR
Land Area	1%	2%	2%	3%	4%	5%
Population (2010 est.)	1%	1%	2%	3%	4%	5%
Urban Area	0%	1%	2%	3%	4%	5%
Wetland Area	22%	26%	34%	40%	46%	48%
Agricultural Land	2%	3%	5%	7%	10%	11%
Crop and Plantation Land	2%	3%	5%	8%	11%	12%
Major Tourism Resorts**	4%	4%	10%	29%	54%	73%
Airports	20%	20%	40%	40%	40%	80%
Road Network	1%	1%	2%	4%	5%	6%
GDP (2008 est.)	1%	1%	2%	3%	4%	5%

** Please note that these are “major” tourism resorts, and not ALL tourism resorts.

Table 14 provides a summary of the specific impacts of SLR by economic sector and land classification at one metre increments of SLR. With a 1m increase in sea level, Jamaica remains relatively safe in the examined industries except for wetlands and airports, where 22% and 20%, respectively, will be severely affected. The impact of rising sea levels may be greatly felt in tourist areas as well, 4% of major tourist resorts will be affected by 1m of SLR and a further 25% will be affected by the subsequent 3m increase in sea levels or storm surge. With a 1m increase in sea levels, Jamaica’s airport in Montego Bay as well as other will have 20% of their function reduced (see Figure 15). The loss of this important piece of infrastructure will have ripple effects on the economy and international trade for Jamaica, especially as an additional 60% of the airport function (80% total) is lost with further sea level rise.

The natural environmental features in Jamaica are also at risk to SLR. Because of the low-lying nature of the southern shoreline and the presence of inlets in the northeast, coastal wetland areas are vulnerable to SLR. Agricultural and plantation lands will be continually affected by SLR starting with 2% of cultivated land impacted by +1m and up to 12% impacted by increases of 6m. The population, road networks and urban areas in Jamaica remain relatively safe to the impacts of a changing climate although they do not remain untouched by SLR. The tourism industry is not so fortunate. Although only 4% of major tourism resorts are affected by a 1m increase in sea level, beyond 3m the impacts will be devastating for this industry. A recent vulnerability assessment of Jamaica's beaches by the National Environment and Planning Agency (NEPA) showed that 95% of Jamaica's beaches are vulnerable to sea level rise and storms. Finally, impacts on GDP are also important to note. The impacts of 1m of SLR will cause a 1% loss in GDP, or US $ 181,025,796.00. Primarily, this will impact the airport and damage wetland areas; however, the impacts will likely be felt in all parts of Jamaica's economy.

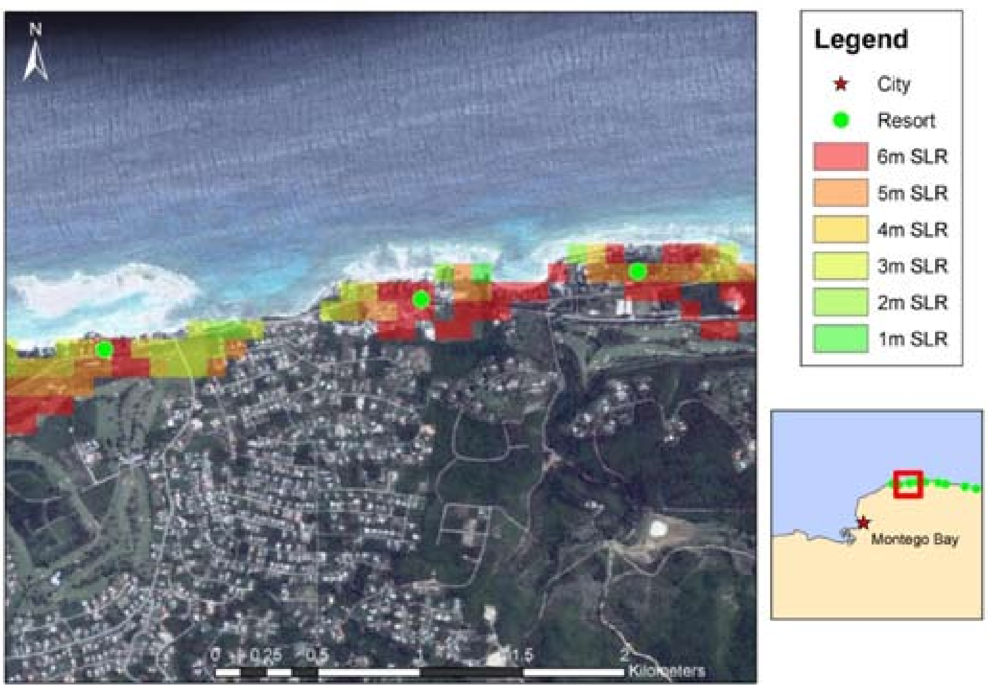


Figure 16: Vulnerability of Major Tourism Resorts in Montego Bay, Jamaica

2.3.3 SLR VULNERABILITY OF OTHER CARICOM NATIONS

The remaining CARICOM States also face varied threats from SLR and a changing climate. The following is a depiction of the topographic features of each nation, along with some of the impacts the country will face as sea levels rise and there is an increase in storms in the Caribbean region.

2.3.3.1 SMALL ISLANDS AND CAYS: CORAL REEF ISLANDS

St. Vincent and the Grenadines: St Vincent and the Grenadines lie in the Windward Islands Chain of the eastern Caribbean. They are comprised of six major, and numerous other islands. The largest island, Saint Vincent, is very hilly and volcanic in origin. It is composed of mainly eroded remnants of several volcanoes, only one of which is considered active (Soufrière) and this rises to 1234m, the highest point on the island. The Grenadine islands are made up of submerged and re-emerged volcanic formations and reef structures. The highest point is on Union Island, where Mount Tobai reaches 308m. The area of St Vincent and the Grenadines is 388km^2; St Vincent itself reaching 344km^2. The total population of St. Vincent and the Grenadines was 115,461 as of the year 2000.

The coastal geomorphology of St. Vincent and the Grenadines is varied (Mills, 2001). On St. Vincent, slopes are steep and the coastal plain is narrow. There is poor reef development offshore of this largest island. Reef development exists in isolated patches on both east and west coasts, limited often by sediment flux, since there are permanent streams on the island, delivering sediment to the coast. In the Grenadines, coral is much more extensive, although in some areas coral is rather degraded. Coastal mangroves are limited, although on Union Island mangroves are extensive. Sandy beaches in St. Vincent are of black volcanic sand except in the south where they are of coralline origin; in the Grenadines the sand is mainly coralline. Seagrass exists off-shore from most reef-protected sandy shorelines in the Grenadines. These coastal features may all be affected by sea level rise and by storms.

There is no detailed information for sea level rise in St. Vincent and the Grenadines, although it may be expected that the mean global current rise of 3.1mm/year is close to the actual value, as has been observed in other nearby islands in the region. Hurricane activity is important in the adaptation and vulnerability of this island chain. In the 132 years prior to 2008, 32 hurricanes came within 60 miles and St Vincent and the Grenadines are brushed by hurricanes on average once every 4.31 years and hit once every 34.50 years National Oceanic and Atmospheric Administration, (NOAA), National Hurricane Center Report. Tropical storms are important as well. Combined with a rising sea level, beaches, mangroves and seagrass areas are at risk, although not as much as some neighbouring islands. The beach erosion study (UNESCO Technical Guide, the World Bank and the Ministry of Agriculture, Lands and Fisheries) states that beaches are not necessarily renewed after a hurricane.

The impact of climate change in St Vincent and the Grenadines through sea level rise and storm (especially hurricane) activity is clear and continuing, and is a cause for concern, although the extent of the vulnerability is uncertain in large part due to data limitations.

2.3.3.2 VOLCANIC ISLANDS[26]

St Christopher and Nevis: St Kitts and Nevis occupy an area of 269km^2: St Kitts is 176km^2 and Nevis 93km^2. Both islands are high and rugged. St Kitts rises to 1156m at Mount Liamuiga, while Nevis rises to 985m at Mount Nevis. The coastline in St Kitts is 78km long. Much of the shoreline of both islands is steep and rugged, but beach areas exist on approximately 20km of the coast. The geology of both islands is of volcanic origin, created by eruptions resulting from the movement of the northern boundary of the Caribbean tectonic plate. The population of St Kitts and Nevis is 40,131 (2009 estimate).

With only small amounts of beach and only low sediment supply from the ephemeral surface streams flowing toward the coast, St Kitts and Nevis are vulnerable to coastal erosion. A rising sea level and increasingly intense hurricane activity would exacerbate coastal erosion. Beaches are vital to tourism, yet the limited supply is highly vulnerable to sea level rise and storms. Further, coral reef areas are vulnerable to increasingly intense hurricanes as well as bleaching (see Section 3.1). Seagrass beds and the few mangroves on the islands are also vulnerable. St Kitts and Nevis will not

26 Saint Vincent was described in the previous section with The Grenadines and will therefore not be discussed here again, it is important to note that it is also of volcanic origin and will see similar impacts as the countries to be discussed below.

lose a large percentage of their land in the event of possible sea level rise and coastal erosion, but will suffer greatly in terms of their economy, society and environment due to losses of very limited coastal lands suitable for tourism or other development.

In a study of beach erosion hazards undertaken by the Organisation of American States, UNESCO Technical Guide, coastal hazard maps were produced at a scale of 1:25000. These identified the highest hazard rated beaches as on the east coast of St Kitts but the west coast of Nevis. The study identified a considerable scale of erosion from recent hurricanes. It could also be added that tsunami activity in the eastern Caribbean might both increase coastal erosion as well as damage infrastructure and involve loss of life. Tsunamis occurring in the context of progressively higher sea levels could be serious for islands like St Kitts and Nevis.

Thus, although St Kitts and Nevis are steep and rugged islands with only narrow coastal areas, rising sea levels and more intense hurricanes that will result from climate change predictions will pose serious problems. The impact of climate change in St. Kitts and Nevis through sea level rise and storm (especially hurricane) activity is clear and continuing, and is a cause for concern, although the extent of the vulnerability is uncertain in large part due to data limitations.

St Lucia: St Lucia occupies an area of 619km^2 and has a coastline of 158km. The island is generally high and steep, rising to 950m at Mt Gimie, although the Pitons, Gros Piton (798m) and Petit Piton (750m) on the west coast of the island are better known as notable features. St Lucia is made up of volcanic rock. The Soufrière volcanic centre has experienced five waves of shallow seismic activity in recent years (Caribbean Disaster Emergency Report, 2003) and concern exists for the possible impacts from future activity. In 2003 the population was estimated to be 149,000.

Sea level rise along the coasts of St Lucia is probably close to the mean global average, 3.1mm/year at the present time. Although, given the known seismic activity on St Lucia, land movement is likely taking place. This might mitigate or exacerbate sea level change, and needs to be examined in more detail. Although the island is generally high and steep, there are several low lying areas, notably in the north-west, and these may be subject to inundation and to salinisation of the water table in the future. Beach erosion will be an increasing problem in future as sea level rises. Monitoring of selected beaches on St Lucia has been carried out by the Fisheries Department and the Physical Planning Department. Several beaches have shown evidence of retreat in recent years, including at Pigeon Island and at Reduit Beach, near vital tourist areas.

Hurricanes have impacted St Lucia several times in the past. National Oceanic and Atmospheric Administration (NOAA), National Hurricane Center Report estimates that the island is brushed every 3.63 years on average, and hit every 19.71 years. Hurricanes have passed within 60 miles of St Lucia 38 times in the last 138 years. Considerable damage has been caused by these hurricanes as well as loss of life. Hurricanes exacerbate the loss of beach, and the Fisheries Department report comments that beaches are not being fully replenished by natural processes after hurricane damage. This limited replenishment of beaches is probably due to the rise in sea level combined with the increasing frequency of hurricanes in recent years, as well as the extraction of sand for building purposes from some areas and the selective building of groynes in other locations (see Figure 17).

The Government of St Lucia's Hazard Mitigation Policy (2006) recognises the problems associated with climate change, and in very recent times these problems have become more severe with the recognition that sea level rise in the future may be more rapid and greater than has been previously estimated. The main impacts are in the degradation of beaches and in local salt water intrusion. The incidence and intensity of hurricanes is probably increasing. Hence St Lucia has serious concerns for climate change in the future.

The impact of climate change in St. Lucia through sea level rise and storm (especially hurricane) activity is clear and continuing, and is a cause for concern, although the extent of the vulnerability is uncertain in large part due to data limitations.

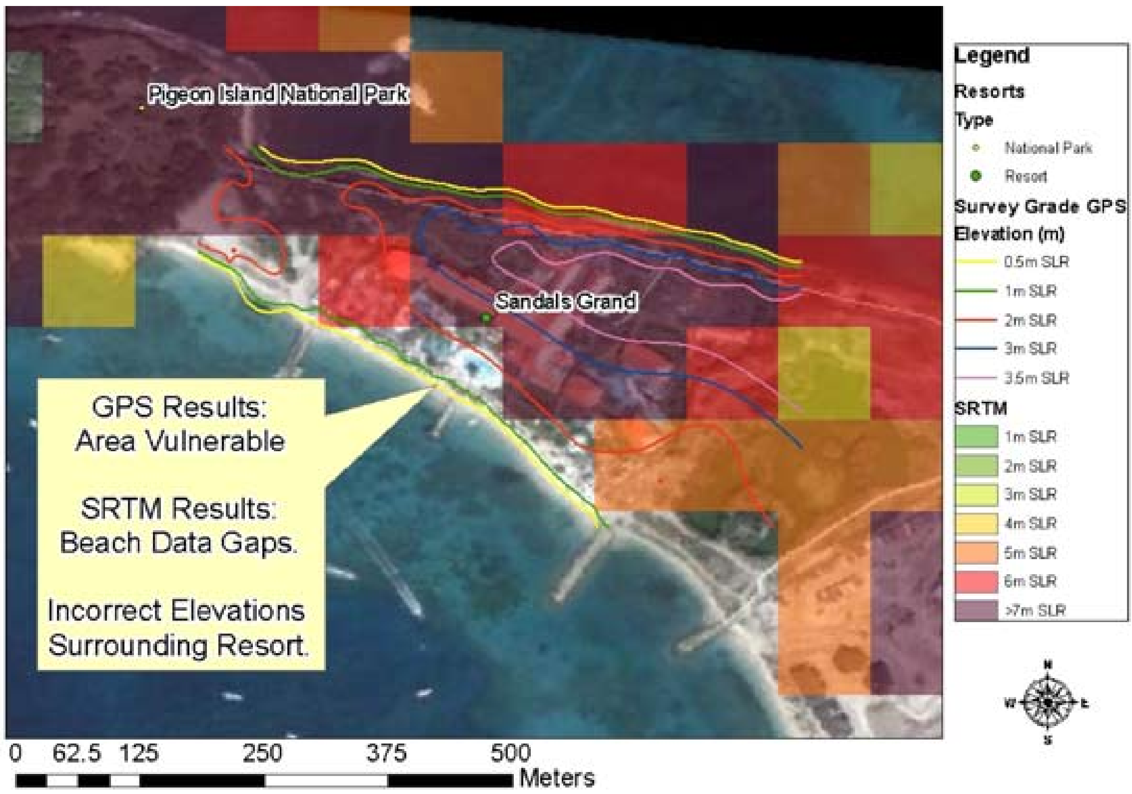


Figure 17: A Comparison of SLR and Storm Surge Vulnerability Using both Satellite-based DEM (90m2) and High-Resolution GPS-based Elevation Data (Gros Iset, St. Lucia)

Grenada: The nation of Grenada consists of three islands: Grenada, Carriacou and Petit Martinique. Grenada occupies an area of 311km^2, and rises to a height of 833m at Mount St Catherine. Carriacou is much smaller, with an area of 34km^2, rising to 291m and Petit Martinique the smallest at 3.2km^2; together the islands occupy 348km^2. The islands are volcanic, consisting of lava flows, ash and pyroclastic deposits with sedimentary rocks locally present. Slopes are steep, and 77% of the land in Grenada have slopes exceeding 20^o while on Carriacou 54% of land exceeds a slope of 20^o. The population for the three islands was estimated at 90,739 in 2009.

Grenada and the other islands are ringed with coral reefs, with extensive mangroves and seagrass beds along coastal areas. The seagrass beds have proven vital in the maintenance of the fisheries industry. An effect of sea level rise is possible salt water intrusion into the ground water table. The small size of these islands and their rather low elevations puts the water table at a high risk to salt water intrusion. The threat of the intrusion of salt water into their vital fresh water supply is of concern because fresh water resources are used for agriculture and other industrial activities as well as supplying the population with their potable water. Although technologies do exist to make salt water drinkable, this is expensive and unnecessary given the recognition of this threat at present. Furthermore, the coral reefs are of fundamental importance to supporting the mangroves and seagrass.

No detailed sea level information exists for Grenada, but as with nearby islands the estimate from IPCC 2007 of the current mean global rise of 3.1mm/year will is a reasonable estimate, given that the nation is in an area where sea surface elevations are close to the mean for the rest of the world according to TOPEX/POSEIDON and JASON 1 satellite measurements. Hurricane activity is somewhat less than that which the islands to the north experience; the NOAA research division commented that in the 138 years to 2008, 51 hurricanes came within 60 miles of Grenada, while the islands have been brushed once every 2.71 years and directly hit every 15.33 years. That said, serious losses to lives and livelihoods have been experienced recently as a result of hurricanes (i.e. Hurricane Ivan, 2004).

Hurricanes combined with SLR have damaged beaches in the island and have also damaged reefs, threatening the survival of mangroves and seagrass beds. The National Science and Technology Council, together with the Fisheries Division, Lands and Surveys Division and Water Resource Unit, have carried out monitoring of Grenada's beaches. It is noted that when Hurricane Lenny struck in 1999, many of the beaches in Grenada, Carriacou and Petit Martinique were severely eroded and surveying at regular intervals has not shown them to have returned to pre-hurricane extents. This effect is in common with other islands, and points to the problems of sea level rise and potential for increasing hurricane activity.

Dominica: Dominica occupies an area of 754km^2 and is a high and mountainous island, rising to 1447m at its highest point, Morne Diablotins. Additionally, Morne Trois Pitons rises to 1423m in the south-west and these peaks are designated as the island's national park. Dominica's coastline measures 148km in circumference. Dominica is a volcanic island and volcanism is evident by the presence of many hot springs. Dominica is rich in water resources and tropical vegetation and its population was 71, 727 in 2003.

With a narrow coastal plain, Dominica might not be thought of as particularly vulnerable to sea level rise; but this is not accurate. Coastal erosion is a major problem that would be exacerbated as sea level rises. Although there are no long-term records of sea level change, and land movement has not been studied in detail, it may be assumed that the IPCC global mean estimate of 3.1mm/year rise at the present time will be close to that actually experienced. This will lead to increased coastal erosion and loss of beaches, or at least, redistribution of sediment along the coast since a rising sea level may result in changes in wave and current activity. Therefore, Dominica is very much at risk to SLR, especially in the coastal plain where erosion is already posing a challenge in the maintenance of the coastal development and ecosystems.

Other major coastal problems result from the impact of hurricanes. According to NOAA, Dominica is brushed by a hurricane every 3.94 years and a direct hit occurs every 23 years. Hurricanes cause loss of life and severe damage to infrastructure, but they also cause loss of beaches. Hurricane David (1979) seriously affected beaches in the south-west, as well as road infrastructure. The Forestry, Wildlife and Parks Division of Dominica and UNESCO have highlighted the problems of beach erosion, producing a checklist for beach and coastline conservation (Chambers, 1998). While beaches might be replenished after a hurricane strike, the frequency of hurricanes may prohibit this rejuvenation of the coastal plain. In addition, hurricanes will be increasingly destructive as sea levels rise; hence determining the frequency and intensity of hurricanes is important.

Thus, although not a low-lying island, Dominica will be affected by climate change as sea level rises and hurricanes may increase. Beaches will suffer as well as communications and buildings. Potential for loss of life will be a continued risk.

Montserrat: Montserrat occupies an area of 102km^2 and its coastline is 40km long. Before its recent eruption, the highest point on the island was Chance's Peak volcano, at 1000m. This has now been destroyed by the eruption of which started in 1995 and ended in 1998. The population of Montserrat before the eruption was about 13,000, however this number was estimated at 5,879 in 2008 because many residents were evacuated and still remain in Britain (Davidson, 2004).

Montserrat is a volcanic island, and the eruption which began in 1995 is well documented. Along the coast, low lying areas are narrow and have been eroded by successive hurricanes, notably hurricane Luis in 1995, hurricane Georges in 1998 and hurricane Lenny in 1999. Beach surveys have identified losses in the beach profile after each hurricane (UNESCO Technical Guide Report). Montserrat lies well within the hurricane zone, and experiences similar frequency strikes to its neighbouring islands (Antigua & Barbuda and St. Kitts & Nevis). As with neighbouring islands, the impact of SLR will be exacerbated by the incidence of hurricanes annually and by the occasional tsunami. Coastal geomorphology has been impacted by recent volcanic activity producing large quantities of volcanic material that, with weathering, as resulting in the growth of some beach areas. In other coastal regions, depletion outpaces this growth because of hurricane activity.

Although there are no long-term records of sea level change, and land movement has not been studied in detail, it may be assumed that the IPCC (2007) global mean estimate of 3.1mm/year rise at the present time will be close to that actually experienced. This will lead to increased coastal erosion and loss of beaches, or at least, redistribution of sediment along the coast since a rising sea level may result in changes in wave and current activity.

Whilst the main concern of Montserrat will be the impact of recent volcanic activity, sea level rise and increasingly intense hurricanes are also of concern.

2.3.4 ISLANDS WITH COASTAL PLAINS

Haiti: Haiti occupies an area of 27,750km^2 and has a 1,771km long coastline. The highest point is Chaine de la Selle, at 2680m. The population is 9,780,064 (World Bank, 2008). The topography is complex, and has largely originated as a result of the North American Plate subduction beneath the Caribbean Plate, as well as its lateral movement to the east while the Caribbean Plate moves to the west. The complexities of the geology have resulted in a varied coastline.

No data are available for sea level change on Haiti, but it seems likely at the present time that the global mean estimate of 3.1mm/year rise is a good approximation for the Haitian coastline. However, it should be noted that since little is known about land movement, this figure is uncertain. Haiti is at risk to earthquakes generated both from lateral movement of the faults that cross the country and from movement in the subduction zone beneath. The January 2010 earthquake, which measured 7.0, demonstrated the severity of this risk, damaging infrastructure and housing in and around the capital city of Port au Prince. Recovery expenses two days after the earthquake are in excess of US$500 million (UN-OCHA, 2010) with economic losses estimated at 15% of GDP, or US$1.7 billion (Martinez and Rothman, 2010).

The Haitian coastline suffers from a number of problems related to sea level change (Caribbean Disaster Emergency Response Agency, 2003). First, because of widespread deforestation coastal landslides are widespread. Some may be initiated by sea level rise, but most are due to run-off from heavy precipitation associated with storms. Second, Haiti is regularly impacted by hurricanes. Statistics from NOAA, (National Hurricane Center Report) indicates that Haiti is brushed by a hurricane every 5.52 years and receives a direct hit every 17.25 years. Hurricanes can cause major changes in beach profiles, and may also precipitate land sliding along steep slopes in the coastal area during heavy rain. A third problem is the threat of tsunami impact. Haiti has been impacted by tsunamis several times in the last 200 years, notably in 1946, when a tsunami caused considerable loss of life.

It is very likely that, in the context of sea level rise and because of widespread deforestation. The effects of both hurricanes and tsunamis on Haiti will be serious. Since most of the population live close to the coastline, it is likely that there will be loss of life in the event that a severe storm or tsunami strikes the coastline.

2.3.5 OTHER ISLANDS

Barbados: Barbados occupies an area of 430km^2 and rises to a height of 336m in Mount Hillaby, in the central highland region, known as the Scotland district. Composed of limestone surmounted by coral reef terraces, the topography of the island is rugged, marked by a series of steps. The population of Barbados was estimated at 277,264 in 2003.

Barbados is an island that is tectonically rising, and has experienced infrequent and small earthquakes in recent history. Fairbanks (1989) estimated that the south coast of Barbados is rising at 0.34mm/year. However, such a rise is much less than estimated rises of the sea surface provided by IPCC reports. Barbados is believed to lie in a sea area which is close to the mean elevation of the sea surface globally, 3.1mm/year. However, most authorities maintain that the rate of sea surface rise will increase over the present century, perhaps to as much as 6mm/year, and since this is much greater than the measured tectonic rise (0.34mm/yr), Barbados will experience flooding.

Areas at risk are largely concentrated along the west and south-west coasts. Areas around Speightstown and Holetown, including notable hotels such as Sandy Lane, all lie at less than 6m above sea level, as do parts of the highway in this coastal area and they will therefore all be affected (see Figure 18) . Other low-lying areas around Bridgetown are vulnerable, as are areas on the south coast around Kendal Point. The mangrove areas at St. Lawrence and Graeme Hall Swamp are also vulnerable. SLR will affect localised mangrove areas in the southwest, and also to the north of Speightstown. Wetland areas in Barbados have been severely diminished with coastal developments. Because of this, it is difficult to predict the extent of wetland vulnerability. In contrast, the International Airport, at 50m above sea level, would be unaffected, but low lying areas south of this are vulnerable.

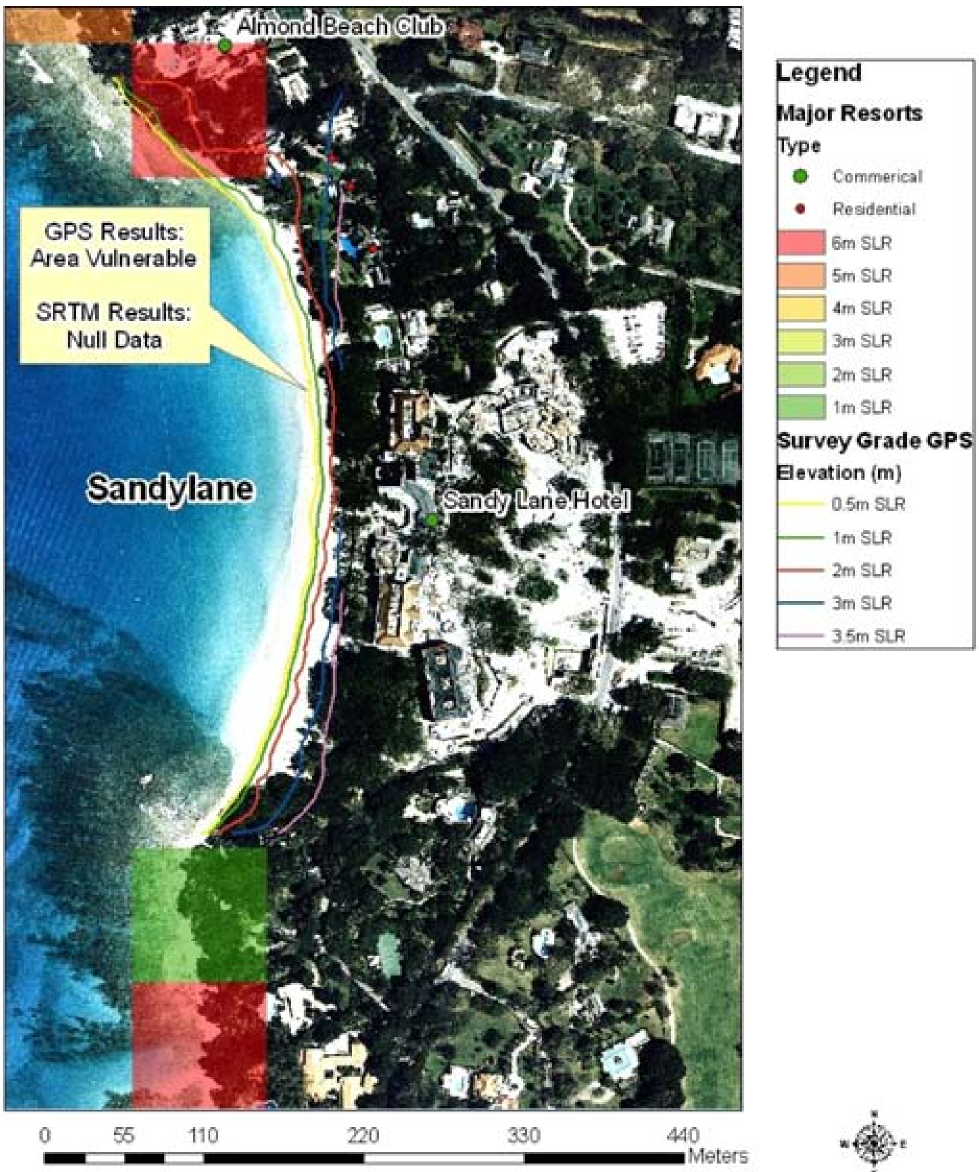


Figure 18: A Comparison of SLR and Storm Surge Vulnerability Using both Satellite-based DEM (90m2) and High-Resolution GPS-based Elevation Data (Sandy Lane, Barbados)

The areas of Barbados most at-risk are largely concentrated along the west coast, where most of the major economic income sources and population exists. The Caribbean Disaster Management Agency (CDEMA, prev. CDERA) has produced valuable hazard maps, and several other useful reports have been produced, notably on the Speightstown area (Scantlebury, 2009). Fish et al. (ibid.) have calculated beach loss (and therefore coastal vulnerability) for different sea level rise scenarios in the Speightstown area, but do not include the added loss from hurricane or tropical storm activity.

Barbados is at risk to hurricane and tropical storm activity, although it has not been as frequently impacted as many of the islands in the more northern, Greater Antilles island chain. Nevertheless, hurricanes will be increasingly destructive as sea levels rise; hence determining the frequency and intensity of hurricanes important.

Thus, on Barbados, the areas most vulnerable to increasing sea level rise, increasing storminess, and periodic tsunami activity, are those that are most economically productive and where the largest population are located. For this reason, the island is particularly vulnerable to climate change.

Trinidad and Tobago: Trinidad and Tobago consists of two main islands and 21 smaller islands off the coast of South America. Trinidad occupies some 4828km^2 and Tobago 300km^2. Trinidad consists of three mountain ranges with peaks of up to 940m in El Cerro del Aripo and 936m in El Tucuche in the northern range. Rolling grassland occurs between these ranges, with a large asphalt bog as well. Extensive mangroves are found along the coasts of Trinidad. Tobago, on the other hand, is a volcanic island, rising to 550m with a narrow coastal plain. The population of Trinidad and Tobago in 2003 was 1,303,000.

The country of Trinidad and Tobago is vulnerable to SLR. In Trinidad, extensive mangrove swamps occupy the western coastline and landward the terrain remains near sea level, with a large area below 6m (Miller, 2005). In Port of Spain, the dockyard area is about 1.8m above mean sea level and the central shopping area only 1.9m. The main government building is at 6.6m above sea level rise and to the east the land rises to 8.9m. Given that the maximum tidal range in the port is 1.5m, the city and low lying central region of the country are vulnerable to sea level rise. Tectonic movement along the Central Range Fault, which, although marked by lateral displacement, may also have a vertical component of movement, could exacerbate this. Modeling of sea level trends between Port of Spain and Port Fontin indicate that sea level is rising at 4.2mm/year in the coastal area in south-west Trinidad. The tectonic component is unclear, but given present and forecast sea level changes from IPCC (+3.1mm/year), there is concern about future changes. Furthermore, a recent study by Singh et al. (2006) observed that petroleum installations on the west coast of Trinidad would be at severe risk of inundation and erosion derived from SLR and storm surge events.

Hurricanes are relatively rare in Trinidad and Tobago. Maharaj et al. (2001) report that in the period 1850-2000, two hurricanes and 5 tropical storms made landfall in Trinidad and Tobago. Tobago is somewhat more vulnerable due to its more northerly location. However, storms visit the islands regularly and Snow et al. (2000) claim that beach erosion of up to 2-4m/year occurs in some areas, due to storms, although exacerbated by sea level rise. In a study of Cocos Bay, eastern Trinidad, Mahibir reported considerable erosion of the beach areas.

On Tobago, bleaching of coral has been evident. Although caused by increases in water temperature rather than sea level rise, this bleaching will inhibit the growth of reefs and thus render them vulnerable to sea level rise. Additionally, mangroves and seagrass beds are located on the landward side of the reefs. Increased sedimentation may also affect reefs and rising sea levels will result in the loss of mangroves, which currently control coastal erosion. Without the coastal mangroves and seagrass beds, coastal erosion will result in sedimentation in the shallow waters near the coral reefs. Hence coral reefs in Tobago may start suffering the effects of climate change very soon because of predicted increases in storminess and SLR in the Caribbean.

2.4 SUMMARY OF THE IMPACT OF SEA LEVEL RISE ON CARICOM NATIONS

The CARICOM nations are vulnerable to a variety of natural hazards, and cyclical variations in climate including ENSO. These processes and their impacts are likely to worsen in the coming decades according to projected changes in climate. The previous section discussed country-specific vulnerabilities to projected increases in SSTs, melting polar ice sheets and resulting increase in sea levels. This section provides a summary of the impacts on the CARICOM countries.

2.4.1 IMPACTS OF 1M SLR

A summary of impacts from a 1m SLR is provided in Table 11. The total land area inundated by 1m SLR is just over 2,700km^2 across all 15 nations. The market price of undeveloped land varies significantly by location and country, but based on an average market price for a hectare of undeveloped land just inland from the coast in four Caribbean nations[27], the value of inundated land at 1m SLR would be just over US $70 billion. The value of developed lands would obviously be much greater. The Bahamas was found to be the most vulnerable nation in terms of loss of total land area (both developed and undeveloped) at a percentage lost of 10%.

A 1m SLR would displace an estimated 115,000 people across the CARICOM nations. The estimated cost to rebuild housing, roads and basic services (water, electricity)[28] for this displaced population would be approximately US $1.8 billion. Suriname has the highest percentage of national population affected (8%) because of greater impacts on urban areas (4% inundated). Other nations with substantive populations affected by a 1m SLR include The Bahamas (5%), Guyana (3%), and Belize (3%). A list of major urban settlements that would be most affected by SLR and storm surge (1 through 6m) is provided in Figure 19.

These same four nations (Suriname, The Bahamas, Guyana and Belize) were also the most economically vulnerable to 1m SLR, with estimated annual GDP (at 2008 levels) losses (or in need of relocation of economic activities that

27 The average market value of US $250,000 was established for land in four CARICOM nations in 2000 by World Bank (2002).

28 This calculation assumes replacement cost of US $30,000 for a four-person home and the replacement of service at an average cost of US $8,173 per person. Both estimates are based on average regional replacement costs in 2000, as quoted in World Bank (2002).

generate GDP) of 6% in Suriname, 5% in The Bahamas, 3% in Guyana, and 3% in Belize. This translates into GDP losses of over US $840 million annually in these four nations alone, and approximately US $1.2 billion for the CARICOM nations (or just over 1% GDP). The geospatial indicator of GDP relates to location of economic activity. It does not account for the damage and replacement costs of infrastructure required to generate that economic activity or the costs of infrastructure associated with the relocation of displaced populations (discussed above).

Further analysis of two sectors of the economy in CARICOM nations, tourism and agriculture, revealed additional key vulnerabilities for some nations. Considering the very close proximity of tourism activities to the coast, it is not surprising that tourism was by far the most vulnerable major economic sector. This is a key finding, as tourism is a major part of the economies of Caribbean nations and this sector has been overlooked in most previous assessments of the impacts of SLR on national economies both here and elsewhere in the world. The World Travel and Tourism Council (WTTC, 2008) estimates that tourism represents 14.8% of GDP and 12.9% of employment (approximately 2 million jobs) in the Caribbean, and the importance of tourism for individual island economies can be much higher (GDP in 2002 (Burke et al. 2004): Antigua and Barbuda 72%, St. Lucia 51%, The Bahamas 46%, Barbados 37%, St. Vincent and the Grenadines 29%, Jamaica 27%, St. Kitts and Nevis 25%, Belize and Grenada 23%, Dominica 22%). The percentage of major tourism resorts at risk to 1m SLR was highest in Guyana (50%), Belize (33%), Trinidad and Tobago (15%), Antigua and Barbuda (9%) and The Bahamas (9%). Figure 16 illustrated the vulnerability of a series of major resorts near Montego Bay, Jamaica. A total of 16 multi-million dollar resort developments were at risk. The replacement cost of these resorts is estimated at slightly over US $1 billion.[29] The permanent or temporary loss and relocation of these major resorts would affect the livelihoods of thousands of employees, in addition to the lost revenues from resort closures.

Because of the coarse resolution of geospatial data available, this study was not able to account for the significant loss of beach area in all CARICOM nations. Beaches are critical assets for tourism and more research is needed to quantify the economic impact associated with their accelerated erosion and almost certain loss that would arise with

29 Replacement construction costs of a mid-specification resort is estimated at US $80,000 per room (as quoted in Fish et al. 2008) and the average size of the 16 lost resorts was 750 rooms (US $60 million per resort). Interviews with major civil engineering firms that operate in the Caribbean found that the rebuild cost on a mid-range resort complex (accommodations and typical associated infrastructure) is approximately US $103 million for a 275,000 sq foot resort (approximately 200 rooms). An estimate of US $100 million per resort was used, even though some of the resorts at risk were much larger than 200 rooms. (Fish et al., 2008).

even limited SLR. Figure 18 (Sandy Lane, Barbados) illustrates a higher resolution coastal surveying technique that is capable of assessing the vulnerability of beach areas that are key to tourism. This study found that Sandy Lane would lose 46.3% of its beach areas with a 1m rise in seal level and this is predicted to negatively affect the rate of tourist return and tourist perspectives on the island of Barbados more broadly.

Also of importance to tourism and the wider economy in each nation, is the vulnerability of key transportation infrastructure. SLR of 1m inundated a total of 11 out of 105 airports, with a reconstruction cost of approximately US $715 million.[30] The vulnerability of airports was highest in Jamaica and The Bahamas. For example, Figure 15 illustrates the vulnerability of the Montego Bay airport, one of the newest in the CARICOM nations, to SLR of 1-2m. Port facilities were more vulnerable, with the land surrounding 14 of 50 ports inundated by 1m SLR. The relocation and replacement cost of this key infrastructure is estimated at US $320 million.[31] Road networks were at greatest risk in Guyana (6%), Suriname (4%), and The Bahamas (2%). A total reconstruction cost to replace inundated roads in the CARICOM nations under 1m SLR exceeds US $178 million.[32] This vital infrastructure will play important roles for tourism operations on a day-to-day basis. Loss of even a portion of the function of major airports and road networks will lead to a reduction in quality and speed of public transportation and also affect the tourism sector's ability to draw in tourists. Delays or reductions in arrivals and departures of cargo ships and cargo and passenger planes will have ripple effects on these small island economies. Furthermore, the use of these transportation services will play increasingly important roles in times of emergency. During the predicted increases in hurricane intensity and frequency, the ability of each nation to safely transport or evacuate residents will demand highly efficient and well-maintained infrastructure.

30 Interviews with civil engineering firms operating in the Caribbean region revealed that airports the size of those recently built at St Kitts and Hato, Curacao are approximately US $65 million (US $45 million for terminal and fittings and US $20 million for asphalt international standard runway with lighting and control structures).

31 Interviews with civil engineering firms operating in the Caribbean region revealed that sea ports similar to the average size of those constructed within the last 10 -15 years are approximately US $20 million, although the range varies widely depending on size.

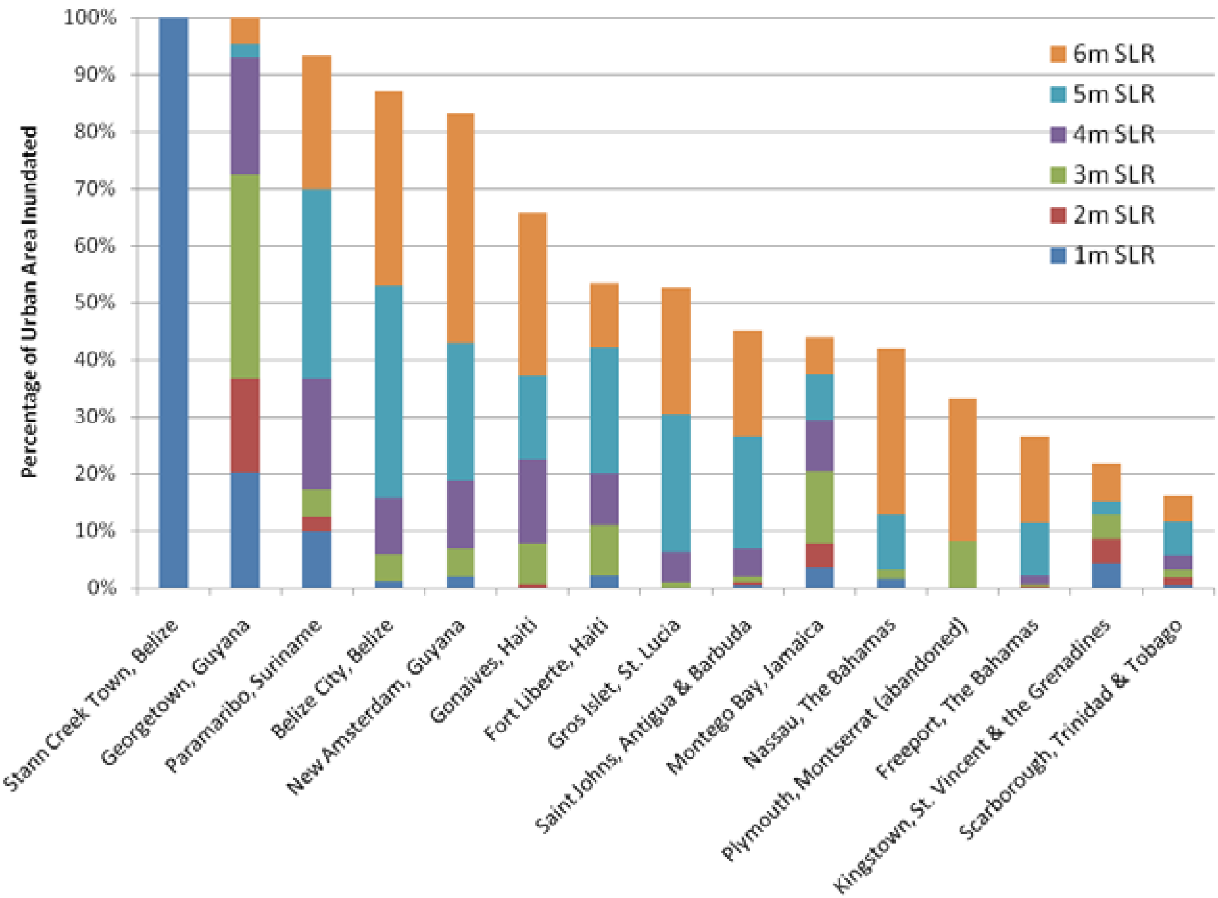
32 The estimate of average construction cost of a 2 lane paved road (US $866,000) was obtained from: http://siteresources.worldbank.org/INTROADSHIGHWAYS/Resources/338993-1122496826968/kmcosts.pdf and further confirmed by construction engineers in the Caribbean.

Table 115: Impacts of a 1m Sea Level Rise in CARICOM Nations

	Land Area	Population (2010 est.)	Urban Area	Wetland Area	Agricultural Land	Crop and Plantation Land	Major Tourism Resorts	Airports	Road Network	GDP (2008 est.)
Antigua & Barbuda	1%	2%	1%	*	1%	0%	9%	0%	1%	2%
Barbados	0%	0%	0%	*	0%	0%	6%	0%	0%	
Belize	1%	3%	1%	17%	1%	0%	33%	0%	0%	3%
Dominica	0%	0%	0%	*	0%	0%	0%	0%	0%	0.1%
Grenada	0%	0%	0%	*	0%	0%	0%	0%	0%	
Guyana	0%	3%	8%	1%	1%	0%	50%	0%	6%	3%
Haiti	0%	0%	0%	1%	0%	0%	0%	0%	0%	0.1%
Jamaica	1%	1%	0%	22%	2%	2%	4%	20%	1%	1%
Montserrat	0%	0%	0%	*	0%	0%	0%	0%	0%	0.1%
St. Kitts & Nevis	0%	0%	0%	*	0%	0%	0%	0%	0%	0.1%
St. Lucia	0%	0%	0%	*	0%	0%	0%	0%	0%	0.1%
St. Vincent & the Grenadines	0%	0%	0%	*	0%	0%	0%	0%	0%	0.1%
Suriname	0%	8%	4%	1%	4%	0%	0%	0%	4%	7%
The Bahamas	10%	4%	3%	15%	3%	2%	9%	13%	2%	5%
Trinidad & Tobago	0%	0%	0%	0%	0%	0%	15%	0%	0%	0.3%

* Due to the small scale of wetland areas and course scale of geospatial data, these nations had no areas classified as wetlands.

Figure 19: Most Vulnerable CARICOM Cities to SLR and Storm Surge (top 15 only)



In summary, conservative estimates of the economic costs of a 1m increase in sea level on CARICOM nations would be a loss of US $1.2 billion in GDP per year; permanently lost land value of US $70 billion; and US $4.6 billion in relocation/reconstruction costs. These figures are based on scientific SLR evidence and do not include other major economic impacts, such as losses in agricultural production, costs of changing energy needs, increased storm or hurricane damage and related insurance costs, necessary water supply construction, increased health care costs, or any non-market value impacts.

Agriculture was found to be less vulnerable than the tourism industry. However, the estimated impact of 1m SLR is still important for food supply and livelihoods. The estimated total agricultural land loss was highest in Suriname (4%), The Bahamas (3%) and Jamaica (2%), however the loss of crop and plantation lands (the highest value agricultural lands) was highest in Jamaica (3%) and The Bahamas (2%). Many nations are dependent on imported agricultural products. Barbados, for example, imports more than half of their agricultural produce and will therefore require sea and airports remain functional in order to supply the fresh produce to their residents and tourist populations. Sea level rise will therefore indirectly affect the agricultural sector in those nations, demanding innovative solutions during times when imported products cannot reach the island (i.e. after major hurricane damage).

SLR also represents a poorly understood threat to natural areas and biodiversity in the region. The area of wetlands inundated by a 1m SLR was highest in Jamaica (22%), Belize (17%), and The Bahamas (15%). The implications for fisheries and water supply in some communities remain important uncertainties. Because of the coarse resolution of geospatial data, the implications of SLR for wetland habitat in many of the smaller CARICOM nations could not be assessed in this study. This is not to say the impacts are any less serious, simply that further research will be needed to generate accurate assessments of the timing and extent of impacts in these areas.

2.4.2 IMPACTS OF 2M SLR

The geographic pattern of impacts among the CARICOM nations was found to remain broadly similar under a 2m SLR scenario; however the magnitude of impacts in the highly vulnerable nations was much more pronounced (Table 16).

For example, The Bahamas would be expected to lose 17% of its total land area, have 8% of its population displaced, lose over 10% of its major tourism resorts and 25% of its airports, and suffer annual GDP loses of over 8%. While projected to lose less land area, more than 16% of Suriname's population would be displaced at the same time that is loses 9% of its agricultural lands and suffers a GDP loss of over 13%. Guyana and Belize would also need to relocate tens of thousands of people (8% or 63,694 and 6% or 15,816 respectively), while also losing substantive GDP (8% or US $256,623,126 and 5% or US $125,784,648 respectively). For the CARICOM members, the value of lost land (valued as undeveloped land) is estimated at over US $143 billion. The annual GDP loss from inundation by 2m SLR was estimated at US $2.3 billion annually (or roughly 2% GDP). Finally, reconstruction/relocation costs estimate for ports, airports, road network, major tourism resorts, and the relocation of nearly 250,000 displaced persons was estimated at US $8.2 billion.

As indicated, SLR is projected to continue throughout the 22nd century and into the future as the world's ice sheets and oceans continue to respond to warmer average global temperatures. A new equilibrium sea level is not anticipated for centuries. Although the eventual extent of SLR remains highly uncertain, this study has analyzed the implications of a higher range of SLR that might be considered worst-case scenarios for CARICOM nations. In addition, the scenarios also provide a useful analysis of sensitivity to storm surges. The amount of land area (in km^2) lost to inundated by the sea is represented in Figure 20, increasing from approximately 10,00km^2 under 3m SLR (2% of land area in the analysis) to over 23,000km^2 (5% of land area in the analysis) under 6m. Much of this land is urban and heavily developed by the tourism industry, transportation and other critical infrastructure[33].

33 These estimates only account for inundation and do not include land areas lost or degraded by accelerated erosion

Table 16: Impacts of a 2m Sea Level Rise in CARICOM Nations

	Land Area	Population (2010 est.)	Urban Area	Wetland Area	Agricultural Land	Crop and Plantation Land	Major Tourism Resorts	Airports	Road Network	GDP (2008 est.)
Antigua & Barbuda	2%	3%	2%	*	1%	1%	27%	0%	1%	3%
Barbados	0%	0%	0%	*	0%	0%	6%	0%	0%	0%
Belize	3%	6%	4%	40%	3%	2%	33%	0%	1%	5%
Dominica	0%	0%	0%	*	0%	0%	0%	0%	0%	0%
Grenada	0%	0%	0%	*	0%	0%	0%	0%	0%	0%
Guyana	1%	8%	21%	3%	2%	0%	50%	0%	15%	8%
Haiti	0%	0%	1%	3%	0%	0%	0%	0%	0%	0%
Jamaica	2%	1%	1%	26%	3%	3%	4%	20%	1%	1%
Montserrat	0%	0%	0%	*	0%	0%	0%	0%	0%	0%
St. Kitts & Nevis	0%	0%	0%	*	0%	0%	14%	0%	0%	0%
St. Lucia	0%	0%	0%	*	0%	0%	0%	0%	0%	0%
St. Vincent & the Grenadines	0%	0%	0%	*	0%	0%	0%	0%	0%	0%
Suriname	1%	17%	9%	4%	9%	0%	0%	50%	9%	13%
The Bahamas	17%	8%	7%	23%	7%	6%	11%	25%	5%	8%
Trinidad & Tobago	1%	1%	1%	0%	2%	0%	15%	0%	0%	1%

* Due to the small scale of wetland areas and course scale of geospatial data, these nations had no areas classified as wetlands.

Figure 21 reveals the increased displacement of current populations from inundated lands under progressively greater SLR and storm surge (1 to 6m). The increased impact of SLR on the combined GDP of the CARICOM member states is represented in

Figure 22. The impacts are significant for the region, but are far greater for the most vulnerable nations. For example, at 3m SLR GDP loss in Suriname is 25%, 17% in Guyana, and 12% in The Bahamas. Figure 23 and 24 illustrate the vulnerability of major transportation infrastructure. The increasing extent of road networks inundated by 1 to 6m SLR and storm surge is displayed in Figure 23. Many major port facilities are threatened at relatively low levels of SLR due to their location near the coast and the vulnerability of surrounding land areas. The proportion of airports affected is initially lower, as many are located inland, but over half of airports in CARICOM nations are vulnerable to 5m SLR (or damage from a combination of SLR and storm surge).

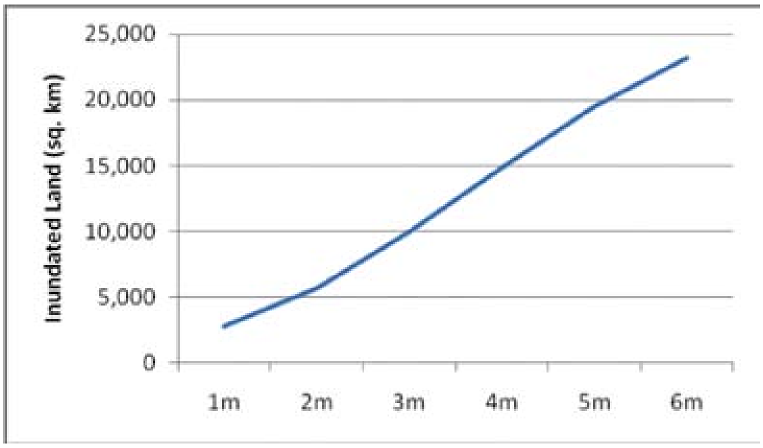


Figure 20: Land Area (sq. km) Inundated by SLR and Storm Surge (1-6m)

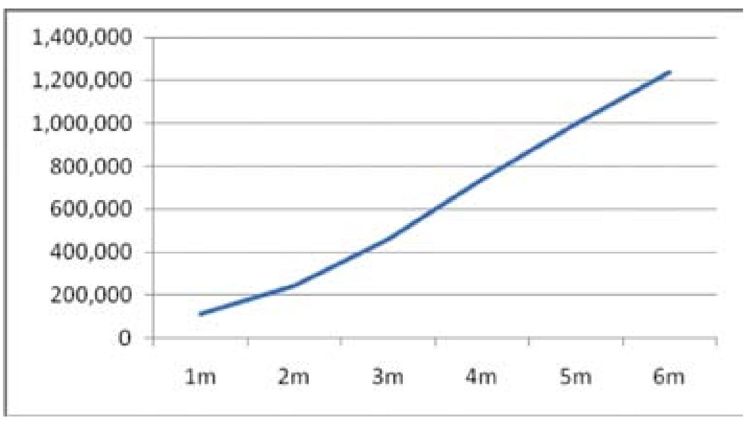


Figure 21: Population Displacement under SLR and Storm Surge (1-6m)

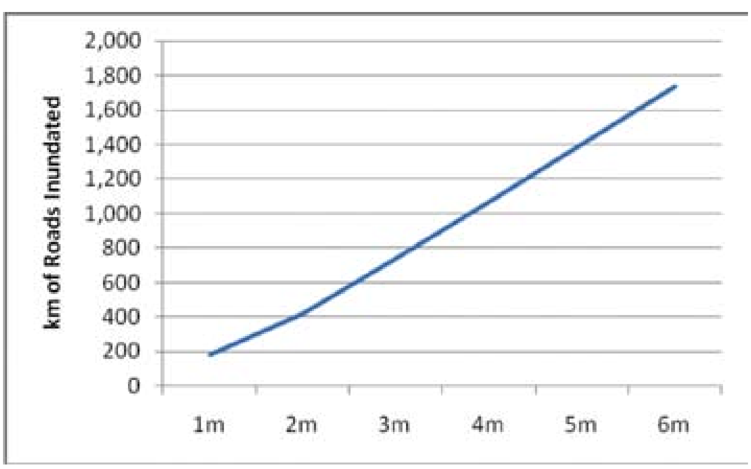


Figure 22: GDP Loss for CARICOM Nations under SLR and Storm Surge (1-6m)

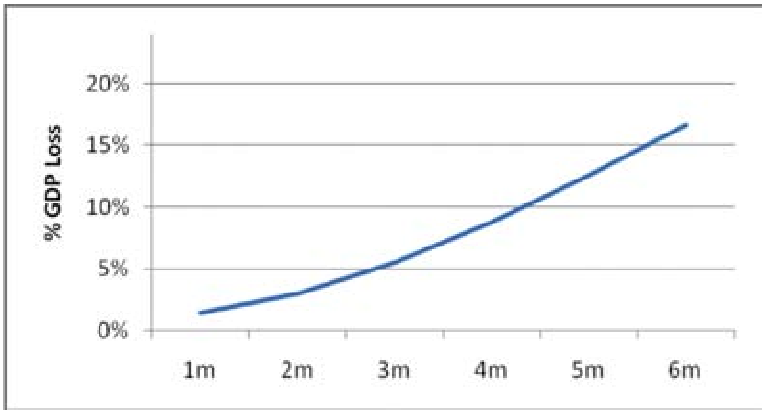


Figure 23: Road Network (km) Loss in CARICOM Nations under SLR and Storm Surge (1-6m)

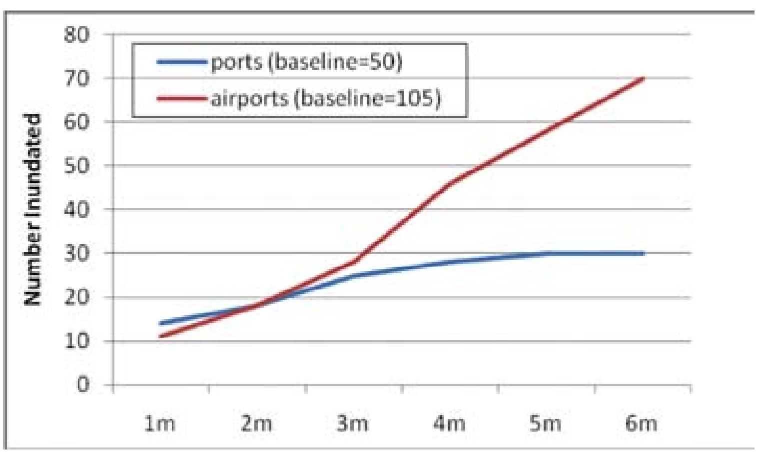


Figure 24: Port* and Airport Facilities Inundated in CARICOM Nations under SLR and Storm Surge (1-6m)

* Port facilities are generally classified as being located in 'water' grid cells in the GIS and inundation therefore refers to surrounding land areas (within 250m).

As the aforementioned impacts clearly illustrate, mean SLR will have a major influence on the future development of the members of CARICOM. Importantly, major flooding damage and accelerated coastal erosion are associated with the storm surge and waves associated with major storms events. Even if the frequency and intensity of hurricanes remain unchanged under climate change, SLR will increase the frequency that coastal infrastructure is exposed to wave action and flooding. When the combination of a 1m to 2m SLR and storm surge of 3m from a major hurricane was examined, approximately 1 million people in the CARICOM nations were found to be at risk. In three nations, more than 25% of the population would be at risk to such a disaster (Suriname 58%, Guyana 30%, and The Bahamas 29%). In addition, over 50% of the major tourism resort infrastructure in the CARICOM nations was also found to be vulnerable to such an event.

This study has revealed highly differential vulnerability to SLR that will cause severe disruptions to the economies of some CARICOM nations where SLR represents an obvious impediment to sustainable development. As significant as the above impacts are for the CARICOM nations, in particular The Bahamas, Suriname, Guyana, Antigua and Barbuda, Jamaica and Belize, it is important to stress that these estimates ***must be considered highly conservative for three reasons.*** First, this study assumes population and GDP remain fixed at recent levels (estimates for 2010 and 2008 respectively). With growing populations, growing economies and increasingly rapid coastal development, where much economic activity is concentrated, this analysis undoubtedly underestimates the magnitude of future impacts in the CARICOM nations. Second, the coarse resolution of geospatial data available for this region-wide analysis masks the vulnerability of coastal infrastructure, natural areas and people to inundation from SLR in some areas. This is because the averaged elevation for an entire GIS grid cell ($90m^2$ in this analysis) with varied heights (e.g., a beach with nearby hills) can be sufficient so that the area does not flood under a 1m SLR. Figures 16, 17, and 18 illustrate examples (Sandy Lane, Barbados; Gros Iset, St. Lucia; Harbour Island, The Bahamas) where SLR does not affect the major tourism resort complexes in the coarse scale GIS analysis that used satellite-based Digital Elevation Model data at all or only under scenarios of 6 to 7m of SLR and storm surge. However, high-resolution elevation data obtained from GPS based coastal surveying (completed by the CARIBSAVE Partnership), clearly identifies all three locations would suffer substantial beach area loss under only 0.5m SLR (see the yellow 0.5m SLR line) and resort infrastructure would be affected by SLR of 2m or less (see the green 1m and red 2m SLR lines). In some forested areas, the satellite radar does not penetrate the canopy of the forest and artificially records the land elevation several meters higher than it is. Third, the coarse scale of this analysis precludes consideration of the implications of SLR for accelerated coastal erosion and its subsequent impacts on infrastructure central to the economies of CARICOM nations. For example, the Bruun "Rule" estimates that beach erosion is approximately 100 times the rate of SLR (i.e., the equilibrium response of beach areas to a 1m SLR would be 100m inland retreat). The vulnerability of tourism infrastructure in particular is likely to be highly underestimated, because this infrastructure generally lacks coastal protection common in cities or other infrastructure (ports, airports, fuel bunkers), because of the need to maintain beach area and aesthetics of pristine ocean views. The analysis also does not account for potential adaptation to protect coastal infrastructure and populations. Such adaptation may reduce the impacts projected here, but will require substantial investment and these costs are not accounted for here. Future studies using high resolution Digital Elevation Models and that account for erosion and not just inundation are needed to understand the true threat SLR poses to the people and economies of CARICOM, as well as to identify the options to adapt to SLR and estimate the costs of such adaptations. Addressing this crucial knowledge gap should be a priority for Official Development Agencies.

3. Differential Impacts of 1.5° and 2°C Global Warming in the Caribbean Region

3.1 IMPACTS ON CORAL REEFS

This section outlines the three largest impacts of climate change on corals and coral reefs in the Caribbean: coral bleaching, infectious disease outbreaks, and ocean acidification. It then reviews recent regional trends in SST and related coral bleaching, as well as acidification. This is provided as background to the analysis of differential impacts under global increases of +1.5°C and 2.0°C scenarios.

3.1.1 TYPES OF CLIMATE CHANGE IMPACTS ON CORAL REEFS

While many factors have contributed to the recent decline of coral reefs in the Caribbean, there is little doubt that rising temperatures, increased outbreaks of infectious disease related to higher ocean temperatures, and increasing ocean acidification are major contributors to this decline. These additional stress factors also greatly reduce the ability of corals to recover from non-climate disturbances, such as pollution, siltation and over-fishing. Other impacts such as SLR and changes in storm activity may influence coral reefs but will have much greater impacts on human societies. Changes in precipitation and ocean circulation patterns are too uncertain to use in scenarios of future impacts on coral reefs.

3.1.1.1 RISING TEMPERATURES AND CORAL BLEACHING

The greatest threat of climate change to Caribbean corals arises from the direct impacts of rising SSTs on coral health. The globally-averaged temperature has risen by 0.74°C in the century (IPCC 2007), and if the current trend of accelerating global GHG emissions continues, a global ocean surface temperature increase of well over 2.0°C is a distinct possibility. Even if greenhouse gas emissions are stabilized in the near future, atmospheric CO_2 that we have already placed in the atmosphere has committed us to at least 1°C of additional warming (for a total of 1.5 - 2.0°C) in this century. Some tropical ocean areas, including parts of the Caribbean, are now experiencing over 0.4°C warming per decade (Strong et al. 2009). Figure 25 shows the rapid warming that has occurred in the last two decades, leading to increasing frequency and intensity of coral bleaching events especially in the Caribbean.

Mass coral bleaching was first seen in the Caribbean in 1983, later recurring 1988, 1995, 1998, and 2005 (Glynn 1990, Wilkinson 2000, Wilkinson and Souter 2008). At the onset of the first mass coral bleaching events (1988), atmospheric CO_2 levels had passed 340 ppm. By the 1990s the return frequency of bleaching and disease outbreaks exceeded the rate at which coral could recover between events. Widespread thermal stress can cause mass bleaching and mortality from malnutrition of many corals and can lead to disease (Bruno et al. 2007, Whelan et al. 2007, Muller et al. 2008). Tissue area on surviving coral colonies has frequently been reduced to a size at which they cease to reproduce (Stone et al. 1999, Loya et al. 2001), further slowing recovery from these events. Climate models have been used to estimate the frequency and intensity of future bleaching events showing strong indications that we are only a few decades from temperatures where annual bleaching becomes a distinct possibility (Hoegh-Guldberg 1999).

Two possible ways that corals may deal with the rapid temperature rise are the evolutionary adaptation of corals to higher temperatures and range expansion. Modeling of mass coral bleaching indicates that Caribbean coral reefs will need to increase thermal tolerance by 0.2 - 0.3°C per decade over the next 30-50 years to avoid regular mortality of corals (Donner et al. 2005). This is discussed further below along with the need for management actions to aid corals' ability to adapt (Baskett et al. 2009b). One potential positive opportunity suggested for rising ocean temperatures is the potential that corals may expand their ranges to more temperate sites (Liu et al. 2003). Fossil evidence shows that there have been past expansions and contractions in corals' ranges, and recent observation suggest that acroporid corals may have been expanding their ranges in recent years (e.g., along southeast Florida coast and Flower Garden Banks). Past changes coincided with fluctuations in temperature and sea level (Precht and Aronson 2004, Precht et al. in press) and have been associated with a reduced penetration of winter storms into the area. However, other habitat requirements such as light availability (Kleypas et al. 1999), and ocean acidification will probably limit poleward expansion. Regardless of success of corals to expand their range, small shifts in reef distribution offer little consolation for the millions of people who depend on the ecosystem services offered by reefs today.

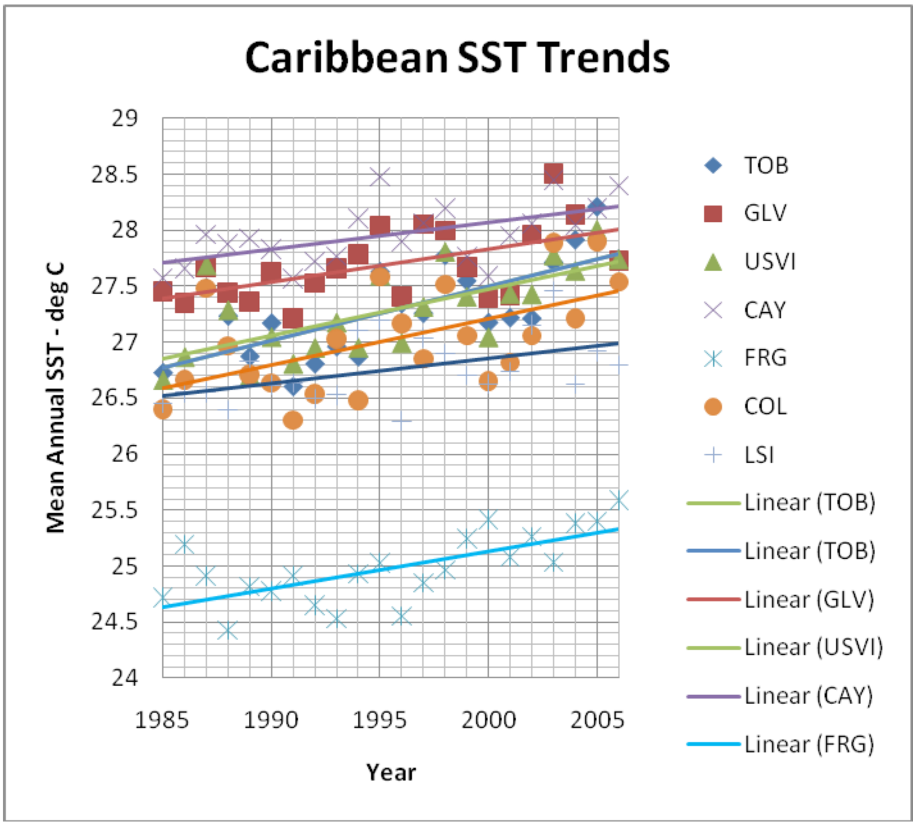


Figure 25: SST time-series of seven representative Caribbean Virtual Stations: 1985-2006 (after Strong et al. 2009).

3.1.1.2 RISING TEMPERATURES AND INFECTIOUS CORAL DISEASE

Coral diseases have been a major factor in the decline of coral reefs in the Caribbean since the 1970s (Harvell et al. 1999). Thermal stress has been correlated with infectious disease outbreaks even at temperatures below those required to cause mass bleaching, especially high summertime temperatures (Bruno et al. 2007). Recently, Muller et al. (2008) found that elkhorn colonies showed higher disease prevalence with higher temperatures and mortality increased in colonies that had bleached. Other preliminary work has found relationships between infectious disease and anomalously warm temperatures in both winter and summer (Heron et al. 2009). This has led several experts to suggest a link between increased incidence and/or virulence of coral disease with increased temperature (Harvell et al. 1999, Patterson et al. 2002, Bruno et al. 2007), perhaps through increased susceptibility of corals to disease (Ritchie

2006). Independent of the mechanism, expected increases in both temperature and the frequency and severity of bleaching events are likely to increase outbreaks of infectious diseases and mortality in corals.

3.1.1.3 OCEAN ACIDIFICATION

Atmospheric carbon dioxide (CO_2) already has increased by 35% from the pre-industrial level of 280 ppm to 385 ppm in 2008 and this rate is accelerating (Metz et al. 2007). As atmospheric CO_2 increase there is a corresponding change in surface ocean chemistry that is accompanied by a decrease ocean pH (hence acidification) and a decline in the availability of carbonate ions. Carbonate ions are the primary control on important carbonate mineral phases (e.g., aragonite) from which many marine organisms compose their shells (measured as aragonite saturation state). This "other CO_2 problem" has been experimentally demonstrated to impact a range of reef processes (coral growth, crustose coralline algae, bioerosion, sediment dissolution, etc.) such that it is likely to compromise reef growth (e.g., net accretion) if unchecked. Further accumulation of anthropogenic CO_2 in the atmosphere will progressively reduce the pH and aragonite saturation state in the oceans. This non-climatic impact of rising CO_2 is almost certainly affecting corals and other marine organisms already (Langdon and Atkinson 2005, Renegar and Riegl 2005, Fabry et al. 2008) – see Figure 26. Optimal coral reef growth is associated with aragonite saturation states above about 3.5, while slower growing, more fragile reefs are associated with lower saturation states (Manzello et al. 2008). Once the average saturation state in the tropical oceans drops below about 3.0, most coral reefs will have already shifted to a net erosional state (Hoegh-Guldberg et al. 2007, Silverman et al. 2009).

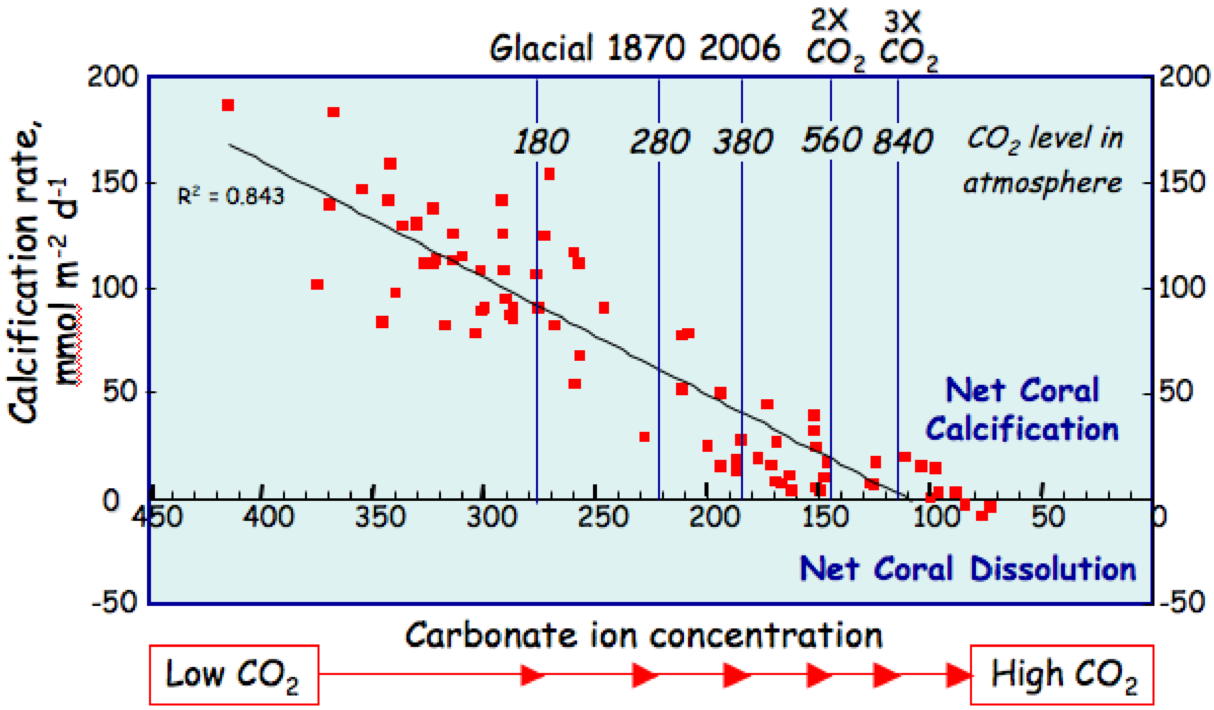


Figure 26: Effect of rising atmospheric CO_2 and declining carbonate ion concentrations on calcification rate. Values are expressed as a percentage of the pre-industrial rate for a variety of corals and reef organisms (after Langdon and Atkinson 2005).

Experts have hypothesized that corals may respond to increased acidification in one or more ways:

1. Corals may grow (extend) more slowly.
2. Coral extension rates may remain constant but skeletal density decreases. This results in corals that are more fragile and more easily broken.
3. Corals may divert energy from other processes such as tissue growth or reproduction to maintain calcification rates.

Almost all studies to date, including studies of calcification in adult (Langdon and Atkinson 2005) and newly settled corals (Albright et al. 2008, Cohen et al. 2009), suggest that rising atmospheric CO_2 will reduce coral growth rates. Recent studies have already found declining linear extension rates in Porites spp. from the Great Barrier Reef and Thailand (De'ath et al. 2009, Tanzil et al. 2009) and in elkhorn corals in Curaçao (Bak et al. 2009). These decreases probably reflect a combination of rising temperature and ocean acidification, and it is expected that ocean acidification will most likely continue to reduce coral growth rates, with some experts expecting over 35% reduction in coral growth rates by the end of the century. Slower growth increases the time it takes corals to recover from physical damage, and makes coral recruits more vulnerable to overgrowth competition, sediment smothering, and incidental predation.

The combination of rising temperature, ocean acidification, and interactions between the two are likely to have synergistic effects and are among the greatest threats to Caribbean corals and coral reefs. Recent work on Pacific Acropora and Porites species suggests that acidification may reduce the temperature threshold at which bleaching occurs (Anthony et al. 2009). Additionally, it is not just corals that are affected by acidification. As atmospheric CO_2 continues to rise, we are likely to see impacts such as those seen in recent community mesocosm studies that showed dramatic declines in the growth rate of crustose coralline algae (CCA) and other reef organisms, and an increase in the growth of fleshy algae (Jokiel et al. 2008, Kuffner et al. 2008). The decrease in CCA growth, coupled with rapid growth of fleshy algae will result in less available habitat, and more competition for settlement and recruitment of new coral colonies. Finally, many important bioeroders use acidic compounds to bore into coral skeletons (Tribollet et al. 2009). This process may be enhanced at lower oceanic pH levels, increasing erosion of corals and reef frameworks. This may have played a role in recent reductions in the topographic complexity in Caribbean coral reefs (Alvarez-Filip et al. 2009). Topographic flattening after coral mortalities reduces habitat space for important fish and invertebrate species, and reduces overall biodiversity.

3.1.1.4 SEA LEVEL RISE

Sea level rise is likely to be less of a threat to corals than either increases in temperature or acidification. Coral reefs exist in a band from near the low tide mark to the point where reduced light inhibits photosynthesis. The depth ranges of corals varies on numerous local and geographic scales (Kleypas et al. 1999). Elkhorn corals, the main reef builder of Caribbean reefs, generally inhabit a relatively narrow zone near the surface of the ocean, and its rapid growth has allowed it to keep up with sea level rise when the world warmed from glacial conditions (Fairbanks 1989, Pandolfi and Jackson 2006, Blanchon et al. 2009). Healthy elkhorn coral are capable of keeping up with the < 1-meter sea level rise estimated in the 2007 IPCC report. However, the recent work by Blanchon et al. (2009) indicates that at the end of the last rapid interglacial warming event 121 thousand years ago sea level rose up to six meters in less than two centuries. Elkhorn coral was able to keep up with only the first 3 meters of rapid sea level rise. Continued sea level rise led to the demise of the original fore reef crests and elkhorn coral was able to keep up by moving into new coastal habitat. Whether it will be able to keep up with future sea level rise will depend on the rate and extent of sea level rise and local environmental stressors, bleaching, infectious disease, and ocean acidification. Additionally, lack of suitable new habitat, limited success in sexual recruitment, coastal runoff, and coastal hardening (e.g., seawalls) will all work together to potentially limit the ability of elkhorn coral and other reef crest species to keep up with rapid sea level rise. In contrast, most coral species inhabit wider depth ranges and are less likely to suffer negative impacts from rising sea level. However, Blanchon et al. (2009) showed that the community of corals in lagoonal settings shifted to a sediment-tolerant assemblage during sea level rise. Thus, future sea level rise will favor species most able to withstand sediment backwash during shoreline retreat, while less tolerant species will be restricted to areas of lower sediment stress. A repeat of such rapid sea level rise would have a dramatic influence on many shallow-water corals, especially elkhorn corals. However, once sea level stabilizes, reefs should be able to resume growth if stresses like temperature increases and acidification were not also occurring.

3.1.1.5 TROPICAL STORMS

It is uncertain how rising temperatures together with other climatic changes change tropical storm frequency, but there is some indication that rising temperatures will increase tropical storm intensity (Knutson et al. 2008). Hurricanes have damaged coral reefs for millennia but, in absence of human disturbance, were previously able to recover (Nystrom et al. 2000). However, other anthropogenic stresses to coral reef ecosystems (sedimentation, nutrient enrichment, ocean acidification) have reduced the ability of coral reefs to recover from any disturbance these storms may bring by slowing coral recruitment, growth, and fitness (Nystrom et al. 2000). In contrast, tropical storms can cool thermally stressed reefs if the storms pass far enough away to prevent damage (Manzello et al. 2007). While the consequences for reefs of a rise in storm intensity are not yet clear, the overall slow rate of recovery in Caribbean reefs (Connell 1997) is a matter of grave concern. Thus, as climate stresses and anthropogenic stresses continue to rise and depress the scope for reef recovery, the passage of storms leaves a greater and greater proportion of Caribbean reefs in a degraded state (Mumby 2006).

3.1.2 UNIQUE CONSIDERATIONS FOR THE CARIBBEAN

3.1.2.1 PAST BLEACHING AND SST TRENDS

The Coral Reef Watch (CRW) program at the US National Oceanic and Atmospheric Administration (NOAA) uses near-real-time satellite measurements of sea surface temperature to monitor for thermal stress. These data provide up-to-date measurements pinpoint areas that are currently at risk for coral bleaching. The most important index that CRW produces is the Degree Heating Week (DHW) (Liu et al. 2006, CRW 2009a, Eakin et al. 2009). Coral bleaching is caused by an accumulation of thermal stress over time. When SST rises above a bleaching threshold temperature, 1°C above the mean temperature for the warmest month (Glynn and D'Croz 1990, Atwood et al. 1992), DHWs begin to accumulate. Thermal stress builds up over a 12-week window, providing a reliable indicator for coral bleaching and mortality.

Examination of tropical SSTs reveal regionally diverse but changing patterns and trends. In 2005, the coral community witnessed a record breaking thermal stress event throughout much of the eastern Caribbean (Wilkinson and Souter 2008). With global satellite SSTs now spanning more than two decades, we now have sufficient data to examine global and basin scale trends. As climatologists have established that some of the extreme variability during the 1990s can be attributed to a mid-90s reversal in patterns of Atlantic-Pacific patterns of teleconnection (Mantua et al. 1997) we consider both the 22-year record (1985-2006) and two decadal intervals (1987-96 & 1997-2006) to assess changing temperatures patterns and trends in the Caribbean and Atlantic.

This Caribbean basin analysis expands on an earlier global study by Strong et al. (2009) making use of NOAA/NASA Version 5.0 Pathfinder daily SST data at 4km resolution (Casey and Cornillon 1999, Kilpatrick et al. 2001). This analysis and resulting basin trends shown in Figure 27, taken from Strong et al. (2009), were built upon our previously published analyses (Strong 1989, Strong 1991, Strong et al. 2006) and both incorporated four additional years of SST data and improved the resolution of our results from 50km to 4km. The Pathfinder SST data are available at http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/ (NODC 2009).

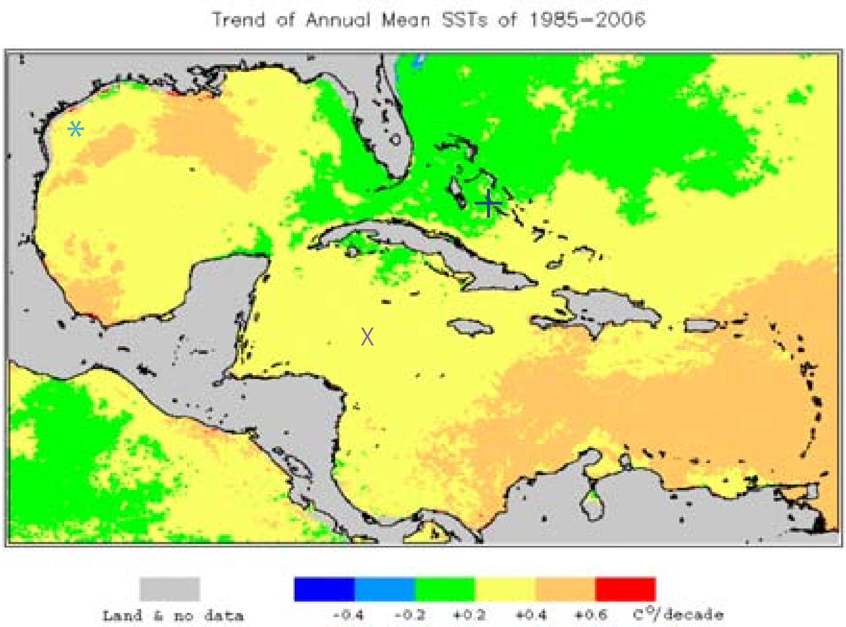


Figure 27: Pathfinder SST Trends – 1985-2006. Shapes designate reef locations of Virtual Stations used in Table 17 (below) and Figure 25.

Month-by-month comparisons of coincident in situ and satellite SSTs at various locations around the Caribbean reveal tight correlations and, most importantly, no biases between the buoy-measured and remotely-sensed data sets over time. Therefore we are confident in our ability to examine tropical oceans more completely than had been possible with in situ SST measurements. Since the satellite-derived Pathfinder SSTs come from continuous, daily, overlapping, operational NOAA satellite missions, they represent the best possible climate-quality global SST data for the tropics from 1985 to the present. Only nighttime Pathfinder data were used to avoid having to account for the diel variation in SST caused by daytime solar heating and nighttime cooling, especially during calm weather conditions. Nighttime data provide the most consistent day-to-day values and only data that were flagged as high quality were used (Kilpatrick et al. 2001). Our annual mean SSTs at each pixel were calculated from the 12 monthly mean SSTs at the pixel. Globally, the satellite-derived SSTs show that over the past 22 years the tropical ocean surface temperatures (35N to 35S) have been increasing at a rate of +0.22°C/decade (Strong et al. 2009).

Caribbean – Atlantic Ocean: Table 17 shows SST trends over the entire 22 years of record (1985-2006) that range from a low of +0.22°C/decade at Lee Stocking Island (Bahamas) to a high nearly twice that, +0.48°C/decade at Buccoo Reef, Tobago. Two decadal intervals (1987-96 & 1997-2006) are included that reveal some surprisingly consistent and robust rates over the whole 22-year period at some of these eastern and southern Caribbean sites. The only good news we can expect to hear is that the most recent three years (2007-09) have not seen summer temperatures quite as high as those that were witnessed during the middle of the present decade.

Table 17: SST trends and tendencies for the seven Virtual Stations shown in Figure 25. Standard deviations of the slopes are included in parentheses. Two additional reference points in mid-Atlantic tropical waters [North and South] are included.

REEF	TRENDS (°C per decade)	TENDENCIES (°C per decade)	
	1985-2006	1987-1996	1997-2006
Buccoo Reef, Tobago (TOB)	+0.48 (0.10)	+0.06	+1.07
Glovers Reef, Belize (GLV)	+0.29 (0.10)	+0.26	+0.82
US Virgin Islands (USVI)	+0.41 (0.10)	-0.14	+0.86
Cayman Islands (CAY)	+0.24 (0.08)	+0.27	+0.82
Flower Gardens, TX (FRG)	+0.33 (0.08)	+0.03	+0.76
Santa Marta, Columbia (COL)	+0.41 (0.13)	+0.11	+1.30
Lee Stocking Island, Bahamas (LSI)	+0.22 (0.09)	+0.26	+0.42
Mid N. Atlantic (20N, 50W)	+ 0.39 (0.11)		
Mid S. Atlantic (20S, 20W)	- 0.04 (0.13)		

Mid-Atlantic Ocean – Extremes: Two additional middle Atlantic SST Virtual Stations were considered as mid-ocean examples on either side of the equator (Table 17). These may help to provide a perspective for what is evolving, particularly over the entire North Atlantic tropical region. Trends are high in the mid-North Atlantic Virtual Station located at (20N, 50W), nearly twice that of the entire global tropical seas (Strong et al. 2009), but there is still no significant trend in the mid-South Atlantic location at (20S, 20W).

With a rigorously reconstructed set of Pathfinder SST data, it is clear that global and Caribbean SSTs are increasing and the rate is accelerating. Of all tropical regions, the Caribbean basin demonstrates some of the most alarming increases. At many sites in the eastern basin warming rates are nearly double those seen globally. The most recent decadal (1997-2006) increases are surpassing those of the previous decade. Coral reefs are already experiencing rapid temperatures increases beyond those to which they may be able to adapt (Donner et al. 2005, Hoegh-Guldberg et al. 2007). In 2005, the Caribbean region experienced record ocean temperatures, with a concomitant record number of hurricanes, mass coral bleaching, outbreaks of coral disease, and widespread coral mortality (Wilkinson and Souter 2008).

3.1.2.2 THE 2005 CARIBBEAN BLEACHING EVENT

From June to October 2005, a warm-water anomaly developed across the tropical Atlantic and greater Caribbean. Elevated temperatures persisted for many weeks, possibly helping to fuel the most active Atlantic hurricane season on record (Shein 2006) and causing the most severe and extensive mass coral bleaching event observed in the Caribbean. As the thermal stress event developed, water temperatures rose across the basin from the South American coast to Central America, then moved eastward to the Antilles and northward to the Gulf of Mexico, Florida, and the Bahamas (Wilkinson and Souter 2008). Unlike many past Caribbean bleaching events, strong tropical climatic patterns were only a minor driver of Caribbean SSTs in 2005; much of the warming was attributable to monotonic climate change, while only a small amount was attributable to the weak 2004-05 El Niño, and even less was attributable to the Atlantic Multi-decadal Oscillation (Trenberth and Shea 2006).

Record SSTs contributed to setting new records during the 2005 hurricane season in the Atlantic and Caribbean, experiencing the greatest number of hurricanes in recorded history (Trenberth and Shea 2006). Hurricanes Katrina and Rita damaged the deep reefs of the Flower Garden Banks in the Gulf of Mexico, while Hurricane Dennis scoured the reefs of Florida (Morgan et al. 2008). Hurricanes Emily and Wilma damaged reefs in Mexico (McField et al. 2008) and Cuba (Jones et al. 2008b). On the other hand, Hurricanes Katrina, Rita, and Wilma passed through the Florida Keys as relatively mild storms, causing considerable cooling of elevated SSTs, alleviating stressful conditions, and resulting in minimal coral bleaching (Causey 2008). Numerous tropical storms and hurricanes around Belize may have benefited the reefs in a similar way, thereby reducing the extent of coral mortality there (McField et al. 2008). Finally, the absence of strong storms across Puerto Rico and the Lesser Antilles meant that storms did nothing to ameliorate the very warm ocean surface temperatures that stressed coral reef ecosystems there (Heron et al. 2008).

Coral bleaching extended across the entire Caribbean region in 2005, and infectious disease and mortality continued through 2006 (Wilkinson and Souter 2008). Mass coral bleaching was documented in the Mesoamerican Reef (McField et al. 2008), the Northern Caribbean (Jones et al. 2008b), Puerto Rico (García-Sais et al. 2008), the U.S. Virgin Islands (Lundgren and Hillis-Starr 2008, Muller et al. 2008, Woody et al. 2008), the Lesser Antilles (Bouchon et al. 2008), Barbados (Oxenford et al. 2008), Southern Tropical America (Rodríguez-Ramírez et al. 2008), and the Flower Garden Banks (Hickerson et al. 2008). Outbreaks of disease, followed by mortality, occurred in corals already stressed by high temperatures in Florida (Ritchie 2006) and the U.S. Virgin Islands (Whelan et al. 2007, Muller et al. 2008, Miller et al. 2009). Long-term effects are still be recorded and are yet to be fully understood, for example, the combination of hurricanes and bleaching events may have impacted coral recruitment in Tobago (Mallela and Crabbe 2009). Climate models have been used to estimate the frequency and intensity of future bleaching events showing strong indications that we are only a few decades from temperatures where annual bleaching becomes a distinct possibility.

3.1.2.3 RECENT PATTERNS OF ACIDIFICATION AND ITS IMPACTS

Using climatic data from the NOAA extended reconstruction SST product (Smith et al. 2008, NCDC 2009) and atmospheric CO_2 reconstructions spanning the last century (CDIAC 2009), Gledhill et al. (2009) reconstructed patterns of carbonate chemistry patterns and trends since 1880. While ocean acidification started in the early industrial period, the rate of acidification now is accelerating. Declining growth of massive corals has been reported for the Great Barrier Reef during recent decades when acidification has been accelerating (De'ath et al. 2009); although both rising temperature and ocean acidification have probably contributed to the decline. Some investigators are now examining Caribbean corals for this pattern.

There is important seasonal and spatial variability in carbonate chemistry is evident across the Caribbean region. This pattern is largely driven by temperature and results in greater variability in temperate regions than in the tropics

– during the warmest months of the year, saturation state is elevated in the Florida Keys relative to the southern Caribbean. These temperate areas of the Caribbean will pass into net erosion during the winter much sooner than more tropical areas. Seasonal changes in carbonate chemistry have recently been identified as an important factor for high-latitude Bermuda corals, where a strong correlation was found between the in situ rates of calcification for the major framework building coral species Diploria labyrinthiformis and the seasonal variability of saturation state (Bates et al. 2009). Long-term acidification, however, is moving fast enough that changes in the last 20 years are greater than seasonality in even high-latitude areas of the Caribbean. As a consequence the current summertime maxima in saturation state in the northern Caribbean are less than the wintertime minima experienced only 20 years ago.

3.1.3 COMPARING CARIBBEAN CORAL REEFS AT 1.5° AND 2.0°C OF WARMING

For the parameters of climate change that are affecting coral reefs, two can be reasonably quantified to differentiate impacts under 1.5 and 2.0°C globally averaged warming scenarios: coral bleaching due to thermal stress and ocean acidification. There is strong evidence that temperature increases will lead to more frequent and severe outbreaks of infectious diseases in corals, but too little is known about the temperature-disease relationships to realistically quantify differences under these two, modestly different temperature regimes. While one can calculate the difference in thermal expansion of the oceans at these two temperature scenarios, this is a much smaller component of potential sea level rise than melting of land ice in Greenland and Antarctica. Unfortunately, there is too much uncertainty in our current understanding to model differences in land ice melting under the two scenarios. As sea level rise will probably have relatively less significant impact on corals (compared to bleaching and acidification), this paper will not contrast differences in sea level impacts. Tropical storms, precipitation, and circulation changes are too poorly understood to address different impacts between these two modestly different scenarios as well.

i. Recent Research on Future Climate Scenarios

Several recent studies have used the observations of mass coral bleaching, like the 2005 Caribbean event, and climate model simulations to evaluate the expected frequency and severity of coral bleaching under different future climate scenarios (Hoegh-Guldberg 1999, Sheppard 2003, Donner et al. 2005, Donner et al. 2007, Donner 2009). In these studies, the SST simulated by the climate model are tested against observations and used to calculate metrics of the heat stress experienced by corals (Sheppard 2003, Donner et al. 2005). The current method for modeling potential coral bleaching using coarse data provided by global climate models is the accumulation of "degree heating months" (DHM). Similar to the NOAA's operational Degree Heating Week product, a degree heating month or DHM is equal to one month of temperatures that are 1°C warmer than the maximum monthly temperature (e.g., the average temperature for the average September in the Caribbean). Historical data analysis has shown that DHM values of more than 1°C-month and more than 2°C-month are strong proxies for NOAA Coral Reef Watch's Bleaching Alert Levels 1 and 2, respectively (Donner et al. 2005).

The various studies on climate change and coral bleaching conclude that Caribbean coral reefs will experience conditions that currently cause severe coral bleaching (DHM > 1 or 2°C-month) one-in-two years within two to five decades (Hoegh-Guldberg 1999, Donner et al. 2005). For example, Donner et al. (2007) used historical observations and climate model simulations to evaluate the probability of the warm water anomaly that caused the 2005 mass coral bleaching event in the eastern Caribbean under past, current and future climates. Their analysis concluded that ocean warming since the Industrial Revolution increased the frequency of the 2005 event from one-in-one-thousand years to less than one-in-one-hundred years; projected warming over the next 20-30 years could make the once rare occurrence a bi-annual event (Donner et al. 2007).

The acceptable frequency of bleaching events is difficult to define, as the timescale for recovery from mass coral bleaching events varies widely, based on factors like historical experience, community structure and other stressors (Hughes and Connell 1999, Marshall and Baird 2000, Loya et al. 2001, McClanahan 2007, McClanahan et al. 2007). The projected frequency of one-in-two years would exceed any observed recovery time for coral reefs around the world (Baker et al. 2008); modeling studies have assumed five years as the minimum acceptable return period, beyond which coral cover would permanently decline below pre-bleaching levels (Sheppard 2003, Donner et al. 2007, Donner 2009).

This increase in thermal stress over the next half-century is robust across the range of IPCC future GHG emission scenarios (Donner et al. 2005, Donner 2009). This warming "commitment" occurs for two reasons. First, the planet is committed to some warming from past GHG emissions due to the lag between the GHG emissions and the climate response. Second, the assumptions about time required to implement mitigating activities in the IPCC scenarios results in similar emissions trajectories over the next two to three decades in each scenario (Nakicenovic and Swart 2000).

Whether future coral bleaching thresholds will remain at current levels, and therefore how much mass bleaching might result from the increased stress, depends on a variety of biological dynamics and management efforts that influence the potential for acclimatization and adaptation in the thermal tolerance of corals and their symbiotes. A comprehensive model-based assessment of mass coral bleaching around the world found that thermal tolerance of the majority (>75%) of Caribbean coral reefs will need to increase by 0.2-0.3°C per decade over the next 30-50 years at the majority to avoid coral bleaching occurring more than one-in-five years (Donner et al. 2005). Donner et al. (2007) specifically evaluated the impact of a 1.5°C increase in thermal tolerance, a best guess of the thermal flexibility of common coral species through a variety of possible mechanisms including flexibility of the coral-algal symbiosis (Berkelmans and van Oppen 2006, Middlebrook et al. 2008), heterotrophic plasticity (Grottoli et al. 2006), and protection of resistant and resilient habitats and populations (West and Salm 2003, Marshall and Schuttenberg 2006). A 1.5°C increase in thermal tolerance in the Caribbean would cause divergence between the bleaching frequencies in the different emission scenarios. In a "business-as-usual" emissions scenario (SRES A1b), mass coral bleaching of the level observed in 2005 would not become a five year event until at least the 2070s; in a lower emissions scenario (SRES B1) , mass coral bleaching would not become a five year event until the latter half of the 22nd century.

Taken together, the studies to date indicate that an increase in thermal stress on Caribbean coral reefs in the next 20-30 years is inevitable because of "committed" warming. However, the findings also show that adaptation, whether via biological mechanisms or management interventions, could permit enough time to lower GHG emissions and avoid coral bleaching events like 2005 from becoming dangerously common this century (Donner et al. 2007, Baskett et al. 2009b, Donner 2009). Whether such increases in thermal tolerance are feasible depend on the rate of an array of physiological, ecological, and evolutionary dynamics relative to the rate of climate change, as discussed below.

Recent work has also demonstrated that we can model and monitor changes in sea surface ocean chemistry in the Greater Caribbean Region in response to ocean acidification (Gledhill et al. 2008). It is based on establishing regional empirical algorithms between parameters measured in situ and remotely sensed observables and then utilizing the high resolution remotely sensed products (Gledhill et al. 2008, Gledhill et al. 2009). It provides an important utility to explore regional to basin-wide trends in ocean acidification on seasonal to interannual timescales. In 2008, NOAA released its Experimental Ocean Acidification Product Suite[34].

The Ocean Acidification Product Suite has revealed two important patterns in carbonate chemistry in the Caribbean. Firstly, the carbonate chemistry varies seasonally, especially in high latitude regions of the Greater Caribbean such as Florida, the Bahamas, and Bermuda. Secondly, increasing atmospheric CO_2 has reduced saturation states in the Caribbean such that the highest Caribbean-averaged monthly saturation states seen today are lower than the lowest seen two decades ago. These observed declines in aragonite saturation state should have diminished regional calcification rates by corals and coral reefs in the Caribbean by nearly 20% relative to preindustrial values assuming the relationship developed by Langdon and Atkinson (2005). The first evidence of such a decline has been seen in coral sclerochronological studies on the Great Barrier Reef (De'ath et al. 2009). Studies investigating such potential declines in the Caribbean are currently underway.

The published and online application of the Ocean Acidification Product Suite has provided near-real-time monitoring and investigation of acidification in recent decades. For this project we have used the same model in combination with scenarios of future levels of atmospheric CO_2 and resulting modeled ocean temperatures in the Caribbean. This approach provides estimates of carbon chemistry parameters, especially the saturation state of aragonite, for various levels of atmospheric CO_2 and warming in the future including 1.5 and 2.0°C levels in the future. These will follow the models and scenarios described in the next section.

34 Updated monthly at http://coralreefwatch.noaa.gov/satellite/oa/index.html (CRW 2009b). The product offers a monthly, 0.25 x 0.25 degree synthesis of satellite and modeled environmental datasets to provide a synoptic estimate of sea surface carbonate chemistry (Ω_{arg}, $pCO_{2(sw)}$, total alkalinity, carbonate ion, and bicarbonate ion) within the oceanic waters of the Greater Caribbean Region (Gledhill et al. 2008).

3.1.3.1 CORAL MODELING METHODS

NOAA's Coral Reef Watch is already using model data to produce a short-term bleaching outlook (Liu et al. 2009). This new prediction system uses experimental NOAA SST forecasts in order to predict bleaching stress up to three months in the future. The outlook product alerts reef managers and scientists around the world to risks in the upcoming bleaching season. These short-term outlooks do not predict climate-scale thermal stress, but similar work can be used to analyze the potential rate of bleaching under future climate change scenarios. The climate scenario analysis in this report follows from a global coral reef assessment conducted by Donner (2009). Simulated SSTs for the Caribbean were obtained from simulations of the coupled atmosphere-ocean GCMs CM2.0 and CM2.1 conducted for the IPCC's AR4 (Randall et al. 2007). These two models from NOAA's Geophysical Fluid Dynamics Laboratory were specifically chosen for recent Caribbean and global coral reef analyses because of high spatial resolution and moderate climate sensitivity (Donner et al. 2007, Donner 2009). The ocean component of the models operates on a high resolution grid particularly in the tropics (longitude 1 degree; latitude ranging from 1 degree in mid-latitudes to 1/3rd -degree at the equator), thus improving representation of tropical climate variability and atmosphere-ocean oscillations like the El Niño / Southern Oscillation (Delworth et al. 2006). The models' climate sensitivities of 2.9°C and 3.4°C lie in the middle of the range of values for models used in the IPCC's AR4 (Randall et al. 2007) (see also Section 1).

Monthly SSTs are presented as the sum of an observed monthly climatology and model anomalies. For example, the SST for March, 2030 in a given scenario is the sum of the March SST in the satellite climatology and the difference between the simulated SST for March, 2030 and the simulated climatological SST for March. The observed monthly SST climatology was determined using monthly data for the 1985-2000 period from the 0.5° x 0.5° latitude-longitude resolution AVHRR pathfinder dataset used by the Coral Reef Watch Program to predict coral bleaching in real-time (Eakin et al. 2009). The simulated SST climatology is based on CM2.0 and CM2.1 ''all-forcing'' simulations, which simulate past climate variability based on forcings of GHG, sulphate and volcanic aerosols, black and organic carbon and solar irradiance. The mean monthly SST for 1980-2000 in each Caribbean grid cell was determined from the eight available all-forcing simulations (CM2.0, n=3; CM2.1, n= 5) and interpolated to the 0.5° x 0.5° latitude-longitude grid of the observed data. The 1980-2000 period was used for the model climatology to maximize statistical agreement between the observations and simulations (Donner et al. 2007).

The SSTs and thermal stress on coral reefs under scenarios of 1.5°C and 2.0°C mean global warming across the Caribbean are derived from CM2.0 and CM2.1 simulations the SRES A1b scenario (Nakicenovic and Swart 2000). The SRES A1b scenario describes a roughly "business-as usual" emissions path, resulting in atmospheric CO_2 concentrations reaching 700 ppm in 2100. In the CM2.0 and CM2.1 simulations of SRES A1b, the decadal mean SSTs across the Caribbean region increase by 2.3°C by the year 2100. To represent the effect of 1.5°C and 2.0°C mean warming on SSTs across the Caribbean, we identified the decade in which the global SST anomaly reached 1.5°C and 2.0°C in the respective CM2.0 and CM2.1 SRES A1b simulations. For example, the 1.5°C global threshold is reached in the decade of 2039-2048 in the CM2.0 simulation and in the decade of 2035-2044 in the CM2.1 simulation. Following this approach, the models show the Caribbean region experiencing warming of 1.13°C and 1.51°C under scenarios of global mean warming of 1.5°C and 2.0°C respectively[35]. The regional to global warming ratio of 0.75 (in both scenarios) in the CM2.0 and CM2.1 ensemble is the same as the ratio reported in the IPCC model ensemble average (Randall et al. 2007).

The thermal stress on corals is estimated using the accumulation of "degree heating months" (DHMs) over a four month rolling window during the identified decades in each model simulation. One DHM (in °C-month) is equal to one month of SST that is 1°C greater than the maximum in the monthly climatology, known as the maximum monthly mean (MMM). The monthly time step is better suited to the temporally coarse archived GCM output than weekly time step used in real-time prediction (Donner et al. 2005). Using this method, the simulated annual accumulation of DHM for a given year is equal to the maximum four-month accumulation of simulated SST (model anomaly plus satellite climatology) in excess of the maximum monthly mean from the 1985–2000 satellite climatology (Donner 2009).

The annual accumulation of DHM for each grid cell for the appropriate decade in each simulation is used to compute the mean annual DHM and frequency of DHM > 2°C-month for the 1.5°C warming threshold and a 2.0°C warming threshold. This analysis is repeated assuming a maximum 1.5°C increase in the threshold at which thermal stress

35 These specific regional outcomes of these two GCMs may differ from other GCMS and the ensemble used in Section 1).

accumulates (i.e., MMM + 1.5°C), in order to gauge the possible effect of adaptation by biological mechanisms and management actions on the frequency of mass coral bleaching events (Donner et al. 2007, Donner 2009). Results are calculated individually for each 0.5° x 0.5° grid cell in the Caribbean region. A 0.5° x 0.5° map of coral reefs, derived from ReefBase and the model's land mask (Donner 2009), features 169 grid cells in the Caribbean region.

At the same time as thermal stress is influencing Caribbean corals, increasing atmospheric CO_2 will be acidifying the surface waters and slowing the growth of corals and coral reefs. While global temperatures lag significantly behind changes in atmospheric CO_2, ocean acidification does not (equilibrium is reached within one year). Therefore, we must consider carbonate chemistry under two different sets of scenarios: the CO_2 at which we achieve equilibrium between temperatures and stabilized CO_2 for both 1.5 and 2.0°C globally-averaged warming (350 ppm and 450 ppm respectively), and also the peak CO_2 levels through which we are likely to transit during the 21st century. Thus, we are considering scenarios of the earth system and ecosystem impacts at 1.5°C and 2.0°C warmer than preindustrial temperatures in two ways:

21st Century warming Earth: These scenarios consider the temperature and most likely atmospheric CO_2 level at the approximate time when the globally averaged temperature reaches 1.5°C and 2.0°C above the pre-industrial temperature. The atmospheric CO_2 level was taken from the scenarios used in running the GCMs.

The Earth at equilibrium: These scenarios consider the temperature and most likely atmospheric CO_2 level once the climate system has stabilized and globally averaged temperature is stable at 1.5°C and 2.0°C above the pre-industrial temperature. The atmospheric CO_2 levels are 350 ppm for 1.5°C and 450 ppm for 2.0°C. These were assigned as boundary conditions for this exercise but are generally believed to be the CO_2 levels that would equate to those levels of warming. Note that we have already overshot 350 ppm and we are likely to overshoot 450 ppm, as our current use will bring atmospheric CO_2 to 450 ppm by 2040. Major international and individual changes would have to be made in a very short time to avoid passing 450 ppm.

In addition to these two scenarios, other important temperatures, atmospheric CO_2 levels, and carbonate saturation state levels are considered as well. These include the atmospheric CO_2 levels that correspond to the estimated range over which reefs are likely to pass into a state of net erosion and the atmospheric CO_2 level at which the Caribbean saturation state will reach 1.0 and coral skeletons become subject to dissolution.

3.1.3.2 CORAL MODELING RESULTS

3.1.3.2.1 IMPACTS OF THERMAL STRESS

The results show that the mean annual accumulation of degree heating months (DHM) in the future would far exceed the current mass coral bleaching thresholds across the Caribbean in both the 1.5°C and 2°C global warming scenarios. In the 1.5°C warming scenario, the mean annual DHM is highest in the south western Caribbean, reaching above 5°C-month, and lowest in the northern Gulf of Mexico, Cuba and the Florida Keys, with values reaching 2-3°C - month (Figure 28a). In the 2°C warming scenario, the pattern in the mean annual DHM is similar, with value reaching above 6°C - month along the coast of Central American and South America (Figure 28b).

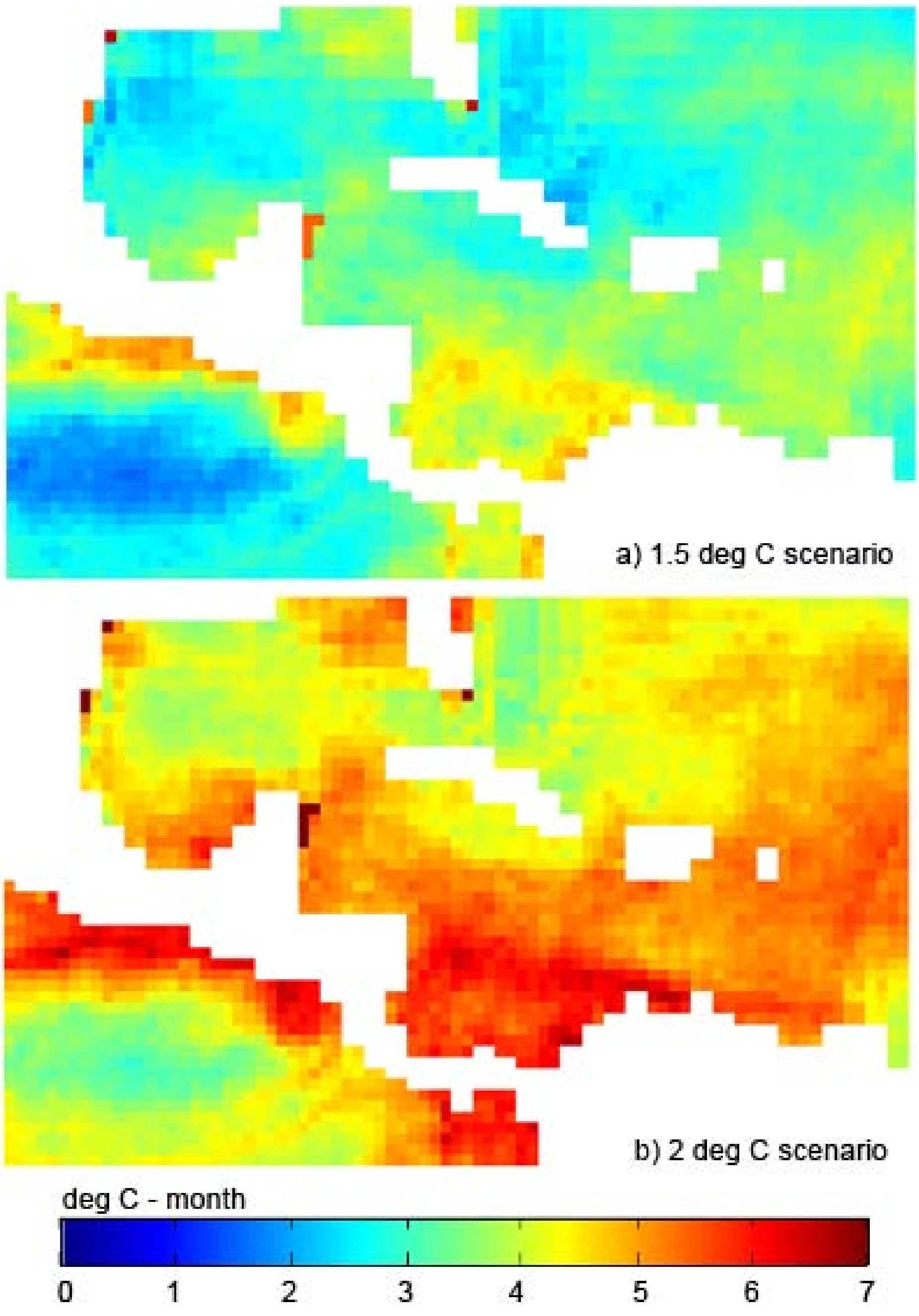


Figure 28: Mean annual degree heating month (DHM, in deg C - month) for the Caribbean region under the (a) 1.5°C global warming scenario and (b) 2.0°C global warming scenario. DHM>1 indicates significant bleaching; DHM>2 indicates widespread bleaching and significant mortality.

The likelihood of a Bleaching Alert Level 2 or “severe” mass coral bleaching event (DHM > 2°C - month) with 1.5°C threshold and 2°C threshold can be estimated by the annual accumulation of DHM for each coral reef grid cell in each year of the decadal time series extracted from the CM2.0 and CM2.1 simulations. The accumulation of DHMs exceeds the Bleaching Alert Level 2 across much of the Caribbean almost every year regardless of whether the warming threshold is set at 1.5°C or 2°C. In the 1.5°C warming scenario, the models simulations find that 99% of coral reef cells experience a Bleaching Alert Level 2 occurring every two years (Figure 29). In the 2.0°C warming scenario, the simulations find that over 99% of coral reef cells experience a Bleaching Alert Level 2 every year (Figure 29). This result follows from previous conclusions about the sharp increase in frequency of thermal stress events with even low levels of warming in the Caribbean (Donner et al. 2007).

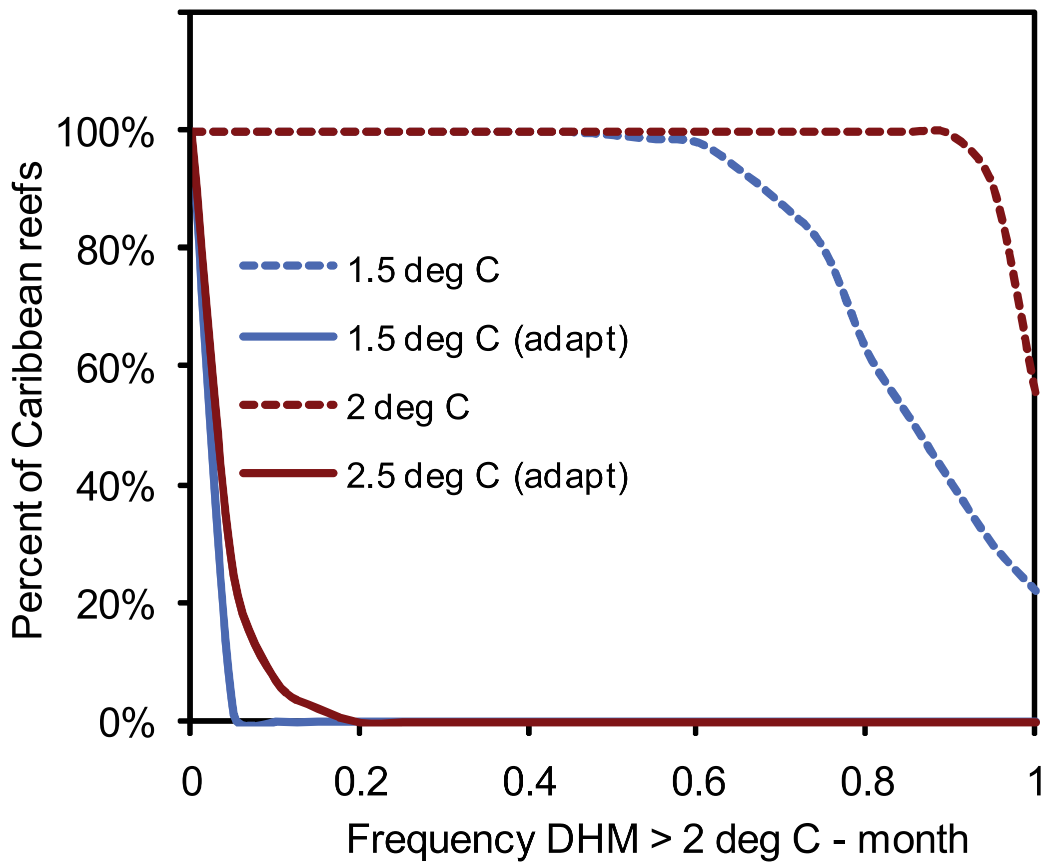


Figure 29: Probability of DHM > 2 Deg C - month for the 169 coral reef grid cells in the Caribbean region in the 1.5 deg (blue) and 2.0 deg (red) warming scenarios. Solid lines assume no change in thermal tolerance; dashed lines assume a 1.5 deg C increase in thermal tolerance. The probability is calculated from ten-year time series from the CM2.0 and CM2.1 simulations under SRES A1b in which mean Caribbean warming reached 1.5 deg C and 2.0 deg C, respectively.

The analysis was repeated using a Bleaching Alert Level 2 threshold based on historical climate variability in each coral reef grid cell (Donner 2009), rather than the set level of DHM > 2°C - month. The use of the variability-based threshold had a very minor effect on the results. For example, in the 1.5°C warming scenario, Bleaching Alert Level 2 events occur every two years in 96%, rather than 99%, of coral reef cells. The similarity between the bleaching frequency results with the standard bleaching threshold and the variability-base threshold suggests that the overall results from this analysis are not biased by historical experience of different coral reefs across the Caribbean.

The theoretical maximum increase in thermal tolerance of 1.5°C (Donner 2009) drastically reduces the mass coral bleaching forecasts in both scenarios. In 1.5°C warming scenario, there is extremely low mean annual DHM accumulation across the Caribbean, evidenced by the many zero values in the middle of the basin. This result is lower than current values because the regional Caribbean warming (1.13°C) is lower than the assumed maximum increase in thermal tolerance (Figure 30a). Since the assumed increase in thermal tolerance matches the regional Caribbean warming in the 2.0°C warming threshold, there is little increase in the mean DHM accumulation in this scenario over current levels (Figure 30b). The mean annual DHM reaches only 0.10°C in the 1.5°C warming scenario, but 0.40°C in the 2°C warming scenario (Figure 30b). In the 1.5°C warming scenario, the probability of a Bleaching Alert Level 2 event is less than 5%, or one-in-twenty years, across all coral reef grid cells in the Caribbean (Figure 29). The probability of a Bleaching Alert Level I event is less than 5% in 85% of Caribbean grid cells. In the 2.0°C warming scenario, Bleaching Alert Level 1 and Level 2 events are more common. For example, the probability of Bleaching Alert Level I and Level 2 events one-in-ten years is 25% and 57%, respectively.

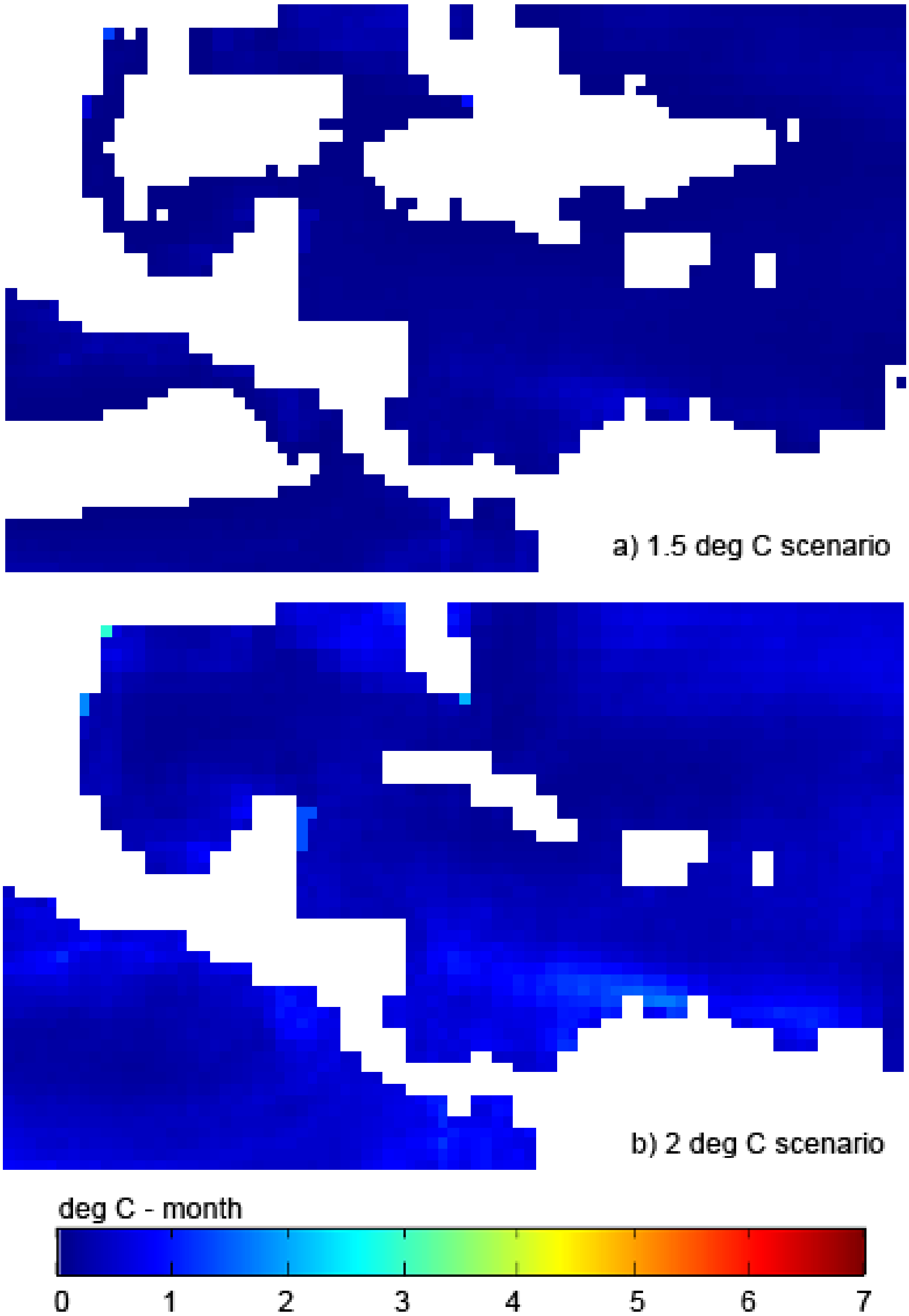


Figure 30: Mean annual degree heating month (DHM, in deg C - month) for the Caribbean region, assuming a 1.5°C increase in thermal tolerance, in the (a) 1.5°C global warming scenario and (b) 2.0°C global warming scenario. DHM>1 indicates significant bleaching; DHM>2 indicates widespread bleaching and significant mortality.

The results indicate that if thermal tolerance could, in fact, increase by 1.5°C across Caribbean coral reefs, due to biological mechanisms and management interventions, there would be some difference in the coral bleaching forecasts for the two proposed warming scenarios. Results from an additional set of scenarios, not shown, suggest a lower increase in thermal tolerance would result in an even more substantial difference between the scenarios. For example, a 1°C increase in thermal tolerance, Bleaching Alert Level 2 events occur one-in-ten years at 80% of the coral reef cells with a 2°C global mean warming, but at only 7% of the coral reef cells with a 1.5°C global mean warming.

The proposed increase in thermal tolerance is highly theoretical and intended as an upper limit; the value of 1.5°C is based on the total thermal flexibility observed in the common Indo-Pacific Acropora species (Berkelmans and van Oppen 2006, Middlebrook et al. 2008). Even if the proposed increase in thermal tolerance is biologically possible, it could take decades to occur (e.g., for temperature-tolerant symbiotes and/or more thermally resistant coral taxa to become dominant) and would come with additional costs such as reduced productivity, growth, and/or fecundity in surviving corals and symbiotes (Loya et al. 2001, Bhagooli and Yakovleva 2004, Little et al. 2004, Sotka and Thacker 2005, Jones et al. 2008a).

In particular, the rate of change of thermal tolerance across a coral reef assemblage depends on a dynamical interaction between coral host and symbiote acclimatization, shifts in community composition, and genetic adaptation (Hughes et al. 2003). Of these dynamics, the instantaneous increase in the thermal tolerance in the simulations presented here best represents either acclimatization or shifts in coral or, more likely, symbiote community composition because such dynamics can occur on faster time scales than genetic adaptation. Shifts in the prevalence of different symbiote types with different thermal tolerances can occur in corals which have the capacity to host multiple symbiote types (Hughes et al. 2003, Sotka and Thacker 2005). However, many corals can only host one symbiote type and therefore do not have the capacity for within-coral shifts in symbiote community composition (Goulet 2006, Baker and Romanski 2007, Goulet 2007).

Therefore, depending on the degree of climate change and thus thermal stress, the coral community composition could shift toward a greater prevalence of coral species that can host multiple symbiote types, that tend to host more stress-tolerant symbiote types, and/or that have physiological or morphological characteristics that lead to greater host stress tolerance. Such shifts might occur slowly given typical coral growth rates and life spans, especially with the association between increased stress-tolerance and slower growth rates in corals (Loya et al. 2001, Bhagooli and Yakovleva 2004). In addition, given the association between stress tolerance and massive-type coral morphology (Loya et al. 2001), coral community composition shifts might cause changes in the reef topography that creates habitat for many species, with cascading effects on the coral reef community (Bellwood et al. 2004). Therefore, the potential for changes in coral diversity and community composition have implications for the diversity of entire reef assemblages.

Furthermore, if coral community response to thermal stress occurs slowly, reefs might pass through population bottlenecks during which coral cover drops substantially following extreme bleaching mortalities. During this period, macroalgae might flourish, depending on nutrient levels and herbivorous fish population sizes (Hughes 1994), and subsequently reduce recruitment and regrowth of coral reefs (McCook et al. 2001). Such dynamics have the potential to impede coral recovery that would otherwise occur (Mumby et al. 2007, Baskett et al. 2009b). Therefore, levels of thermal stress that might allow coral reef persistence when considering corals in isolation have the potential to lead to dramatic shifts in the composition of tropical reefs when considering additional interacting species (Baskett et al. 2009b).

Finally, another possible response to climate change is genetic evolution in thermal tolerance, especially in the symbiotes given their short generation time (Ware 1997, Lasker and Coffroth 1999). In general, whether adaptive evolution can keep up with the rate of environmental change depends on a variety of parameters such as the heritability of the evolving trait, the strength of selection acting on that trait, and the maximum population growth rate (Lynch et al. 1991, Lynch 1996). Given that a number of these parameters are poorly known for symbiote thermal tolerance, one cannot make precise forecasts of adaptive potential. However, population genetic models of evolution in symbiote thermal tolerance in response to future climate change indicate that the rate of climate change, as it ranges between large-scale emission reductions and business-as-usual IPCC future climate scenarios (550-720 ppm stabilization), could determine whether evolution can track contemporary climate change (Baskett et al. 2009a). Such model sensitivity to the future climate scenario occurs under multiple climate models and at multiple locations globally, including Caribbean locations (Baskett et al. 2009a). Unfortunately, most adaptations to warming, such as shifts in the productivity of zooxanthellae, may exacerbate the problems caused by simultaneous ocean acidification (Hoegh-Guldberg et al. 2007). In sum, taking all of these ecological and evolutionary dynamics into consideration further indicates the importance of rate of climate change in determining overall coral reef response suggested by the adaptation simulations presented here.

3.1.3.2.2 IMPACT OF ACIDIFYING OCEAN WATERS ON CARIBBEAN CORALS AND CORAL REEFS

In addition to the thermal stress impacts on corals, continued increases in atmospheric CO_2 will have dramatic impacts on the carbonate chemistry of the Caribbean. The model used to monitor changes in ocean chemistry during recent years (Gledhill et al. 2008) was applied to scenarios of potential atmospheric CO_2 increases. While global temperatures lag significantly behind changes in atmospheric CO_2, ocean acidification does not (equilibrium is reached within one year). Therefore, we considered carbonate chemistry under two different sets of scenarios: the CO_2 at which we achieve equilibrium between temperatures and stabilized CO_2 for both 1.5°C and 2.0°C globally-averaged warming (350 ppm and 450 ppm respectively), and also the peak CO_2 levels through which we are likely to transit during the 21st century. This clearly supports the need to eliminate GHG emissions as soon as practicable to maintain temperature rise to less than 1.5°C increase.

Since global temperatures lag significantly behind changes in atmospheric CO_2, both sets of model runs described above were used here (21st century warming earth and earth at equilibrium). The atmospheric CO_2 levels that correspond to those decades at which we expect to reach global temperatures 1.5°C above pre-instrumental will be much higher in this century (490 ppm) than when the climate system eventually equalizes (350 ppm). Similarly, 21st century atmospheric CO_2 levels at 2.0°C above pre-industrial (550 ppm) are much higher than those at equilibrium (450 ppm). The model was run using global values of atmospheric CO_2 because CO_2 is so well mixed in the atmosphere and mixes into the surface ocean waters within a year. Therefore, global values do not differ significantly from Caribbean atmospheric values or Caribbean surface ocean CO_2.

Figure 31 shows the relationship between atmospheric CO_2 levels and average aragonite saturation state in Caribbean surface waters over a range of atmospheric CO_2 levels of 340-560 ppm. Important levels to note correspond to 350, 450, 490, and 550 ppm. From the 1980s, when atmospheric CO_2 rose above 350 ppm, to today, the average aragonite saturation state across the Caribbean has been at a level considered adequate (but sub-optimal) for coral reef growth (3.5-4.5). If we can revert atmospheric CO_2 concentrations back to 350 ppm and maintain 1.5°C of warming, the average aragonite saturation state across the Caribbean would remain at levels generally considered to be adequate for coral reef growth (3.5-4.5). However, achieving this stabilization would still transit through a period whereby saturation states would decline between 20-25% relative to pre-industrial values (pre-industrial saturation state was approximately 4.7) before returning to conditions better than today's (Figure 31, green line). In contrast, stabilizing at 2.0°C (Figure 31, red line) would require transiting through a period when CO_2 reaches around 550 ppm and saturation states decline by more than 30% relative to pre-industrial values, making it unlikely that coral reefs will be able to maintain net growth in light of natural erosion and dissolution. Once atmospheric levels drop back to 450 ppm the saturation state levels would recover to values greater than 3.6 – a level considered adequate to sustain reef growth. The curves in Figure 31 are probably unrealistically optimistic – it is doubtful that we will achieve such an abrupt about-face in both emissions and total atmospheric CO_2. However, they advise us on the impacts to carbonate saturation state and coral reefs. The longer CO_2 remains at high levels, the greater the damage to reefs. If atmospheric CO_2 is allowed to exceed 900 ppm aragonitic limestone like that built by corals begins to dissolve.

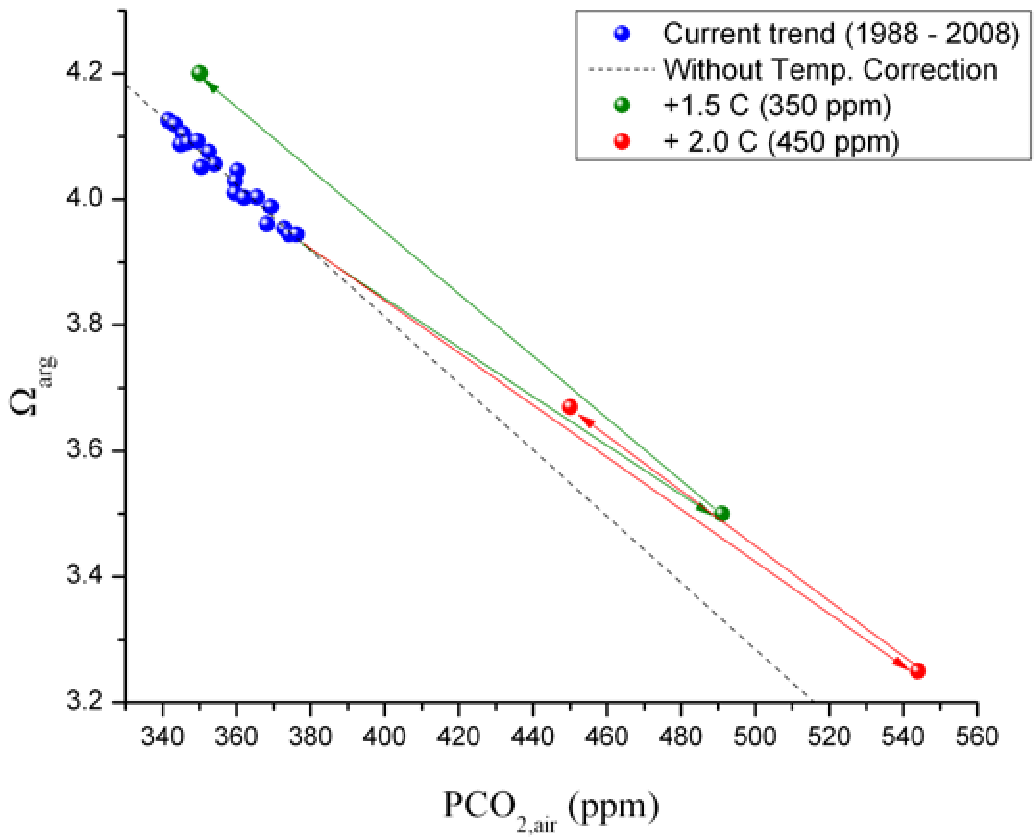
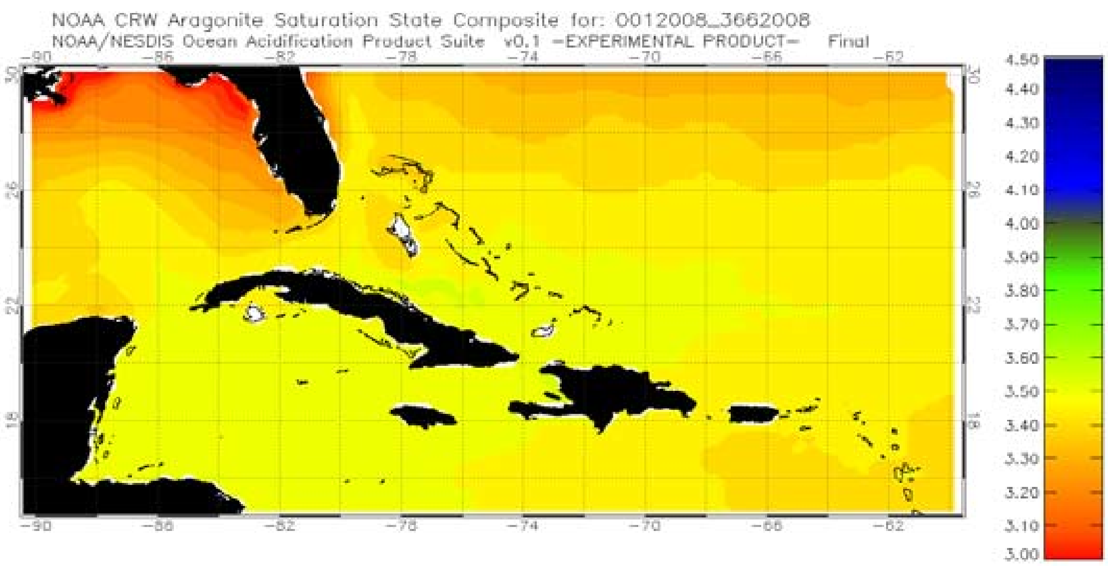


Figure 31: Relationship of global atmospheric CO_2 level to aragonite saturation state in the Caribbean.

The recent data are shown as the blue globes. The green and red globes follow the path of saturation state changes if global temperature is stabilized at 1.5° and 2.0°C above pre-industrial, respectively. At an atmospheric CO_2 of 530-570 ppm we reach a saturation state of 3.0, below which reefs are unlikely to maintain enough growth to balance natural erosion and dissolution.

As with temperature stress, saturation state varies across the Caribbean. Figure 32a shows the variation of saturation state that we are likely to see in the 21st century decade when we reach 1.5°C above pre-industrial levels, and approximately 490 ppm atmospheric CO_2. Figure 32b shows saturation states at 2.0°C and 550 ppm. The difference between these two scenarios is the difference between conditions that are largely adequate for reef growth and those that are nearing the point where erosion exceeds reef growth. Additionally, these saturation states are reported relative to aragonite. Biogenic carbonate mineral phases containing high amounts (>10%) of magnesium frequently occur amongst coral reefs and these minerals tend to be more soluble than aragonite. Furthermore, these values represent annual mean oceanic values and it is well documented now that in most reef zones there can be a step-down in aragonite saturation state as a consequence of calcification processes. In the evening hours, respiration can also serve to drive saturation states even lower. In addition, considerable seasonality occurs particularly in the upper latitudes of the region. Consequently, it is likely that while annual mean oceanic aragonite saturation states may be adequate, within the reef zone itself it is likely we will experience net carbonate loss from some reefs within the region during the higher CO_2 transits. This clearly supports the need to eliminate GHG emissions as soon as practicable and work to maintain temperatures as close to 1.5°C increase as possible.

(a)



(b)

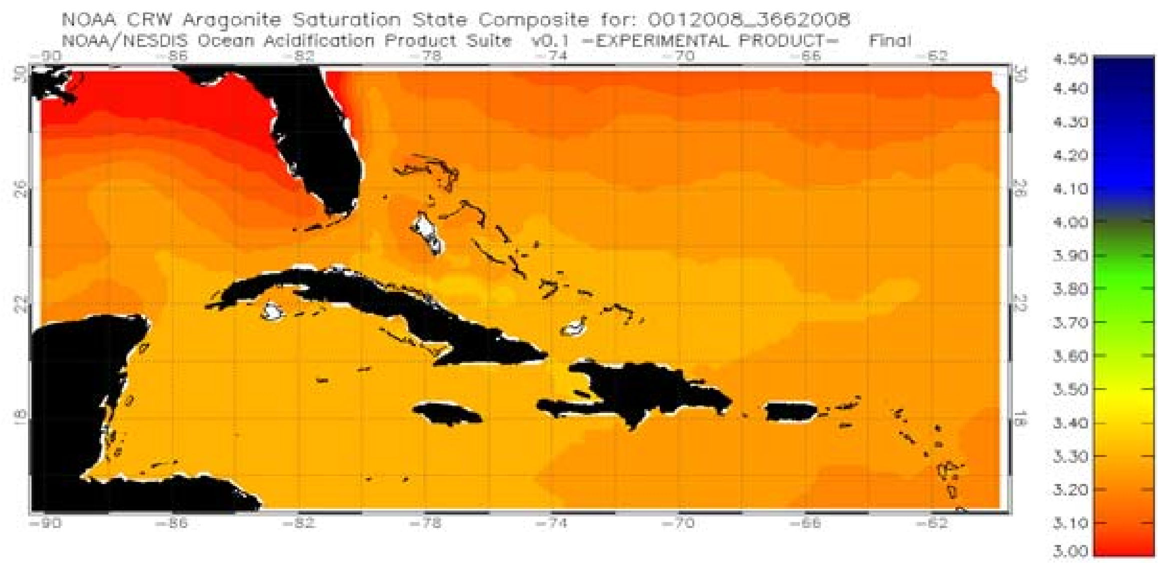
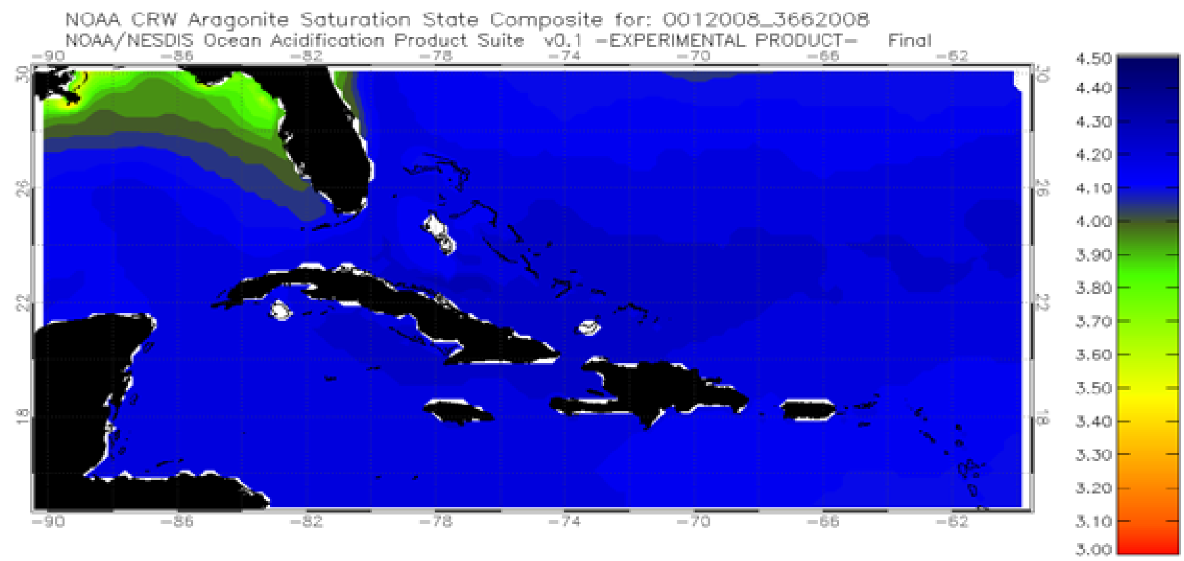


Figure 32: Map showing annual mean aragonite saturation state values during the 21st century decade when globally averaged atmospheric temperatures reach (a) 1.5°C above the pre-industrial value (and estimated 490 ppm CO_2), and (b) 2.0°C above the pre-industrial value (and estimated 550 ppm CO_2).

These correspond to the atmospheric CO_2 conditions in the 21st century decades in which the conditions in Figure 32 are reached. Note that saturation state > 4.5 is considered optimal for coral growth, 3.5-4.5 is adequate, and below 3.0 erosion is likely to exceed reef growth.

In contrast, Figure 33 shows conditions in a future century when the climate system has reached equilibrium. The difference is striking, as corals across most of the Caribbean are in conditions that are in the upper half of the range adequate for reef growth at 1.5°C and 350 ppm. At 2.0°C and 450 ppm, conditions may near the bottom of the range considered adequate and, as discussed above, will suffer repeated bleaching even if we assume corals can adapt to 1.5°C of warming. Unfortunately, recent work has shown that more acidic conditions may increase the susceptibility to bleaching (Anthony et al. 2009, Crawley et al. 2009) and we know that slower reef growth will hinder the ability of corals to grow back after bleaching events.

(a)



(b)

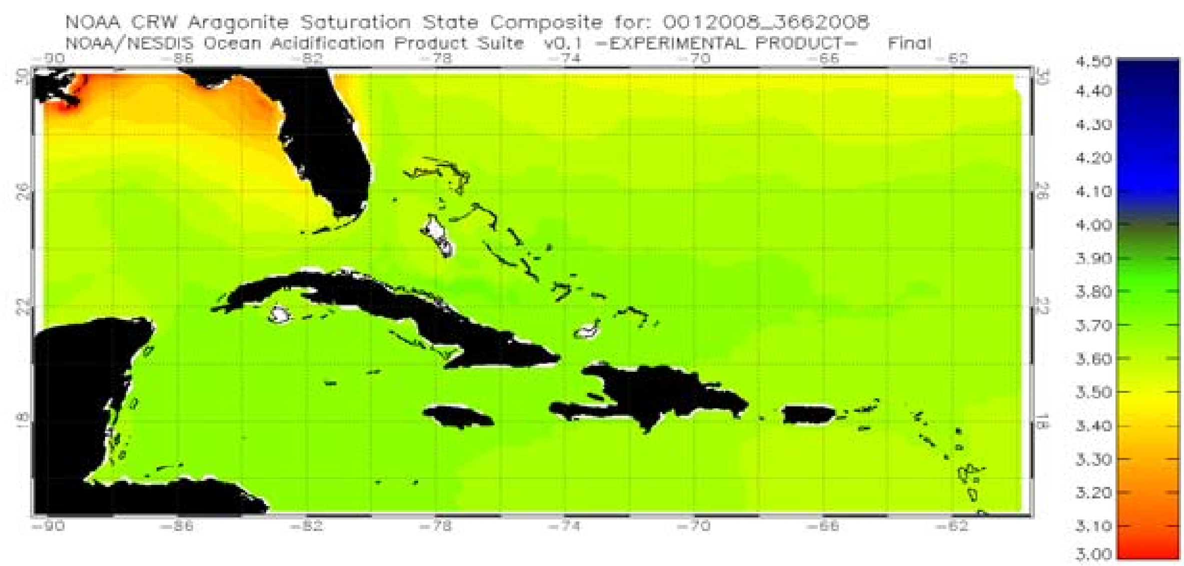


Figure 33: Map showing annual mean aragonite saturation state values in the future is stabilized at an atmospheric CO_2 level and globally averaged atmospheric temperatures of (a) 350 ppm CO_2 and 1.5°C above the pre-industrial value, and (b) 450 ppm CO_2 and 2.0°C above the pre-industrial value. Note that saturation state > 4.5 is considered optimal for coral growth, 3.5-4.5 is adequate, and below 3.0 erosion is likely to exceed reef growth.

3.1.4 CONCLUSIONS AND RECOMMENDATIONS

Adaptation through biological mechanisms and management may allow some Caribbean coral reefs to avoid severe degradation from frequent bleaching events and survive up to a 1.5°C warming. Such adaptation is uncertain and, if possible, would come with other costs such as reduced diversity and productivity. In summary, two sets of actions are required for the continued survival of coral reefs:

(1) Rapid reduction of CO_2 emissions and eventual reduction of atmospheric CO_2 level, and

(2) Management actions to help corals survive until we stabilize the climate system.

For the latter, we need to develop a comprehensive set of actions that (a) reduce the local impacts of climate change and ocean acidification, and (b) enhance resilience of coral reef ecosystems. It is highly unlikely that adaptation through biological mechanisms and management will be sufficient to avoid severe degradation of coral reefs from frequent bleaching events if the temperature increase exceeds 1.5°C above pre-industrial levels. More importantly, most adaptation to warming is likely to exacerbate the problems caused by acidification making the combination of these two impacts even more severe. These impacts will be even more severe at 2.0°C.

3.2 IMPACTS ON WATER RESOURCES

The IPCC AR4, projects global mean precipitation to increase by around 4-5%, but finds overall decreases over many sub-tropical areas (including tropical Central America and the Caribbean). In addition, it is considered very likely that when precipitation occurs it will become more concentrated in shorter duration, intense events interspersed with longer periods of relatively dry conditions (Bates et al. 2008). Not only would this high runoff increase the risk of flooding, it would also reduce the amount of groundwater recharge which occurs and cause problems for those countries which are dependent on surface water but do not have sufficient water storage. A significant increase in the number of consecutive dry days has also been found for the Caribbean region (Bates et al. 2008). Section 1 of this report provides a detailed discussion of potential changes in precipitation patters under climate change.

Multiple research papers have assessed GCMs for likely changes to water resources, but few have looked at more than one or two models (e.g. Arnell, 2004; Alcomo et al. 2007). Alcomo et al. (2007) assessed global changes in water stress under climate change and included multiple factors including precipitation and socio-economic trends under different climate scenarios. They found that, for many areas, water stresses increase under climate change (e.g. southern Europe); but others (e.g. southern Asia) water stress decrease. However, since their focus was global, there is a lack of detail for the Caribbean region.

Published research on water resources and climate change focuses on global projections of water resources, rather than focussing on particular regions. Consequently it is difficult to derive projected impacts of climate change on water resources in the Caribbean region, since many countries are smaller than the scale of the mapping used. In this analysis, the GCM outputs used in the AR4 were obtained from the IPCC Data Centre and the Caribbean region was extracted. In addition, GCM projections were thresholded at the point where global mean temperature increases reached 1.5°C and 2.0°C, and precipitation projections extracted.

3.2.1 PROJECTED IMPACTS ON PRECIPITATION PATTERNS IN THE CARIBBEAN REGION

For freshwater resources, precipitation is one of the most important drivers (Kundzewicz et al., 2007), but is considerably more difficult to model than temperature, primarily due to its high spatial and temporal variability and nonlinear nature. Climate model projections for precipitation flux were obtained for the B1, A1B and A2 scenarios from the IPCC Data Distribution Centre: 17 model projections were available for the B1 scenario; 21 were available for A1B; and 15 for A2.[36] Twenty-year projected averages were obtained, and the percentage change in precipitation between 1980-1999 and 2080-2099 was calculated for each model.

The three month average precipitation changes for the Caribbean region for the B1, A1B and A2 scenarios are shown in Figure 34. For much of the Caribbean region, the projected change to mean precipitation is negative (see also Section 1). For the B1 scenario, the projected changes are generally small and display high uncertainty in that not all models agree on the direction of the change, with some models projecting an increase in precipitation. However, the greatest uncertainty in the direction of projected change is expected where the mean of the projections is close to zero, which is the case for large areas of the moderate B1 scenario. For the A2 scenario, the projected changes are more substantial and there is a high level of agreement on the direction of change across the climate models, with large parts of the region projected to experience a greater than 25% drop in average precipitation levels.

The largest changes in the projections are observed in the generally wet months of June - August, across the whole region. Between March and May, the largest decreases are projected for the north and west of the Caribbean region, with smaller mean precipitation changes and greater uncertainty in the south. Between September and November, this situation is reversed with the larger decreases projected for the south-east of the region, and smaller changes and greatest uncertainty elsewhere.

While there is considerable variability in GCM projections of precipitation, on the whole, the Caribbean region is projected to have a decline in precipitation levels (see also Section 1). For those CARICOM states which are already facing issues of water insecurity, this is likely to increase the severity of their water resource problems; for other states which currently have sufficient water resources, a decline in precipitation levels may introduce new water resources issues.

36 See http://www.ipcc-data.org/ar4/var-precipitation_flux.html for a list of available models.

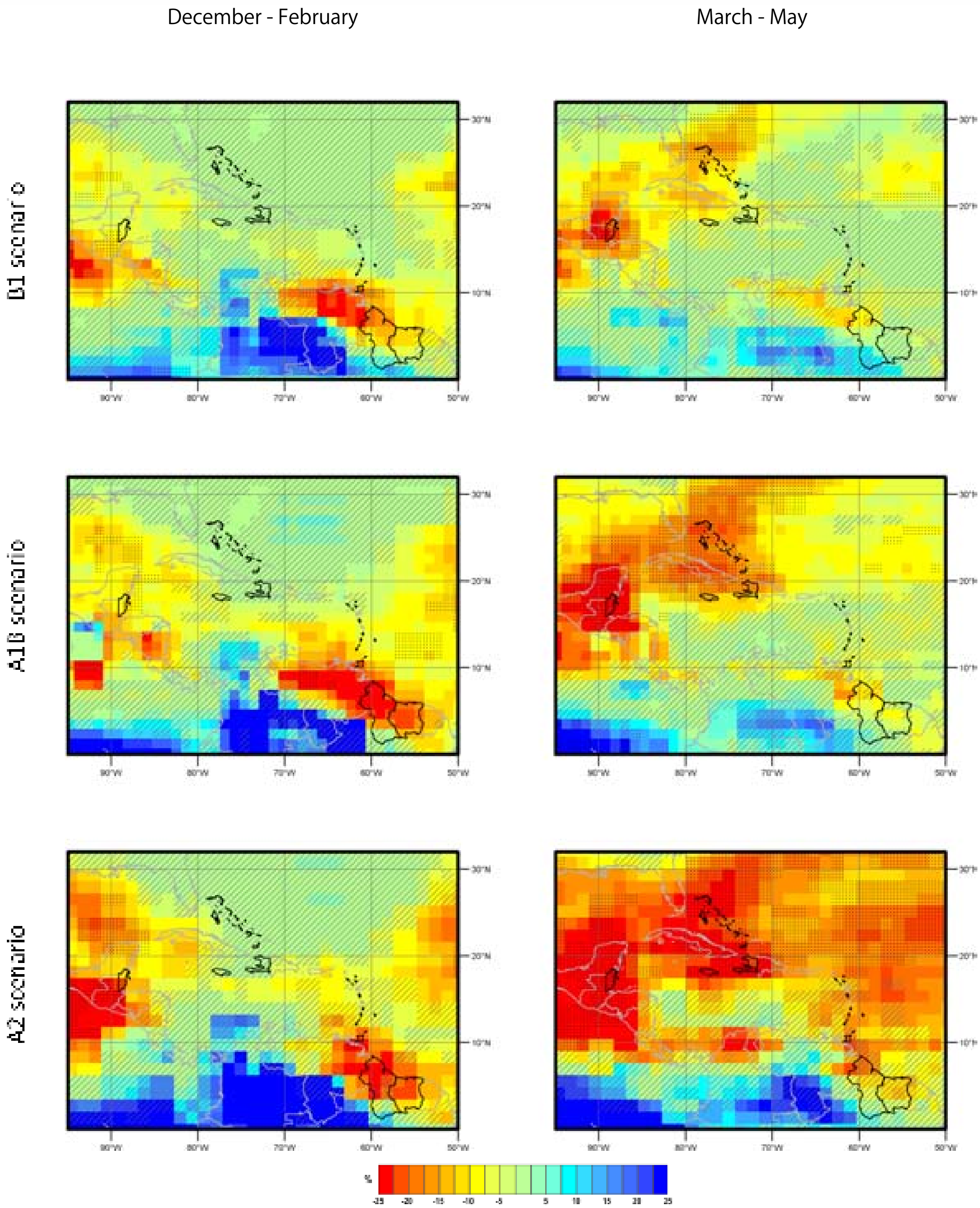


Figure 34: Mean GCM projections of change to precipitation for the Caribbean region for 2080-2099, relative to 1980-1999, for three-month periods of December-February, March-May, June-August and September-November. The top row shows projections for scenario B1, the middle row shows A1B and the bottom row shows scenario A2. Cross-hatching indicates where less than 66% of the GCMs agree in the direction of the change; stippling indicates where more than 90% of the GCMs agree in the direction of the change. Country outlines are shown in grey, with CARICOM nations indicated in black.

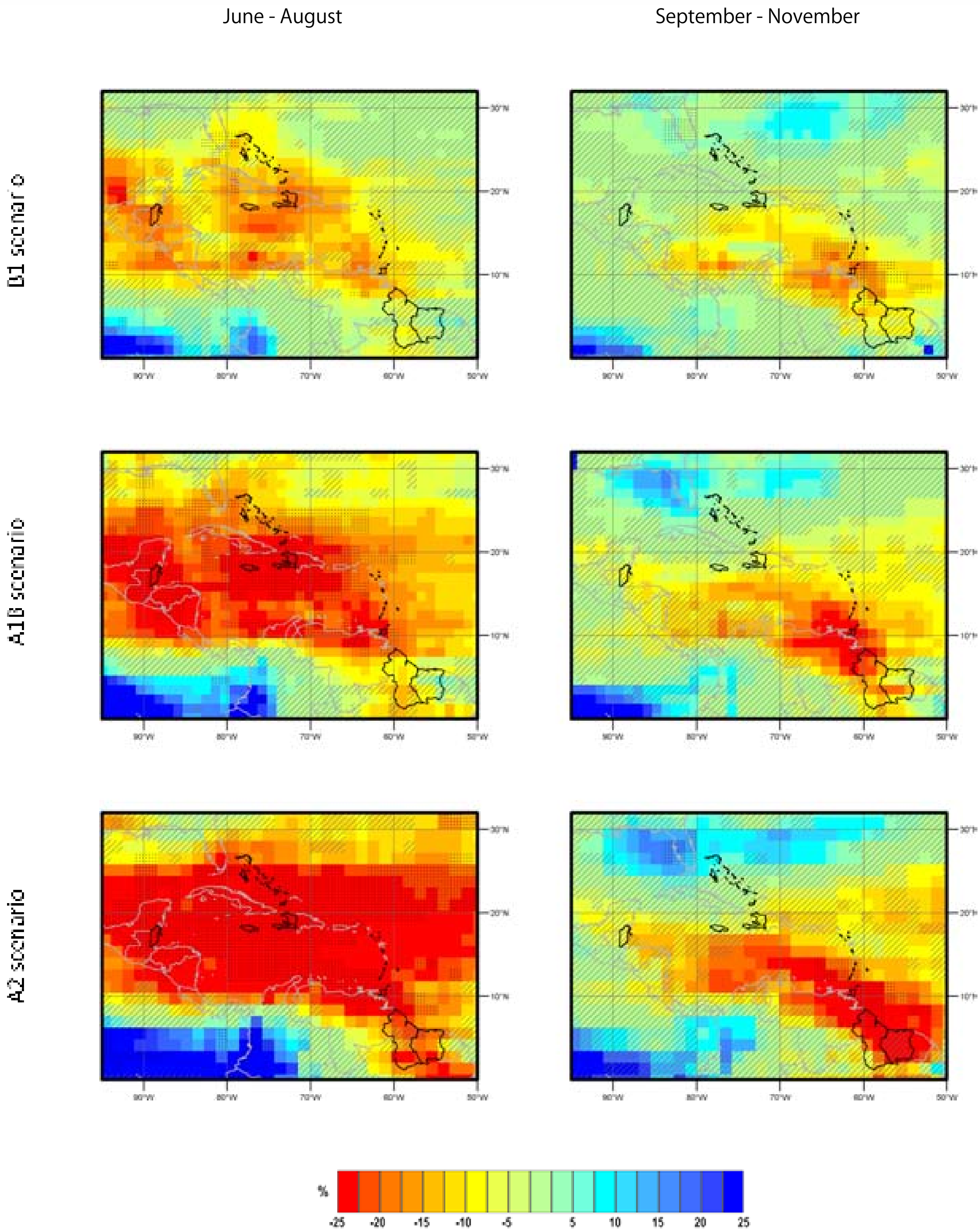


Figure 34 (continued).

3.2.2 PROJECTED IMPACTS ON WATER RESOURCES OF INDIVIDUAL COUNTRIES

In this section summaries of the current water resource situation in each CARICOM member state are provided and, in particular, how the water resources of each state may be affected by climate change. In Table 18 the projected annual precipitation levels for 2080-2099 in each country is shown, together with changes to precipitation levels which are based on climate model predictions of 1980-1999, not measured precipitation for each country. This distinction is important since it illustrates the fact that GCM predictions are over large areas rather than for specific point locations and so are not comparable to station measurements. Each individual grid cell in a climate model may be as much as 150km across, or 22500km^2 in area: this is more than twice the size of Jamaica (the third largest island in the Caribbean behind Cuba and Hispaniola), around the size of Belize (the fourth largest CARICOM nation behind Guyana, Suriname and Haiti), and more than 200 times the size of Montserrat (the smallest CARICOM nation). For this reason, each projection must be treated with caution since, for the majority of countries in CARICOM, each of the GCM cells which cover island states largely represents the open water of the Caribbean Sea and misses much of the orographic effects of small island topography on rainfall. Therefore, projections of precipitation at each location are very different to observed levels; however, the relative changes to precipitation found in the vicinity of each CARICOM country are valuable since actual observed rainfall is intrinsically related to the situation in the wider area surrounding it. Hence, the projected general declines in precipitation are a cause for concern for CARICOM states. In order to more fully assess the impact of the climate projections on water resources in each country, it would be necessary to scale the climate projections to the level at which hydrological processes occur (Kundzewicz et al., 2007) using downscaling methods (see Fowler et al. 2007).

In each of the climate scenarios provided in Table 18, the mean of the IPCC AR4 GCM projections is shown, together with the standard deviation. These values are based on calculations using outputs from the same set of global climate models as those in Figure 34, which were the same as those used for the IPCC AR4 report. While there is considerable variability in the projections, as illustrated by the relatively high standard deviation across the GCM projections, models consistently project a decline in precipitation across almost all countries, in all scenarios, and these declines are larger in the higher GHG emissions scenarios of A1B and A2. The mean monthly change in daily precipitation rates across projections for all climate models available from the IPCC is shown in Figure 35. Each plot shows the average GCM projection for 2080-2099 for each month, based on predictions for 1980-1999. These illustrate that, for many countries, the decline in precipitation is projected to occur during the months which are usually wet, and particularly during the months of May to August.

Table 18: Multi-model climate projections of total annual precipitation for CARICOM states in 2080-2099.

	Scenario: B1				Scenario: A1B				Scenario: A2			
	Mean projected annual rainfall[1] (mm)	Standard deviation (mm)	Change[2] (mm)	% Change	Mean projected annual rainfall[1] (mm)	Standard deviation (mm)	Change[2] (mm)	% Change	Mean projected annual rainfall[1] (mm)	Standard deviation (mm)	Change[2] (mm)	% Change
Antigua and Barbuda	604	299	-34	-5.3	616	295	-94	-13.3	649	361	-178	-21.5
Bahamas (north)	1055	390	-54	-4.8	1113	375	-110	-9.0	1113	379	-130	-10.4
Bahamas (south)	804	473	-18	-2.1	927	410	-86	-8.5	856	480	-136	-13.7
Barbados	722	383	-83	-10.3	757	449	-145	-16.0	715	364	-269	-27.3
Belize	825	658	-63	-7.1	900	694	-192	-17.6	710	646	-204	-22.3
Dominica	684	360	-48	-6.5	668	391	-109	-14.1	654	367	-197	-23.2
Grenada	650	257	-119	-15.5	677	317	-191	-22.0	581	262	-288	-33.2
Guyana (north)	874	664	-107	-10.9	825	445	-171	-17.2	778	676	-192	-19.8
Guyana (south)	1204	647	22	1.9	1124	567	-34	-2.9	999	691	-74	-6.9
Haiti	691	554	-36	-4.9	632	434	-98	-13.5	641	522	-179	-21.8
Jamaica	652	435	-60	-8.4	784	372	-140	-15.2	678	408	-198	-22.6
Montserrat / Saint Kitts & Nevis [3]	659	362	-35	-5.1	616	295	-94	-13.3	649	361	-178	-21.5
Saint Lucia	705	373	-65	-8.4	675	332	-167	-19.8	592	279	-244	-29.2
Saint Vincent and the Grenadines	653	280	-95	-12.6	675	332	-167	-19.8	581	262	-288	-33.2
Suriname (north)	1000	696	-61	-5.7	912	521	-125	-12.0	765	550	-183	-19.3
Suriname (south)	1012	569	-30	-2.9	939	491	-84	-8.2	952	823	-108	-10.2
Trinidad and Tobago	738	629	-140	-15.9	651	399	-241	-27.0	622	621	-318	-33.8

Source: IPCC Fourth Assessment Report (SRES Scenarios) multi-year climate model means, available from http://www.ipcc-data.org/

Notes:

[1] Projected annual rainfall is obtained from the mean of multiple climate model predictions for 2080-2099. Climate projections are for large grid cells which generally include a high proportion of open sea and miss the spatial complexity of rainfall patterns, particularly with regard to high topography on small islands. For this reason, values should be used as a general guide of trends only.

[2] Changes are relative to climate model output for 1980-1999.

[3] Monserrat and Saint Kitts & Nevis have the same values since they are in close proximity and occupy the same grid cell in available IPCC Fourth Assessment climate model output.

Table 19: Projected percentage differences in precipitation for each CARICOM state at 1.5 and 2.0°C increases in global average temperature.

	1.5°C (%)									2.0°C (%)								
	Dec-Feb			Jun-Aug			Annual			Dec-Feb			Jun-Aug			Annual		
	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Antigua and Barbuda	-26.7	-1.0	20.3	-31.7	-7.7	13.3	-29.2	-3.4	19.0	023.0	-2.0	22.3	-40.3	-9.7	20.8	-33.3	-4.7	20.8
Bahamas (north)	-20.0	5.6	46.3	-13.6	19.6	108.0	-16.6	11.2	66.5	-27.0	10.3	69.6	-9.3	22.0	97.7	-18.2	14.4	75.8
Bahamas (south)	-19.3	3.0	33.3	-10.6	18.3	107.6	-16.2	9.5	62.2	-29.0	5.0	43.3	-11.6	22.6	110.0	-19.1	12.6	72.3
Barbados	-19.3	1.6	24.3	-8.3	14.6	65.3	-15.7	7.3	44.8	-28.3	2.3	35.6	-13.3	19.0	68.6	-20.5	9.3	54.6
Belize	-21.0	1.0	26.6	-6.0	12.6	51.0	-15.6	5.6	36.7	-28.0	0.0	32.0	-10.3	16.3	53.6	-20.4	7.1	41.4
Dominica	-22.3	0.6	29.3	-4.3	8.3	29.3	-15.0	3.6	27.2	-29.3	-1.3	37.0	-11.3	10.3	34.3	-20.5	4.2	31.5
Grenada	-24.0	1.3	35.0	-5.6	5.6	21.6	-16.2	2.9	24.8	-31.3	-1.3	48.0	-12.3	6.0	22.6	-21.8	2.2	30.6
Guyana (north)	-24.3	2.0	46.0	-9.3	3.3	14.0	-18.5	2.3	27.7	-32.3	-1.0	57.3	-13.3	2.6	17.6	-23.6	1.0	33.6
Guyana (south)	-24.3	1.0	49.7	-15.6	0.0	12.6	-22.2	0.7	29.5	-34.0	-1.6	58.3	-18.6	-1.0	14.3	-27.5	-1.1	33.3
Haiti	-25.6	-2.0	41.0	-25.3	-2.6	12.0	-25.7	-1.2	29.5	-35.6	-4.0	60.3	-28.3	-4.3	15.0	-31.6	-3.4	35.6
Jamaica	-29.6	-5.3	29.6	-31.6	-5.3	10.6	-30.2	-3.1	26.2	-38.3	-7.3	48.6	-35.3	-7.6	14.0	-35.9	-6.0	31.1
Montserrat	-37.3	-8.3	29.3	-29.6	-6.3	13.3	-32.2	-4.4	27.2	-40.3	-11.3	37.6	-36.3	-9.0	15.3	-36.9	-7.6	28.3
St. Kitts & Nevis	-46.3	-12.0	33.0	-30.3	-6.3	16.3	-36.7	-5.4	34.6	-45.6	-15.6	42.0	-39.3	-10.3	16.3	-40.1	-9.1	30.9
Saint Lucia	-58.6	-13.3	53.3	-34.3	-7.0	16.3	-40.4	-5.5	43.5	-59.6	-19.0	52.6	-44.3	-11.3	16.0	-44.2	-10.2	34.1
St. Vincent and the Grenadines	-51.6	-14.3	44.0	-37.6	-7.6	15.3	-42.4	-7.1	37.8	-58.6	-20.6	43.3	-52.0	-11.6	15.0	-47.3	-11.3	31.2
Suriname (north)	-52.3	-11.3	34.3	-39.0	-8.0	13.6	-42.0	-6.9	31.2	-59.3	-18.3	30.3	-52.0	-12.3	14.3	-48.8	-10.4	30.6
Suriname (south)	-36.3	-7.3	38.3	-40.6	-9.0	9.6	-38.0	-6.6	27.0	-43.3	-13.0	37.0	-51.3	-14.0	10.3	-44.4	-9.4	33.6
Trinidad and Tobago	-29.0	-7.0	14.0	-42.3	-10.0	10.6	-36.8	-7.2	18.4	-36.0	-11.0	20.6	-55.6	-16.3	8.0	-42.7	-10.2	23.9

Note: differences are based on the 1970-1999 precipitation mean, and are derived from 21-year means centred on the projected year of 1.5 or 2.0°C global mean temperature increases. Statistics are based on multi-model ensembles.

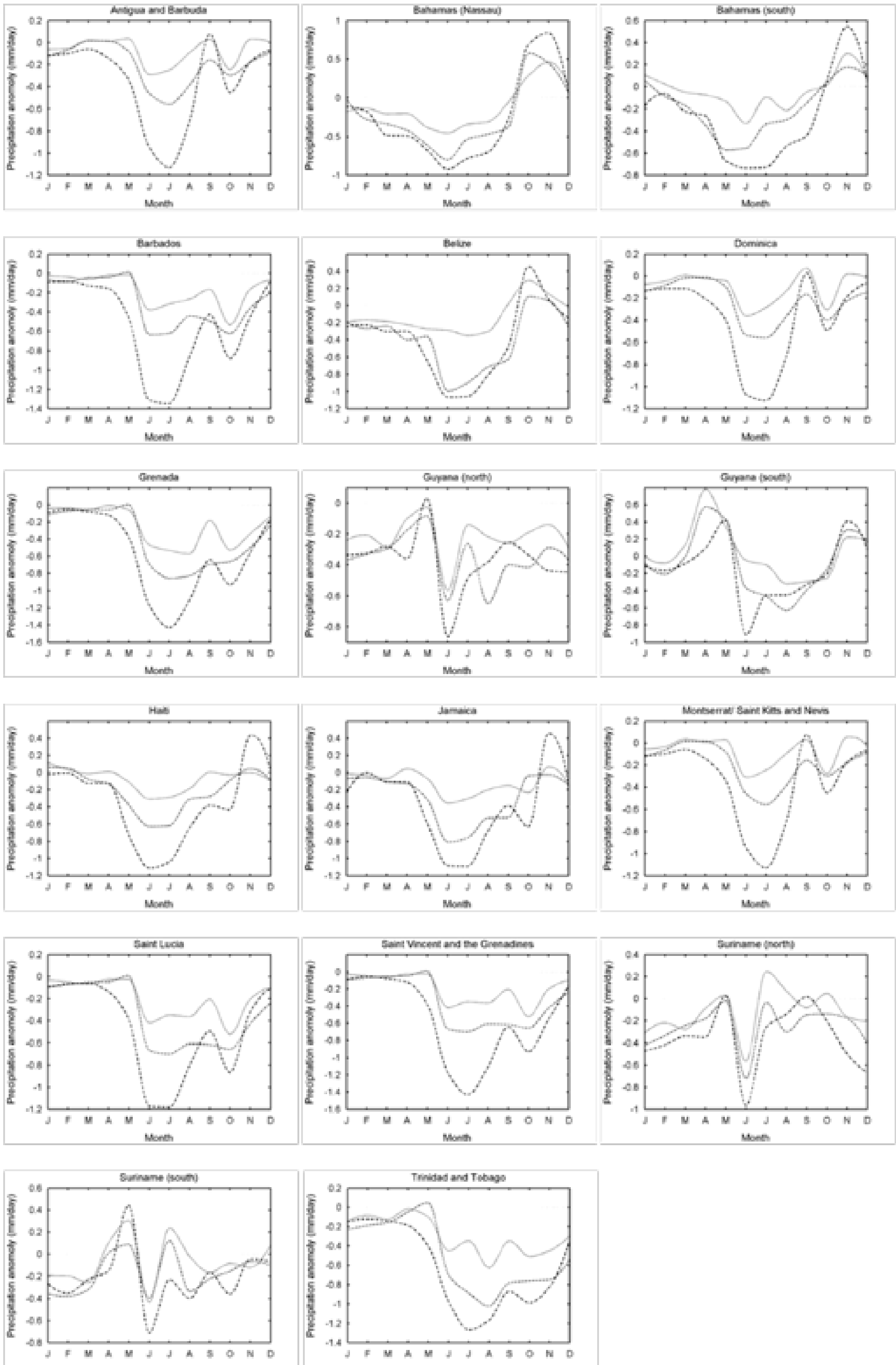


Figure 35: Multi-model mean climate projections of average monthly precipitation anomolies for 2080-2099 for CARICOM states, based on climate model predictions for 1980-1999. Projections for three SRES scenarios are shown: the light-grey/solid line is B1; medium-grey/dotted is A1B; and black/dashed is A2.

Antigua and Barbuda

Antigua and Barbuda are islands with a moderate arid and tropical maritime climate. The average annual rainfall for Antigua ranges from 890 to 1400 mm; for Barbuda, average annual rainfall is lower, ranging from 508 to 991 mm (USACE, 2004b). Fresh water is a scarce resource in the country and there is a history of water shortages and droughts.

Water supply in Antigua is obtained from a combination of surface water, ground water and desalination plants, with desalination providing 60% and 75% of the water supply in the wet and dry seasons, respectively (USACE, 2004b). Despite the high costs associated with it, desalination is deemed necessary due to undependable alternative supplies. The limited groundwater reserves are also threatened by excessive use and saltwater intrusion. During droughts, the proportion of water provided by desalination may increase to 83% (USACE, 2004b).

Barbuda is dependent predominantly on ground water (USACE, 2004b), which is in a semi-fragile state due to a high water table: the ground water is less than 1.5 meters below ground surface and an increase in sea level could lead to saltwater intrusion. Barbuda is also susceptible to drought, with annual rainfall falling below 706 mm ten times between 1965 and 2000.

Hurricanes and tropical storms can make drought conditions in Antigua and Barbuda worse by removing the topsoil through runoff caused by extreme rainfall associated with the events, which leads to the formation and deepening of gullies and the erosion of topsoil (USACE, 2004b). This erosion increases the amount of runoff during normal rainfall events, leading to a reduction in groundwater recharge.

Multi-GCM IPCC AR4 climate model projections of 2080-2099 for the area around Antigua and Barbuda suggest an overall decline in precipitation of -34 mm/year (-5.3%) for scenario B1, -94 mm/year (-13.3%) for scenario A1B and -178 mm/year (-21.5%) for scenario A2 (Table 18). These changes are predominantly projected to occur during the wetter months of May to August (Figure 35), which would lead to a reduction in the recharge of groundwater resources, increase the risk of drought for the islands and intensify the impact of drought conditions. A reduction in groundwater recharge could also increase the likelihood of saltwater intrusion into aquifers. When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Antigua and Barbuda is -3.4% (-4.7%) (Table 15).

The Bahamas

The Bahamas consist of around 700 islands, of which only a few are inhabited. Precipitation decreases north-south from around 1300 mm/year in the north to less than 750 mm/year in the arid islands in the south. The islands are extremely low-lying (the highest point is 63 m on Cat Island), making them extremely susceptible to sea-level rise and storm surge (USACE, 2004a) (see also Section 2). Freshwater resources are vulnerable and considered scarce. There is almost no fresh surface water in the Bahamas. Freshwater is instead derived from precipitation which percolates into shallow karstic limestone aquifers less than 1.5 m from ground surface, and sits on top of shallow saline water (USACE, 2004a). The Bahamas is currently completely reliant on this single source of water. Water is distributed by barge to islands with an insufficient supply (USACE, 2004a).

Tourism is the primary revenue generator for the country and is dependent on reliable supplies of freshwater. Tourists consume 2-3 times the amount of water than residents. Agriculture is also important for the economy of the country but is highly dependent on irrigation. Water is therefore a critical economic resource (USACE, 2004a). Water is already scarce, and if sources are threatened by climate change, this could have a major impact on the economy.

Over-abstraction can cause salt-water intrusion leading to aquifer abandonment. Salt-water intrusion has occurred on New Providence, where the capital, Nassau, is located and the greatest water demand exists (USACE, 2004a). Although central pumping stations are monitored, there are many domestic or hand-dug wells that exist and these are not well controlled. Saltwater intrusion is therefore a concern in densely populated areas (USACE, 2004a).

Shallow aquifers are extremely vulnerable to small rises in sea-level in climate change. Sea-level rise would reduce the capacity of fresh-water aquifers and increase the risk of saltwater intrusion through over-abstraction (USACE, 2004a). A reduction of precipitation would also reduce the amount of groundwater recharge and similarly lead to an increase in the risk of saltwater intrusion.

Storm surges from past hurricanes have caused extensive damage to aquifers in the Bahamas, as they have led to contamination from seawater, sewage, pesticides and petroleum products (USACE, 2004a). Sea-level rise would increase the risk of aquifer contamination from future hurricanes by reducing the level of the storm-surge required for contamination to occur.

IPCC AR4 projections of 2080-2099 for the Bahamas area suggest an overall decline in average daily precipitation amounts throughout the year, although there is considerable variability in model projections. In northern Bahamas, mean projections suggest an average total annual change in precipitation of -54 mm (-4.8%) under the B1 scenario by 2080-2099, -110 mm (-9.0%) under A1B and under the A2 scenario a change of -130 mm (-21.5%) (Table 18). These declines are spread over the months of January to September, with a projected increase in precipitation for October and November (Figure 35). In the southern Bahamas, mean projections suggest an annual change of -18 mm (-2.1%), -86 mm (-8.5%) and -136 mm (-13.7%), respectively, again spread over the months of January to September (Figure 35). When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in the Bahamas is +11.2% (+14.4%) for the north and +9.2% (+12.6%) for the south (Table 19).

Barbados

Barbados has substantial annual rainfall ranging from around 750 mm/year in coastal lowlands to 2000 mm/year on the central ridge and with an annual average 1422 mm (AQUASTAT, 2009a). It consists predominantly of highly permeable coral limestone geology which covers 84% of the island. This leads to rapid percolation of rainfall and consequently most rivers are dry and the only source of potable water is groundwater (Brewster and Mwansa, 2000). To the east of the island in the Scotland District, rocks are comprised of impermeable oceanic sediments and most of the rainfall is lost through run off to the sea. Water deficits are occasionally experienced during the dry season, particularly in agriculture, which for a large part is non-irrigated and rain dependent.

Most groundwater extraction is done as far inland as possible, since quality decreases rapidly towards the sea (Brewster and Mwansa, 2000). A brackish water reverse osmosis desalination plant was implemented in February 2000, but the country is still primarily dependent on groundwater extraction. The aquifers are vulnerable to saltwater intrusion, particularly since recent lower levels of rainfall have resulted in reduced groundwater recharge. During the 1994 drought, a rise in groundwater salinity levels was experienced (Brewster and Mwansa, 2000).

IPCC AR4 projections of 2080-2099 for the Barbados area suggest a decline in precipitation, with mean projections suggesting an overall annual decline of -83 mm (-10.3%), -145 mm (-16%) and -269 mm (-27.3%) for scenarios B1, A1B and A2, respectively (Table 18). A drop of 27% would be significant for Barbados, since it already has issues with drought and groundwater salinity. The greatest declines are projected to occur in the months of June and July (Figure 35). When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Barbados is +7.3% (+9.3%) (Table 19).

Belize

Belize has substantial surface and groundwater resources, with a high per captia availability of freshwater. The average annual rainfall is 1705 mm (AQUASTAT, 2009b), which can vary from less than 1500 mm/year in the north to more than 4000 mm/year in the far south. A lack of data prevents a complete assessment of groundwater reserves in Belize (Tollner, 2007), but groundwater is vital with almost 95% of the freshwater supply coming from groundwater in rural areas (Frutos, 2003). In urban areas, 70% of the total water used is from surface water resources.

Climate projections for 2080-2099 suggest declines in total annual precipitation with mean values of -63 mm (-7.1%), -192 mm (-17.6%) and -204 mm (-22.3%) for scenarios B1, A1B and A2, respectively. However, these declines are relatively minor compared to the available water resources in Belize, and masks the projected monthly trend of drier conditions for June and July and wetter conditions in October and November (Figure 35). When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Belize is +5.6% (+7.1%) (Table 19).

Dominica

Dominica is a mountainous island with abundant rainfall and surface water resources. Rivers are the main source of water supply for potable use, irrigation, and hydropower in Dominica (Nurse et al. 2001). The country has a total of 365 rivers and streams and high rainfall is more than 6500 mm/year on the highest slopes, reducing to 500-1500 mm/year on lower ground where towns occur (Drigo, 2001). The abundance of surface water has meant that the exploration of ground water resources has been unnecessary. However, hydrological studies have indicated that there are only limited aquifers with low yields (USACE, 2004b).

Water shortages may be experienced during the dry season occurring January to May with flows dropping by around 30% (USACE, 2004b). The water shortage is compounded as a result of increased water consumption during the dry season for watering of lawns and gardens and an increase in bathing (USACE, 2004b).

Within the past few decades, more extended periods of drought have occurred, which are well correlated with reduced flows in the Castle Comfort, Roseau, Layou, and Geneva Rivers (Government of Commonwealth of Dominica, 2000). Since rivers are the main source of fresh water for domestic, agricultural and power generation use, declining flows are a matter of serious national concern (Nurse et al. 2001).

The heavily vegetated slopes on Dominica help to retain surface runoff and sustain river flows. However, hurricanes can cause defoliation and other damage to vegetation which leads to temporary changes in the hydrological cycle in affected watersheds (Drigo, 2001).

Annual rainfall totals are projected to decrease by 2080-2099, with IPCC AR4 GCMs projecting an overall change of -48 mm (-6.5%) for scenario B1, -109 mm (-14.1%) for A1B and -197 mm (-23.2%) for A2. Most of this decline is projected to occur in the wetter months of June – August (Figure 35), however, model projections tend to miss extreme events such as droughts. A projected decline in overall precipitation levels across the Caribbean region suggests an increase in the frequency of drought events, to which countries such as Dominica which rely primarily on surface flows would be particularly vulnerable. When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Dominica is +3.6% (+4.2%) (Table 19).

Grenada

Grenada is a three-island state comprising of the islands of Grenada, Carriacou and Petite Martinique. Grenada and Carriacou are both characterised by mountainous terrain with a large proportion of the land area comprising of steep slopes above 20°. A small proportion of land is at sea-level, but this area contains the principal urban development and critical socio-economic facilities.

On Grenada, 90% of the water supply is sources from the surface, with 10% being obtained from groundwater, either via wells, boreholes or springs (Department of Economic Affairs, 2001). Taking into consideration losses from the distribution system, demand is greater than total supply. The importance of groundwater increases during the dry season, when they are used to augment surface water resources from which yields drop by 25% (Department of Economic Affairs, 2001). In Carriacou and Petite Martinique, groundwater forms the main source of water supply used on the islands.

Saltwater intrusion is a concern in the country, where most boreholes are within 100 m of the coastline (Department of Economic Affairs, 2001). Groundwater has been found to be particularly vulnerable in the south of Grenada, and on the island of Carriacou where some wells have been abandoned due to increasing chloride concentrations. Sea level rise would reduce the availability of groundwater on the island of Grenada, which may threaten the ability to maintain water supply during dry periods. In Carriacou and Petite Martinique, many wells close to the coast would have to be abandoned (Department of Economic Affairs, 2001).

IPCC AR4 projections for 2080-2099 suggest a decrease in total annual precipitation levels of -119 mm (-15.5%), -191 mm (-22.0%) and -288 mm (-33.2%) for scenarios B1, A1B and A2, respectively. These declines are amongst the highest projected for CARICOM states and would cause substantial problems putting more pressure on groundwater abstraction. The months of May through to November are all projected as drier (Figure 35). When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Grenada is +2.9% (+2.2%) (Table 19).

Guyana

Guyana has substantial hydrological resources. Rainfall varies from 2290 mm/ year on the coast to 3560 mm/year in rainforest areas in the southwest (USACE, 1998). Approximately 90% of the population live within the coastal lowlands region which occupies around 10% of the country and is predominantly below sea level. Sea defences prevent daily flooding of the region with each tidal cycle, but occasional breaches have lead to prolonged inundation of areas and problems with salinisation (USACE, 1998).

Guyana utilises both surface and groundwater resources, with groundwater from a coastal aquifer system supplying around 90% of the domestic water use (USACE, 1998). Surface water is primarily used for industrial and agricultural purposes. The coastal aquifer system is brackish to saline in an area in the northwest of the country; saltwater intrusion is a concern in the eastern coastal lowlands (USACE, 1998). Inland, wells may become dry during the dry season.

IPCC AR4 projections for 2080-2099 indicate drier conditions in the north of the country with total annual precipitation declines of -107 mm (-10.9%), -171 mm (-17.2%) and -192 mm (-19.8%) for scenarios B1, A1B and A2, respectively (Table 18). All months in northern Guyana are projected to have declines in precipitation, although there is substantial variability in the model projections (Figure 35). In the south, very little change is projected with a marginal increase for scenario B1 (+22 mm; +1.9%) and marginal decreases for A1B (-34 mm; -2.9%) and A2 (-74 mm; -6.9%), although these annual figures mask projected increases in precipitation for the months of March to May and decreases for July to October (Figure 35). When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Guyana is +2.3% (+1.0%) for the north and +0.7% (-1.1%) for the south (Table 19).

Haiti

Haiti is a densely populated country which has abundant water supplies which should be sufficient to meet demand. However, due to poor infrastructure, there is a lack of access to clean water, a situation compounded by internal migration from rural areas to towns and cities (USACE, 1999). Haiti receives an average annual rainfall amount of 1400 mm, but this is unevenly distributed and with some areas receiving less than 400 mm/ year, and others more than 3600 mm/ year (USACE, 1999). Untreated or partially treated surface water is used for domestic purposes by much of the population, although much of this is contaminated.

Groundwater resources are highly variable, with 84% of the reserves occurring in alluvial plains and valleys. Alluvial aquifers near the coast have substantial saltwater intrusion caused predominantly by over abstraction.

IPCC AR4 projections for 2080-2099 for Haiti suggest a marginal annual decline in total annual precipitation under the B1 scenario (-36 mm; -4.9%), and larger declines for A1B (-98 mm; -13.5%) and A2 (-179 mm; -21.8%) (Table 14). The majority of the decline is projected to occur between May and August (Figure 35). These changes are insubstantial compared to the large amount of water resources available, but may increase the likelihood of saltwater intrusion in some aquifers due to a reduction in the amount of ground water recharge. When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Haiti is -1.2% (-3.4%) (Table 19).

Jamaica

Jamaica has abundant water resources with an average annual rainfall of 1981 mm. Water resources are unevenly distributed through the island. The topography of the island is generally mountainous, with coastal plains and a large mountain range running the length of the island. This topography causes substantial variation in rainfall. Northern mountain slopes receive 3000-5000 mm/year, compared to less than 1500 mm/year on southern slopes with Kingston receiving only 762 mm/year. There is also substantial seasonal variability of rainfall leading to supply difficulties. Demand for water and its availability are unevenly distributed – the greatest demand is in the dry south, whereas the greatest availability exists in the north.

The country is heavily dependent on groundwater for much of the water supply, a substantial part of which is used for irrigation. Groundwater provides 92% of water to all sectors, predominantly from limestone aquifers which are directly recharged via rainfall and indirectly from streamflow. Saline intrusion into aquifers is a serious concern in coastal aquifers, particularly on the southern plains (USACE, 2001a). Reservoirs also exist but a large proportion of these have significant siltation, primarily caused by erosion associated with deforestation.

IPCC AR4 projections for 2080-2099 indicate declines in total annual precipitation for the Jamaica area of -60 mm (-8.4%), -140mm (-15.2%) and -198mm (-22.6%) for scenarios B1, A1B and A2, respectively (Table 14). The majority of the decline is projected for the months of May to August (Figure 35). These declines would likely be an issue in the drier southern areas, particularly on the southern plains where saltwater intrusion into aquifers has occurred. When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Jamaica is -3.1% (-6.0%) (Table 19).

Montserrat

Montserrat possesses high quality water from volcanic aquifers, but over several years yields from these springs have generally declined since they have not been recharged sufficiently by rainfall (CDERA, 2004). Alternative groundwater sources are being sought in order to meet demand. In 2003 the British Geological Survey conducted a groundwater survey and identified new sources in the Belham valley, which are now in the process of being explored (CDERA, 2004).

IPCC AR4 projections for 2080-2099 indicate a moderate decline in total annual precipitation, with figures of -35mm (-5.1%) for scenario B1, -94mm (-13.3%) for A1B and -178 mm (-21.5%) for A2 (Table 18). These changes are largely projected for the months of May to August (Figure 35). A lack of current data on the status of new groundwater resources prevents an assessment of the likely significance for Montserrat, however, they would cause existing groundwater reserves to decline still further. When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Montserrat is -4.4% (-7.6%) (Table 19).

St. Kitts and Nevis

These small, mountainous islands have highly variable rainfall totals with the majority of precipitation being orographic in nature. The lower southeast of St. Kitts receives on average 1020mm of rainfall annually, which rises to 3810 mm in the central mountain ranges, with an average evapotranspiration of 1140mm/year (USACE, 2004b). The wet season is between June and October; the dry season is between November and April. Normal rainfall for Nevis is 1170mm / year, however, several years of drought occurred during the 1990s: 1990/1991 (942mm annual average rainfall), 1993 (942mm) and 1997 (885mm) (USACE, 2004b). Water in the islands is sourced from a combination of surface water and ground water.

The primary source of freshwater on St. Kitts is rainfall and surface runoff. However, surface water supplies are variable and insufficient to meet demand. Many streams are ephemeral with flows only during the wet season. During the dry season, some rural areas do not have enough water and there are insufficient water storage facilities (USACE, 2004b). The main groundwater supply is from a coastal aquifer which has been subject to saltwater intrusion.

On Nevis, groundwater accounts for 80% of the public supply and the aquifers have not been found to be at risk of saltwater intrusion (USACE, 2004b). Rural communities on Nevis experience water shortages during the dry season.

Neither island has any large natural reservoirs and desalination plants are not utilised. Domestic rooftop catchment systems may contribute significantly to domestic water supplies, particularly in Nevis (USACE, 2004b). Around 85% of agriculture in the country is rain fed, with the remaining irrigated from reservoirs and springs.

IPCC AR4 projections for 2080-2099 indicate annual total precipitation for Saint Kitts and Nevis is projected to decline by -35mm (-5.1%) for scenario B1, -94mm (-13.3%) for A1B and -178 mm (-21.5%) for A2 (Table 18), largely between the months of May and August (Figure 35). When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in St. Kitts and Nevis is -5.4% (-9.1%) (Table 19).

St. Lucia

St. Lucia is volcanic in origin and is of mountainous nature. Rainfall ranges from 1450 mm/ year on the coast to 3450 mm/ year in the central forest area. The majority of rainfall is orographic in nature. Rainfall is the primary source of freshwater, with the majority falling from August to November. Water supply can be a problem during the drier months of February to April, due to the inadequacy of water storage facilities (Water Resources Management Unit, 2001). Groundwater sustains baseflows in rivers through the drier months, from where water is extracted and used for supply. While studies have indicated that groundwater reserves are good, problems exist with water hardness, salinity and iron content and the reserves have not been exploited (Water Resources Management Unit, 2001).

Most demand for water exists in the north of the island, where 60% of the population reside and where tourism is more developed. Although the northern region benefits from a reservoir, the water distribution system is inadequate (Water Resources Management Unit, 2001). The country is susceptible to drought, particularly in the southern half of the island. Here, water supply is inadequate to meet demand, and this region is particularly susceptible to drought. Despite this, several development projects for the area are planned, including hotels which depend on a reliable supply of water (Water Resources Management Unit, 2001).

IPCC AR4 projections for 2080-2099 suggest that total annual precipitation in the St. Lucia area would decline -65 mm (-8.4%), -167 mm (-19.8%) and -244 mm (-29.2%) for the B1, A1B and A2 scenarios, respectively (Table 18). Little change is projected for the already dry months February to April; the majority of decline is projected to occur between

May and November (Figure 35). When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in St.Lucia is -5.5% (-10.2%) (Table 15).

St. Vincent and the Grenadines

Average rainfall in the St. Vincent and the Grenadines is 1583mm/year (AQUASTAT, 2009c) which increases to 3800 mm/year in the central mountains of St. Vincent. Surface water availability in St. Vincent is considered adequate to supply all needs and, while they exist, groundwater reserves have not been fully explored or developed (Cooper and Bowen, 2001). The decline of forest reserves in St. Vincent is considered to be a large threat to watersheds and the water supply (Cooper and Bowen, 2001).

While there is no scarcity of fresh surface water in St. Vincent, there is limited surface water in the Grenadines (Cooper and Bowen, 2001), and supplies are obtained from groundwater abstraction. There have been some reports of saltwater intrusion into aquifers in the Grenadines due to over abstraction.

Total annual precipitation is projected to decline by 2080-2099 with IPCC AR4 projections of -95 mm/year (-12.6%) for scenario B1, -167mm/year (-19.8%) for A1B and -288 mm/year (-29.2%) for A2 (Table 18). These declines would likely affect the Grenadines more than St. Vincent, particularly with respect to a reduction in groundwater recharge and a subsequent increase in the likelihood of saltwater intrusion. The majority of decline is projected for the months of May through to November, with little change projected for drier months of January-April (Figure 35). When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in St Vincent and the Grenadines is -7.1% (-11.3%) (Table 19).

Suriname

Suriname has good hydrological resources and extracts only 0.2% of internal renewable water resources per year for water supply (USACE, 2001b). Average annual rainfall in Paramaribo is 2200 mm. Throughout the country, annual rainfall varies from less than 1750mm to more than 3000 mm/year.

Around 95% of the population live within the coastal zone in urban areas. These areas rely on groundwater with large proportion of the population having access (USACE, 2001b). Saltwater intrusion in wells resulting from over abstraction is increasing and is contributing to water supply contamination (USACE, 2001b). Away from coastal areas, surface water is generally used and this is subject to contamination in places.

Precipitation in Suriname is projected to decline in IPCC AR4 climate models, particularly in the north of the country. For the B1 scenario, the mean projected change in total annual precipitation is -61mm (-5.7%) for the B1 scenario, -125mm (-12.0%) for A1B and -183mm (-19.3%) for A2. In the south, projected total annual precipitation changes are -30mm (-2.9%), -84mm (-8.2%) and -108mm (-10.2%), respectively. The timing of projected changes throughout the year is highly variable with some months projected to increase in precipitation. This is likely due to wide discrepancy in climate model projections, as indicated by the high standard deviation in projected figures which are 52-86% of the mean projections, which are probably due to a projected increase in precipitation to the south of the country – a change in the position of this gradient will cause substantial variability in GCM projections. Changes to precipitation for Suriname are unlikely to greatly impact water resource availability. However, much of the coastal area of Suriname is very low lying and is susceptible to sea-level rise. Saltwater intrusion into aquifers is likely to increase, which could threaten the availability of freshwater to urban populations. When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Suriname is -6.9% (-10.4%) for the north and -6.6% (-9.4%) for the south (Table 19).

Trinidad and Tobago

In Trinidad, the average annual rainfall is 2000mm, with a high evapotranspiration rate accounting for 60% of rainfall received in some areas (Water Resources Agency, 2001). In Tobago, average rainfall is 3800mm/year at high elevations and less than 1250 mm/year in the south-west lowlands. Despite the relatively high rainfall, a water deficit in the country has still been recognised and efforts are being made to increase the capacity of the water supply infrastructure

(Water Resources Agency, 2001).

Substantial aquifer reserves are contained in Trinidad in sedimentary rocks, but coastal aquifers are threatened by saltwater intrusion caused by over abstraction and sea-level rise, particularly in the northwest of the island (Water Resources Agency, 2001). In Tobago, groundwater is abstracted from sedimentary deposits in the southwest of the island and these too are at risk from sea-level rise (Water Resources Agency, 2001).

IPCC AR4 projections for 2080-2099 suggest an overall decline in total annual precipitation of -140 mm (-15.9%) for scenario B1, -241 mm (-27.0%) for A1B and -318 mm (-33.8%) for A2, representing amongst the most substantial drop in annual precipitation for all CARICOM states (Table 14). These changes are projected to occur predominantly during the wet season between the months of May to November (Figure 35). Such declines would increase the risk of saltwater intrusion in the northwest, and increase pressure on the water supply infrastructure. When GCMs reach the threshold global mean temperature increase of 1.5°C (2.0°C), the mean change in precipitation in Trinidad and Tobago is -7.2% (-10.2%) (Table 19).

3.2.3 SUMMARY OF IMPACTS ON WATER RESOURCES IN CARICOM STATES

The greatest declines in precipitation are projected with the higher levels of average warming in scenario A2 (3.4°C by 2080-2099), compared to scenarios B1 (1.8°C) or A1B (2.8°C). Across all CARICOM states, projected changes to total annual precipitation ranges from +1.9% to -15.8% for the B1 scenario, -2.9% to -27% for the A1B, and -6.9% to -33.8% for the A2 scenario. The average projected changes in CARICOM states are -7.0%, -14.3% and -21.3% for the B1, A1B and A2 scenarios, respectively. When GCMs reach the threshold global mean temperature rises of 1.5°C the average projected change in precipitation across all CARICOM states is small at -0.4% (range: -27.2% to +34.1%); for 2.0°C, the average projected change is -1.8% (range: -32.0% to +37.4%). For several nations (Bahamas, Barbados, Belize, Dominica and Grenada), there is an average projected increase in precipitation levels at 1.5°C and 2.0°C; these changes revert to a decline in precipitation by 2080-2099 under B1, A1B and A2 scenarios. A reduction in precipitation reduces both the available surface water reserves and also the level of groundwater recharge. This later impact can lead to increased risk of saltwater intrusion to aquifers, particularly those close to the coast, and reduces the amount of available water within aquifers. Sea level rise will exacerbate the effect of drier conditions on salinisation of aquifers – the reserves would be squeezed from both underneath via the rising saltwater layer, and above via reduced recharge rates.

Most CARICOM nations have already experienced saltwater intrusion into aquifers: Antigua and Barbuda (particularly Barbuda), The Bahamas, Barbados, Grenada (particularly Carriacou and Petite Martinique islands), Guyana, Haiti, Jamaica, St. Kitts and Nevis (St. Kitts island), St. Vincent and the Grenadines (Grenadines islands), Suriname and Trinidad and Tobago. Of these, those countries with coastal aquifers which are particularly vulnerable to sea-level rise are: Antigua and Barbuda, The Bahamas, Grenada, Suriname and Trinidad and Tobago. Should sea-levels rise substantially (see Section 2 for discussion), all coastal aquifers would be threatened. A decline in precipitation levels would reduce the level of groundwater recharge which, along with increasing sea-levels, could increase the risk of saltwater intrusion.

CARICOM nations which have been particularly prone to water shortages or drought conditions are: Antigua and Barbuda, The Bahamas, Barbados, Dominica (in the dry season when demand is also highest), St. Kitts and Nevis (particularly Nevis island) and St. Lucia (in the dry season). Of these, the aquifers in Barbados have experienced saltwater intrusion due the drought conditions reducing the amount of groundwater recharge. Antigua and Barbuda are heavily reliant on desalinisation, particularly during periods of drought.

Declines in precipitation would lead to an increase in the risk of periods of drought for the Caribbean region, which are likely to occur more frequently and be more severe. Countries which rely mainly on surface water rather than aquifers could be affected by declining precipitation levels since surface water generally responds more rapidly to drought conditions than aquifers where flows in rivers decline or stop altogether. Dominica, Grenada (main island), St. Kitts and Nevis (St. Kitts island), St. Lucia and St. Vincent and the Grenadines (St. Vincent island) are all nations which rely on surface water rather than obtaining supplies from aquifers. Declining precipitation levels may make these nations vulnerable to water shortages, particularly if they have already experienced periods of drought, such as Antigua and

Barbuda, The Bahamas, Barbados, Dominica, St. Kitts and Nevis and St. Lucia.

There are several reported cases where hurricanes have lead to a reduction in water resource availability in some countries. In Antigua and Barbuda, extreme rainfall from hurricanes has caused the loss of topsoil and has eroded gullies. This has lead to increased surface runoff from normal rainfall which subsequent reduction in groundwater recharge (USACE, 2004b). In the Bahamas, storm surge from hurricanes have damaged aquifers via contamination from flooding. Sea level rise would exacerbate this problem. In Dominica, temporary changes to the hydrological cycle in some watershed have been experienced due to damage caused to vegetation by hurricanes. If hurricanes were to increase in frequency and/or intensity, as some research suggests (e.g. Knutson and Tuleya 2004; Trenberth, 2005; Emanuel, 2005) (see also Section 1), these kind of impacts would likely increase. Vegetation cover could also become reduced in some areas due to declining precipitation levels. If this were to occur, these areas would be particularly vulnerable to the kind of effects experienced in Dominica.

3.3 IMPACTS ON AGRICULTURE

Unfettered climate change will have substantial negative effects on agriculture productivity in many parts of the developing world. A recent Food Policy Report from the International Food Policy Research Institute (IFPRI) (Nelson et al. 2009) found that by 2050 climate change could cause yield declines for the most important crops (rice, wheat, maize, and soybeans) in the developing countries assessed. Their results suggest that climate change will result in additional price increases for the most important agricultural crops. Higher feed prices will result in higher meat prices. As a result, climate change will reduce the growth in meat consumption slightly and cause a more substantial fall in cereals consumption according to their findings. Calorie availability in 2050 could not only be lower than in the no climate-change scenario, it could actually decline relative to 2000 levels throughout much of the developing world. By 2050, the decline in calorie availability could increase child malnutrition by 20% relative to a world with no climate change. Climate change could also eliminate much of the improvement in child malnourishment levels that would occur with no climate change. The IFPRI report however does not include any information specific to the CARICOM countries.

In this section, available information for CARICOM countries is summarized and new country-specific results based on a variety of climate change scenarios are provided. Given the lack of agricultural data availability for many CARICOM countries, the analysis must be considered preliminary. Due to data limitations, it does not distinguish between the relative effects of a 1.5°C and a 2.0°C rise in the global annual mean surface air temperature change. Instead it compares the effects of a range of GCMs that result in roughly similar temperature increases of 1.5°C and 2°C in the Caribbean.

Agriculture does not contribute to a significant share of GDP in many countries of the region as can be seen in Table 20. However, even in countries where agriculture is not a major sector, subsistence agriculture is critical to the livelihoods of poor people. Any climate change effects will disproportionately affect the poor.

In Dominica, where 18% GDP comes from agriculture, most of the agricultural sector is comprised of small farmers with less than 10 hectares of land and with minimal technological and purchased inputs (Challenger 2004). Other countries where agriculture contributes more than 10% of GDP include Belize (15%; Guyana (31%) and Haiti (28%) (see Table 20).

A significant share of the population in several of the CARICOM countries depends on agriculture. Haiti and Montserrat have the largest agricultural employment with 60% and 33% respectively of total economically active population working in agriculture. Other countries such as Belize, St. Kitts and Nevis, Antigua and Barbuda, St. Lucia, St. Vincent and Grenadines and Dominica have agricultural employment rates higher than 20% of total employed population (Table 20).

Table 20: CARICOM value added share, total value, and employment in agriculture, 2005

Country	Agricultural value added (% of GDP)	2005 value (million U.S. dollars)**	Agriculture employment (% of total employment)
Antigua and Barbuda	4	34.8	21.62
Bahamas*	3	150.0	2.78
Barbados	4	122.4	3.27
Belize	15	166.5	24.39
Dominica	18	54.0	20.69
Grenada	5	25.5	20.00
Guyana	31	244.9	15.36
Haiti*	28	1,078.0	59.87
Jamaica	6	669.0	18.14
Montserrat	-	-	33.33
Saint Kitts and Nevis	3	12.9	22.73
Saint Lucia	4	35.2	20.99
Saint Vincent and Grenadines	8	35.2	20.75
Suriname	6	106.8	17.02
Trinidad and Tobago	1	151.4	6.89

Sources: Agricultural value-added: World Bank. Agricultural share of total employment: POPSTAT/FAO.

Note: Agricultural employment = total economically active population in Agr/total economically active population.

* 2000 data.

** 2005 GDP times agricultural value added share.

Table 21 reports total area harvested in the CARICOM countries in 2005. Haiti has by far the largest area with over 1 million hectares. Guyana and Jamaica are second and third with somewhat less than 200,000 hectares. Of the total harvested area in CARICOM, maize makes up 20.3%, rice 15.73% and sugarcane just under 10% (see Table 22).

Table 21: CARICOM countries area harvested, 2005 (hectares)

Antigua and Barbuda	2,278
Bahamas	7,455
Barbados	10,621
Belize	73,141
Dominica	17,230
Grenada	10,963
Guyana	190,745
Haiti	1,078,863
Jamaica	163,841
Montserrat	352
Saint Kitts and Nevis	2,927
Saint Lucia	9,402
Saint Vincent and Grenadines	13,967
Suriname	55,058
Trinidad and Tobago	43,987
Total	1,434,890

Table 22: Harvested area of selected crops, CARICOM countries

	hectares	Percent of total harvested area
Groundnuts	32,752	2.28
Mangoes, mangosteens, guavas	41,781	2.91
Cowpeas	44,323	3.09
Coffee	52,025	3.63
Cassava	80,531	5.61
Coconuts	90,580	6.31
Sugarcane	136,925	9.54
Rice	225,669	15.73
Maize	291,743	20.33

Source: FAOSTAT.

Table 23 lists the most important commodities by value in the CARICOM countries. For almost all countries, livestock products have the largest value with tropical fruits and sugar cane also among the highest value agricultural products.

Commodity	Production (Int $1000)	Production (MT)
Antigua and Barbuda		
Cow milk, whole, fresh	1,436	5,400
Cattle meat	1,074	519
Fruit, tropical fresh nes	686	6,000
Mangoes, mangosteens, guavas	348	1,430
The Bahamas		
Chicken meat	6,726	5,767
Vegetables fresh nes	3,846	20,500
Lemons and limes	2,456	9,400
Grapefruit (inc. pomelos)	2,216	13,000
Barbados		
Chicken meat	18,106	15,523
Sugar cane	8,515	410,000
Pigmeat	2,645	2,612
Cow milk, whole, fresh	1,834	6,900
Belize		
Oranges	38,820	220,896
Sugar cane	24,925	1,200,050
Chicken meat	16,112	13,814
Grapefruit (inc. pomelos)	9,722	57,015
Dominica		
Bananas	4,175	30,000
Grapefruit (inc. pomelos)	2,899	17,000
Cow milk, whole, fresh	1,622	6,100
Oranges	1,265	7,200
Grenada		
Nutmeg, mace and cardamoms	4,018	2,800
Avocados	1,028	1,600
Hen eggs, in shell	775	920
Coconuts	633	7,000
Guyana		
Rice, paddy	94,512	458,700
Sugar cane	58,139	3,099,200
Chicken meat	26,474	22,697
Cow milk, whole, fresh	7,978	30,000
Haiti		
Cattle meat	89,970	43,500
Mangoes, mangosteens, guavas	63,307	260,000
Plantains	43,142	280,000
Bananas	41,755	293,000

Commodity	Production (Int $1000)	Production (MT)
Jamaica		
Chicken meat	112,365	96,334
Goat milk, whole, fresh	49,737	165,000
Sugar cane	40,875	1,968,000
Coconuts	28,126	311,000
Montserrat		
Cattle meat	1,489	720
Cow milk, whole, fresh	598	2,250
Chicken meat	89	76
Pigmeat	65	65
St. Kitts and Nevis		
Sugar cane	2,180	105,000
Cattle meat	187	90
Hen eggs, in shell	183	220
Chicken meat	163	140
St. Lucia		
Bananas	7,227	54,000
Pigmeat	1,327	1,311
Coconuts	1,266	14,000
Pepper (Piper spp.)	1,200	260
St. Vincent and the Grenadines		
Bananas	4,702	51,000
Roots and Tubers, nes	1,137	10,000
Plantains	798	3,600
Spices, nes	647	500
Suriname		
Rice, paddy	32,273	179,012
Bananas	8,203	71,084
Chicken meat	7,577	6,496
Cattle meat	2,733	1,321
Trinidad and Tobago		
Chicken meat	67,127	57,550
Sugar cane	9,865	475,000
Fruit Fresh Nes	5,997	37,600
Pigmeat	2,961	2,924

Table 183: Value and quantity produced of the main agricultural commodities in CARICOM countries

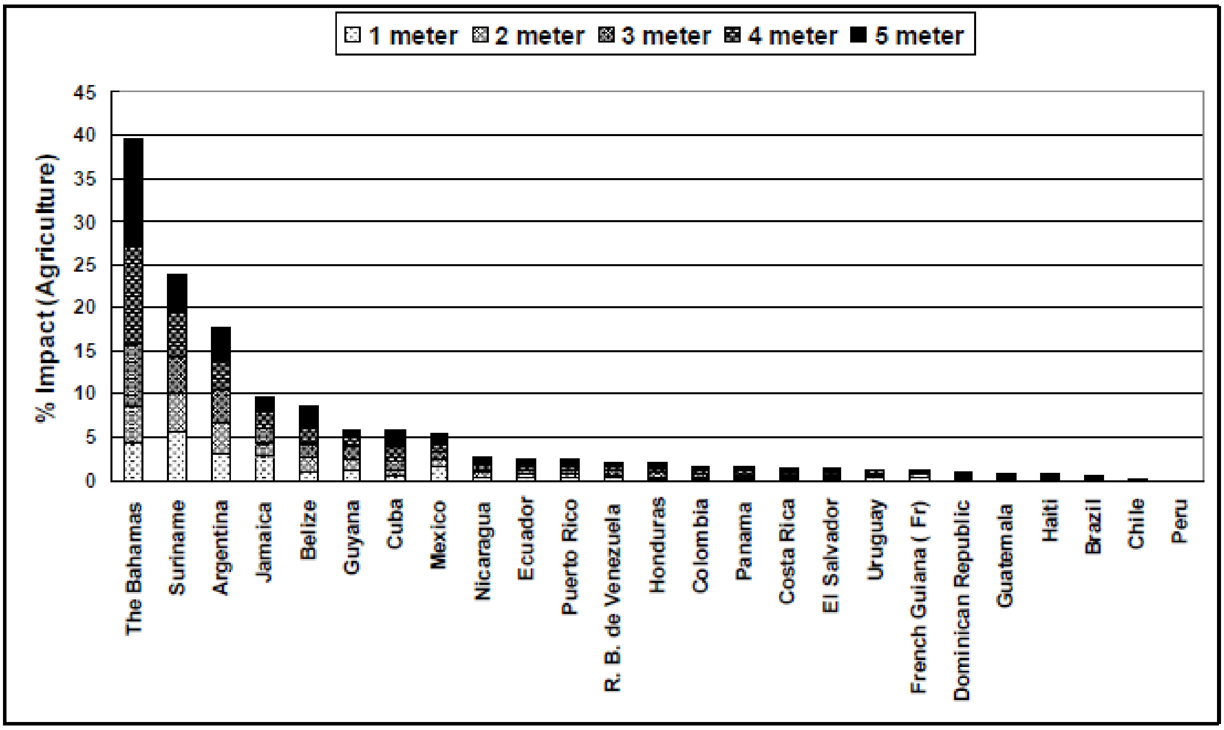


Figure 36: Latin America & Caribbean: Agricultural extent affected by sea level rise

Very few studies have been done of the impacts of climate change on agriculture in the Caribbean and no studies are available that address the impacts on Caribbean fruits, roots and tubers that are important in many CARICOM countries. Simulations done by O'Brien (2000) in Antigua and Barbuda suggest that temperature increases alone do not significantly impact crop yields. However, when such increases are accompanied by precipitation decreases, seasonal yields for all crops decrease. Simulations also show that changing the planting dates in rainfed agriculture can help to cope with water stress. If the planting date is in the last weeks of September, an increase of 1.03°C in temperature and a decrease of 13.75% in precipitation in 2050 causes a decrease of 36% in cotton yields. However, yields would not be affected if planting date is shifted to the beginning of October (Table 19).

Table 24: Yield reduction under rain-fed conditions at Coolidge, Antigua (clay soil conditions)

Crop	Planting date	Output	Base	2050 (T = +1.03 °C)				
				-13.75%P	-6.875%P	Temp +1.03°C	+6.875%P	+13.75%P
Onion	Sep-23	Actual water use (mm)	445	429	440	452	462	471
		Potential water use (mm)	526	550	550	550	550	550
		Actual irrigation reqt (mm)	132	171	160	150	138	145
		Cumulative reduction in yield (%)	24.4	35.1	31.7	28.2	25.3	22.5
	08-Oct	Actual water use (mm)	555	560	566	567	567	567
		Potential water use (mm)	561	574	574	574	574	574
		Actual irrigation reqt (mm)	31	56	45	38	31	44
		Cumulative reduction in yield (%)	2.8	5	3.1	2.8	2.8	2.8
Vegetable	Sep-23	Actual water use (mm)	364	366	373	376	376	376
		Potential water use (mm)	366	379	379	379	379	379
		Actual irrigation reqt (mm)	22	51	39	30	21	24
		Cumulative reduction in yield (%)	3	18.2	7.6	3.3	2.9	2.9
	08-Oct	Actual water use (mm)	413	393	406	415	420	421
		Potential water use (mm)	424	425	425	425	425	425
		Actual irrigation reqt (mm)	24	56	32	23	15	15
		Cumulative reduction in yield (%)	8.7	20.5	13.2	7.8	4.3	3.6
Cotton	Sep-23	Actual water use (mm)	510	486	499	514	529	542
		Potential water use (mm)	653	685	685	685	685	685
		Actual irrigation reqt (mm)	275	330	316	303	286	288
		Cumulative reduction in yield (%)	28.5	36.0	34.1	31.7	29.4	27.3
	07-Oct	Actual water use (mm)	697	710	710	710	710	710
		Potential water use (mm)	697	710	710	710	710	710
		Actual irrigation reqt (mm)	23	99	63	35	21	16
		Cumulative reduction in yield (%)	0.0	0.0	0.0	0.0	0.0	0.0
Pasture	Sep-23	Actual water use (mm)	1095	998	1047	1100	1146	1194
		Potential water use (mm)	1773	1797	1797	1797	1797	1797
		Actual irrigation reqt (mm)	731	855	803	749	698	659
		Cumulative reduction in yield (%)	86.3	92.0	89.9	87.2	84.5	81.4
	08-Oct	Actual water use (mm)	1152	1032	1098	1157	1195	1233
		Potential water use (mm)	1773	1797	1797	1797	1797	1797
		Actual irrigation reqt (mm)	695	842	774	714	670	645
		Cumulative reduction in yield (%)	86.0	92.0	89.6	86.8	84.4	81.7

The O'Brien study does not account for possible increases in climate extremes which are likely to have a harsher impact on agriculture than changes in mean temperature and precipitation according to the Intergovernmental Panel on Climate Change (Easterling et al. 2007).

In Trinidad and Tobago, Singh and El Maayar (1998, reported in IIPC 2001) project a decline in sugarcane yields of 20-40% under a doubled CO_2 climate change scenario as a result of moisture stress caused by a warmer climate.

The first national communication of Guyana also projects yield losses as a result of temperature and precipitation variations. For sugarcane, yields are expected to decrease by 30% and 38% in 2020-2040 (doubled CO_2) and 2080-2100 (tripled CO_2). Rice yields are also expected to decrease by 3% and 38% in 2020-2040 (doubled CO_2) and 16% in 2080-2100 (tripled CO_2) in comparison to yields in 1975-1995 (National Climate Committee 2002).

For this report, new runs of the crop modeling system for selected crops grown in CARICOM countries were undertaken using the DSSAT crop-simulation suite of models of the daily development of a specific variety of a crop, from planting to harvest ready. The modeling requires daily weather data, including maximum and minimum temperature, solar radiation, and precipitation, a description of the soil physical and chemical characteristics of the field, and crop management information, including crop, variety, planting date, plant spacing, and inputs such as fertilizer and irrigation[37].

Three crops of importance in the CARICOM countries were modeled (rice, maize, and cowpeas) using the best available data for soil conditions and nutrient levels with two climate profiles – current conditions and those in 2050 using the Mk3.0 results and ECHam5 results from the A2 scenario. The CSIRO-Mk3.0 model has an average temperature increase of 1.38°C while the ECHam5 model has a 1.96°C increase. The models also project substantial differences in precipitation. The CSIRO-Mk3.0 model results in an additional 16.38 mm of precipitation on average. The ECHam5 model, on the other hand, has 117.49 mm less precipitation in 2050 on average than in 2000. For rainfed crops, both temperature and precipitation effects were included. For irrigated rice, water availability was assumed to be sufficient and yield effects are only from changes in temperature. Then we computed the ratio of yield with 2050 climate to yield with 2000 climate. Figure 37 and Figure 38 show the distribution of yield changes for CARICOM countries.

Table 25 reports the average yield effects for irrigated and rain-fed rice, and rain-fed maize and cowpeas.

37 More details are available in Technical Appendix 1 of Nelson, G. C., M. W. Rosegrant, et al. (2009).

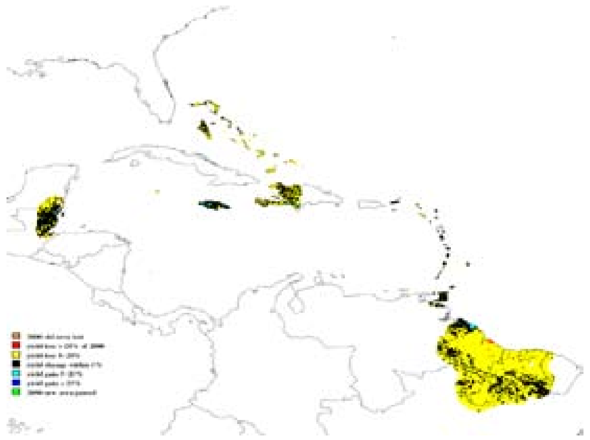


Figure 37. Relative yield effects, rain-fed maize CSIRO, A2 scenario

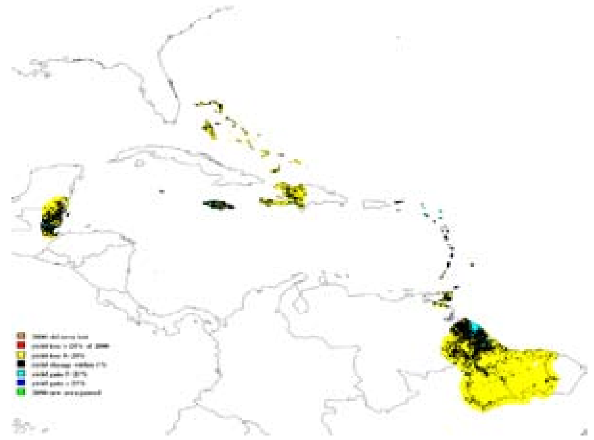


Figure 38. Rain-fed maize yield effects, Echam, A2 scenario

Table 25: Yield effects of the A2 scenario, 2050 climate relative to 2000 climate (percent)

	CSIRO-Mk3.0 (average temperature increase of 1.38 °C)	ECHam5 (average temperature increase of 1.96 °C)
Irrigated rice	-8.24	-8.43
Rainfed rice	-4.34	-2.96
Rainfed maize	-6.81	-6.81
Rainfed cowpea	-7.65	-6.67

Source: Authors' calculations.

Climate change has been found to generally have negative effects on yields in CARICOM countries. For the three key crops in CARICOM countries the biological effects of 2050 climate relative to 2000 climate are yield declines ranging from 3% to over 8% (as shown in Table 25). If these results apply to all crops, an assumption for which there is still little evidence, the estimated effect on agriculture value ranges from US $85 million per year to US $243 million per year. The effects of the particular climate change scenarios used do not differ much with underlying differences in temperature. This result is possibly due to the increases in precipitation that accompany higher temperatures, but at this stage in the analysis, this explanation is mainly speculation.

The differences in average temperature between the two GCM/scenario combinations do not result in any consistent effects on yields. Only for irrigated rice does the scenario with higher temperature result in higher yields. For the rainfed crops, the higher temperature scenario results in either no change or an increase in yields.

Table 216: Estimates of 2050 agricultural value lost to climate change in CARICOM countries

Country	Agricultural value added (percent of GDP)	2005 value (million U.S. dollars)**	Value lost to climate change, lower bound (2.96% of 2005 value)	Value lost to climate change, upper bound (8.43% of 2005 value)
Antigua and Barbuda	4	34.8	1.03	2.93
Bahamas*	3	150.0	4.44	12.65
Barbados	4	122.4	3.62	10.32
Belize	15	166.5	4.93	14.04
Dominica	18	54.0	1.60	4.55
Grenada	5	25.5	0.75	2.15
Guyana	31	244.9	7.25	20.65
Haiti*	28	1,078.0	31.91	90.88
Jamaica	6	669.0	19.80	56.40
Montserrat	-	-	-	-
St. Kitts and Nevis	3	12.9	0.38	1.09
St. Lucia	4	35.2	1.04	2.97
St. Vincent and Grenadines	8	35.2	1.04	2.97
Suriname	6	106.8	3.16	9.00
Trinidad and Tobago	1	151.4	4.48	12.76
Total		2,886.60	85.44	243.34

* 2000 data

** 2005 GDP times agricultural value added share

The effects of the particular climate change scenarios used do not differ much with underlying differences in temperature. This result is possibly due to the increases in precipitation that accompany higher temperatures, but at this stage in the analysis, this explanation is mainly speculation. To better understand the potential effects of climate change on CARICOM agriculture, the follow data and analyses are needed: improved downscaling of climate scenarios (to levels similar to that provided by the CARIBSAVE Partnership for the nations of Jamaica and The Bahamas[38]); improved characterization of the crop varieties grown, including location specific information on agronomic environments; and more detailed characterization of the agricultural sectors and their roles in CARICOM economies.

38 Eleuthera, The Bahamas Destination Profile Report, The CARIBSAVE Partnership, Department for International Development (DFID), UK www.caribsave.org
Montego Bay, Jamaica Destination Profile Report, The CARIBSAVE Partnership, Department for International Development (DFID), UK www.caribsave.org
Negril, Jamaica Destination Profile Report, The CARIBSAVE Partnership, Department for International Development (DFID), UK www.caribsave.org

Similar to other countries in the developing world, climate change will bring declines in yields of important crops in the CARICOM countries. These serious biological outcomes must be addressed by investments in crop research, agro-biodiversity, agro-technology and development and dissemination that provide farmers with new varieties and management techniques that will help them adapt to the climatic changes. These investments need to begin now to deal with the expected changes in regional climate in the next 10 to 20 years. At this stage we cannot effectively analyze the differences between the 1.5°C and 2°C global temperature increase thresholds, especially at the level of CARICOM countries. However, the consequences of even the smaller increase highlight the need for urgent action.

4. Climate Change Impacts on Pacific Island Countries

The Pacific region is home to twenty-two Pacific island countries and territories. As shown in Figure 39 and Table 22, this sea of islands spreads over almost 20 million square kilometres of ocean and hosts a population of approximately 9 million, a number expected to increase by 50% by 2030 (FAO, 2009).

Although the Pacific region is geographically, culturally and economically diverse, Pacific island countries are particularly vulnerable to impacts of climate change because of their social, institutional and economic characteristics including small size, food and water insecurity, limited economics of scale and isolation from markets, food import dependence, relative poverty and growing urbanisation, fragile ecosystems and susceptibility to natural disasters.

Figure 39: The Central and South Pacific region

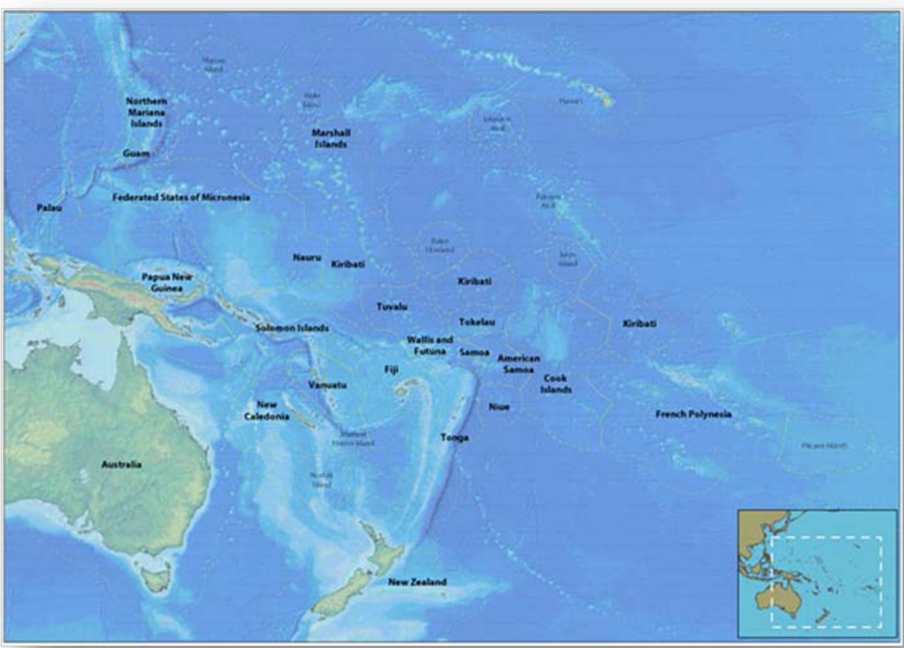


Table 27: Pacific island countries and territories: principal physical and economic features (SPREP, 2009)

Country	Land area (km 2)	Sea area (EEZ) in thousands km 2	2000 population estimates			Gross domestic product		
			Total	Density (persons/ km 2)		Total (thousands US$)	Per capita (US$)	Year
American Samoa	200	390	64,100	321	2.9	437,900	6,995	2003e
Cook Islands	237	1,830	18,700	79	-0.5	182,175	8,553	2006*
Federated States of Micronesia	701	2,780	118,100	168	1.9	235,900	2,183	2007*
Fiji Islands	18,333	1,290	824,700	45	1.6	2,695,666	3,175	2006*
French Polynesia	3,521	5,030	233,000	66	1.6	5,640,452	22,472	2004
Guam	541	218	148,200	274	1.0	3,700,000	22,661	2005
Kiribati	811	3,550	90,700	112	2.5	61,433	653	2006*
Marshall Islands	181	2,131	51,700	286	2.0	149,219	2,851	2007
Nauru	21	320	11,500	548	1.8	27,661	2,807	2005-2006
Niue	259	390	1,900	7	-3.1	10,006	5,828	2003
New Caledonia	18,576	1,740	212,700	11	1.8	7,129,631	29,898	2006e
Northern Mariana Islands (CNMI)	471	777	76,700	163	5.5	948,659	12,638	2005
Palau	488	629	19,100	39	2.2	170,144	8,423	2007e
Papua New Guinea		3,120	4,790,800	10	2.3	6,044,220	991	2006
Pitcairn	39	800	47	-	-	-	-	-
Samoa	2,935	120	169,200	58	0.6	532,000	2,872	2007
Solomon Islands	28,370	1,340	447,900	16	3.4	373,800	753	2006
Tokelau	12	290	1,500	125	0.0	-	-	-
Tonga	649	700	100,200	154	0.6	234,484	2,319	2006
Tuvalu	26	900	9,900	381	0.9	17,514	1,831	2002
Vanuatu	12,190	680	199,800	16	3.0	459,010	2,127	2006
Wallis and Futuna	255	300	14,400	56	0.5	-	-	-

e - estimate; * - provisional

Pacific island countries have contributed little to the causes of anthropogenic climate change, but they are among the most vulnerable and least able to adapt to its effects, with many of the observed and projected impacts of climate change paralleling those of the Caribbean region. The majority of people in the Pacific live in rural areas and are dependent on local natural resources and ecosystems for their food, water, shelter and livelihoods. Livelihoods are primarily subsistent and in many cases, communities are already highly vulnerable to droughts, floods and other natural disasters. Limited access to markets, government services and transport infrastructure further reduces community resilience to external shocks and stresses.

In the absence of a concerted global effort to reduce GHG emissions, significant impacts are anticipated on coastal communities and atolls, the security of water and food supplies, the health of Pacific island people and natural ecosystems. Essential industries including fisheries, agriculture and tourism will all be at risk. Building resilience to climate change is a key priority for the region, particularly as some of the impacts are already being felt. Despite being estimated to contribute less than 1% carbon dioxide emissions to 2020 (SOPAC, 2007), Pacific island countries have expressed their desire to contribute to the global effort of reducing GHG emissions. Priorities for addressing climate change have been expressed regionally through the Pacific Leaders' Call to Action on Climate Change, the Pacific Plan for Strengthening Regional Coordination and Integration, the Niue Declaration on Climate Change and the Pacific Islands Framework for Action on Climate Change 2006-2015, and nationally through documents such as the National Adaptation Programmes of Action (NAPA) and United Nations Framework Convention on Climate Change (UNFCCC) National Communications.

This section provides an overview of climate change impacts in the Pacific region, and includes research undertaken since the release of AR4 in 2007. This section also provides an overview on the current climate in the Pacific before presenting an analysis of the differences between two scenarios for global warming, the first a global warming of 1.5°C and the second of 2.0°C. In order to highlight specific issues of climate change impact and adaptation in the Pacific, five case studies are also presented.

4.1 CURRENT CLIMATE IN THE PACIFIC

Current climate conditions in the Pacific can generally be described by the observed annual temperature and precipitation averaged over a 30-year period and thus includes seasonal variation. As shown in Figure 40a and 40b, most Pacific island countries are located in tropical and sub-tropical regions with warm year-round temperatures and high to moderate rainfall. However, the averages tend to obscure the climate variability from year to year, which can be quite large, and the occurrences of extreme climatic events, which can cause considerable damage and disruption.

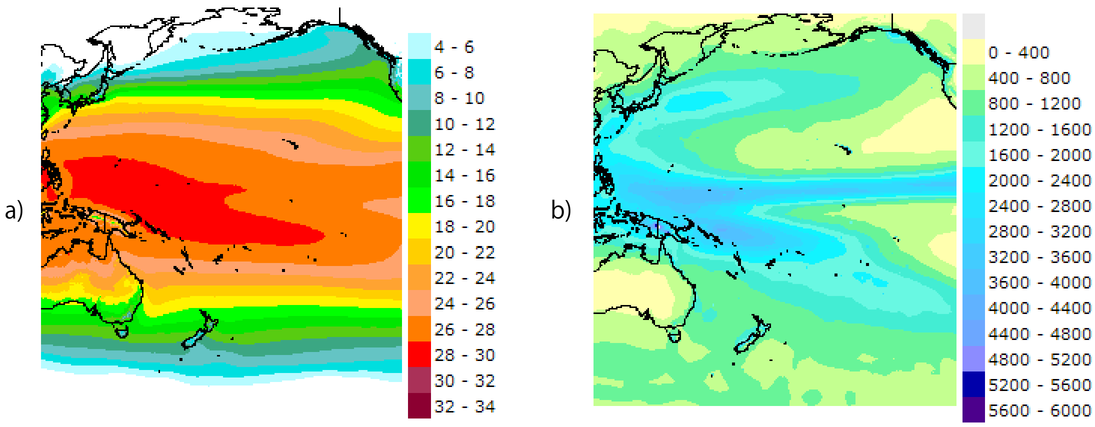


Figure 40: a) annual average temperature (in °C); b) annual average precipitation (mm/yr)

Extremes of rainfall, temperature and tropical storms pose significant risks to Pacific island countries. The key climate-related hazard risks in the Pacific include flooding, drought and wind/storm surges from tropical cyclones. It is estimated that on average, between 7 and 8 cyclones per year occur in the Pacific region[39].

Disaster losses can represent a major portion of GDP for small island developing states (SIDS), and thus seriously impede economic and social development. For example, Tropical Cyclone Ofa in 1990 turned Niue from a food-exporting country into one dependent on imports for the next two years, and Tropical Cyclone Heta in 2004 had an even greater impact on agricultural production in Niue (Mimura et al., 2007). Economic impacts of climate change and the costs of adaptation have yet to be assessed comprehensively at the regional and country level in the Pacific to inform national development strategies and investment decisions.

The climate of small islands in the central Pacific is influenced by several contributing factors such as tradewind regimes, the paired Hadley cells and Walther circulation, seasonally varying convergence zones such as the South Pacific Convergence Zone (SPCZ) and the Inter Tropical Convergence Zone (ITCZ), semi permanent sub tropical high

39 http://www.bom.gov.au/pacificsealevel/pdf/AMSAT_extreme_factsheet.pdf

The **South Pacific Sea Level and Climate Monitoring Project** was developed as an Australian response to concerns voiced by Pacific island countries about the potential impacts of human-induced global warming on climate and sea levels in the South Pacific. The project is sponsored by the Australian Agency for International Development (AusAID) and has been implemented over a number of multi-year phases.
The observational record is relatively short in climate terms and so the derived sea level trend values are still being influenced by inter-annual and inter-decadal sea level variability. Nevertheless similar trend values are beginning to emerge across the region especially after corrections for local land movement and atmospheric pressure changes are applied. For more information visit:
http://www.bom.gov.au/pacificsealevel/index.shtml

pressure belts and zonal westerlies to the south, with El Niño-Southern Oscillation (ENSO) as the dominant mode of year to year variability.

ENSO is defined by the surface pressure difference between Tahiti and Darwin, Australia, and by the warming or cooling of surface waters of the tropical central and eastern Pacific Ocean. El Niño is the warm phase of the oscillation and La Niña is the cold phase. The accepted definition is a warming or cooling of at least 0.5°C averaged over the east-central tropical Pacific Ocean, persisting longer than five months. This happens at irregular intervals of 2–7 years and lasts 9-24 months.

When El Niño occurs, there is a weakening of the pressure gradient and a corresponding weakening (or reversal) of the easterly trade winds. Warm water spreads from the western Pacific and the Indian Ocean to the east Pacific. It takes the rain with it, which can cause extensive drought in the western Pacific and increased rainfall in the normally dry eastern Pacific. The effects of El Niño across the Pacific are pronounced. For example: The El Niño of 1997/98 saw drought wipe out two thirds of Fiji's new sugar cane plantings. Tonga's squash exports were reduced to more than half. Papua New Guinea required emergency food aid for those in isolated highlands and low lying islands. More than 30 Federated States of Micronesia atolls ran out of drinking water, while Marshall Islands needed assistance for desalination plants to supply the population with fresh water as wells had run very low. Large areas of Samoan natural forests were destroyed by fire sparked by extremely dry conditions. The El Niño also significantly altered seasonal tuna catches for many Pacific Islands, including Samoa and Tonga. ... La Nina also has its consequences. After the 1997 El Niño, grossly distorted rainfall patterns brought flash floods to Fiji, while Kiribati, Nauru and Tahiti which had previously enjoyed high rainfalls of El Niño suffered droughts. Kiribati needed desalination plants to supply the population with drinking water (ABM, 2007).

Moreover, during El Niño episodes there is an eastward extension of the tropical cyclone region, which reverses during La Nina years. As well, the tuna fisheries shift eastward during El Niño. Sea level drops in the western Pacific by the order of 20cm, which can expose coral reefs with damaging effects. The effects on weather vary with each event, but ENSO is associated with floods, droughts and other weather disturbances in many regions of the world as well as the Pacific. Pacific island countries, being dependent upon agriculture and fishing, are especially vulnerable.

4.2 PROJECTED CLIMATE CHANGES IN THE PACIFIC

Projections of climate and sea-level changes for the Pacific region under global warming scenarios of 1.5°C and 2.0°C occur at different future dates depending on emission rates of GHG and on the sensitivity of the climate system to increases in GHG concentrations. This section produces "snapshots" of the climate and sea-level changes on the various future dates at which these levels of global warming were exceeded. Modelling in this section uses temperature increases of 1.5°C and 2.0°C above the 'current day' baseline of 1961-1990 (2.2°C and 2.7°C above pre-industrial temperatures respectively). The earlier sections of this report use temperature increases of 1.5°C and 2.0°C above pre-industrial temperature, taken to be 0.7°C cooler than the current day (see discussion in Section 1.1.3).

Attention here is on the additional changes that are introduced in the Pacific for sea level rise, mean temperature and precipitation because of the extra warming of 0.5°C at the global scale – with the central question being: does the extra warming at the global scale produce significant changes at the regional scale?

In order to examine the different patterns of climate change that could occur in the Pacific region, the outputs of GCMs are used[40]. For any given GHG emission scenario, individual GCMs can show quite different regional patterns of changes in temperature, precipitation, wind and other climate elements. Better results are achieved when multiple GCMs are combined – an "ensemble" approach (see Section 1 for discussion). Accordingly, this section uses the

40 Obtained from the PCMDI database

median value of ensembles of up to 21 GCMs, depending on the climate parameter being examined, in order to portray the changes that may occur in the Pacific region (CLIMsystems 2009).

As well, GCMs produce different rates of global warming due to differences in their "climate sensitivity" – the responsiveness of the climate system to increases in GHG.[41] Table 28 shows the dates at which the 1.5°C and 2.0°C thresholds are exceeded for different emission scenarios and sensitivity values, as projected by the simple climate model MAGICC (Wigley 2007) used in the IPCC AR4 and tuned to the more complex GCMs. For example, for high climate sensitivity and a high emission rate (A1FI) the 2.0°C threshold could be exceeded by as early as 2042, while a low sensitivity and low emission rate (B1) would delay the warming beyond the year 2100.

Table 28: Future dates at which the 1.5°C and 2.0°C thresholds of global warming are exceeded, as produced by the MAGICC model run with IPCC SRES emissions scenarios and model assumptions consistent with the IPCC AR4.

	1.5°C			**2.0°C**		
	low	**mid**	**high**	**low**	**mid**	**high**
A1B	2082	2048	2035	>2100	2062	2044
A1FI	2060	2044	2034	2076	2053	2042
A1T	>2100	2046	2032	>2100	2063	2042
A2	2074	2051	2037	2092	2063	2047
B1	>2100	2067	2043	>2100	>2100	2057
B2	>2100	2056	2037	>2100	2076	2050

The approach is to "normalise" the GCM regional patterns by dividing each by their global-mean warming, giving a pattern of change per degree of global warming. In effect, this approach removes the effect of the differences in climate sensitivity between the models and allows the regional patterns of climate changes to be more directly compared, without regard to time. The ensembles of normalised patterns can then be scaled by 1.5°C and 2.0°C in order to examine the magnitudes of regional climate changes for the two temperature level values and to examine the differences between them.

4.2.1 PROJECTED TEMPERATURE-PRECIPITATION-WIND CHANGES IN THE PACIFIC

41 The equilibrium "climate sensitivity" refers to the equilibrium change in annual mean global surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration. From the IPCC AR4, the value of the climate sensitivity is estimated to range from 2.0 to 4.5 °C, with a mid estimate of 3.0 °C. The uncertainty in the value is due to uncertainties in the "climate feedbacks" (e.g. changes in cloudiness, snow and ice cover) which can enhance or retard the rate of global warming from greenhouse gases, and how they are represented in global climate models.

To assess what the climate of the Pacific region will be like under two scenarios of global warming, the global mean temperature increases are applied to the regional ensemble patterns. Figure 41 shows the results for annual mean temperature. The area with the highest temperatures in Figure 41a (red) has increased substantially as compared to Figure 43. If global warming was uniform, the extra 0.5°C heating (Figure 41b) would be found everywhere. However, it can be seen that the Pacific island countries experience slightly less than 0.5°C (white). This is because the climate of the islands has a strong maritime influence and, under global warming, the surface of the ocean heats up slower than the surface of large land masses. Nonetheless, even small changes of up to 0.5°C can have large effects on the frequency of extreme hot days, especially in Pacific island countries that already experience very hot climates.

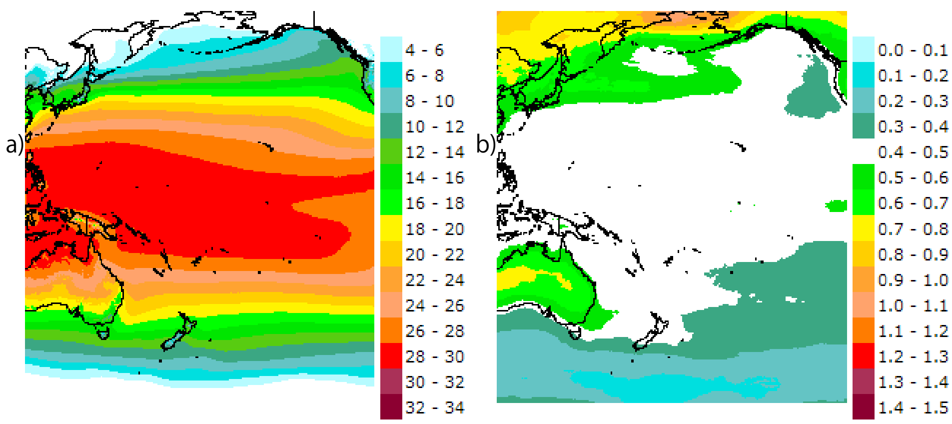


Figure 41: a) Regional annual mean temperature at a global mean increase of 1.5°C; b) additional increase from going to 2.0°C

The regional precipitation pattern under the 1.5°C is shown in Figure 42a, and the incremental change (in %) as a result of the additional global warming to 2.0°C is shown in Figure 42b. There is clearly a latitudinal pattern to the change in precipitation. The equatorial regions (yellow-orange colour) tend to get wetter, with up to 7% increases for the additional 0.5°C warming, while temperate regions tend to experience drying (green). In between (white) there is a mix. Overall, the incremental change in precipitation from 1.5°C to 2.0°C is generally small, regardless of the direction of change.

a)

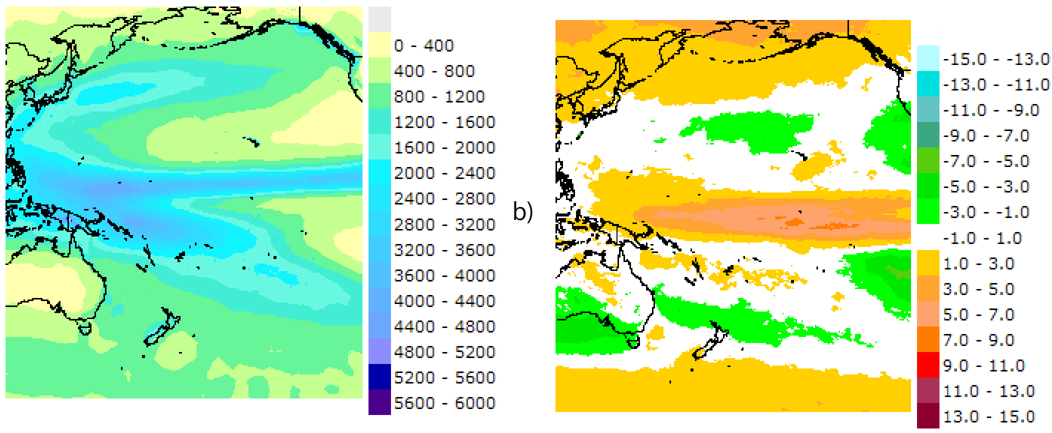


Figure 42: a) Precipitation (in mm) at 1.5°C increase in global mean temperature; b) change in precipitation (%) from an additional heating to 2.0°C

For annual mean wind speed, the relative change (%) for the additional 0.5°C of global warming is shown in Figure 43 in the white area, the wind speeds stay the same, in the orange areas they increase (up to 4%), while in the green areas they decrease (up to -2%). It should be noted that because these are average changes over a year, the implications for short-term seasonal variability and extreme winds are difficult to interpret, which is made more difficult due to the veracity of pattern of GCM ensemble itself. Regardless, the changes between the 1.5°C and 2.0°C are relatively small.

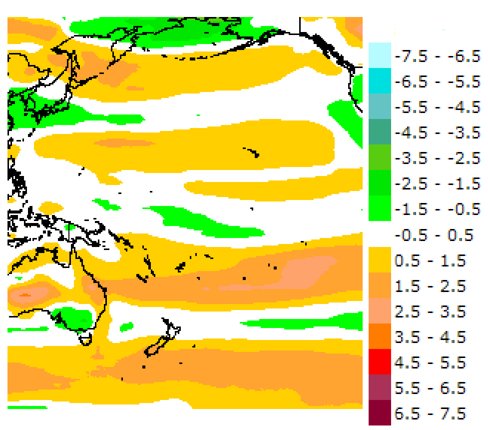


Figure 43: Change in annual mean wind speed (%) between 1.5°C and 2.0°C warming

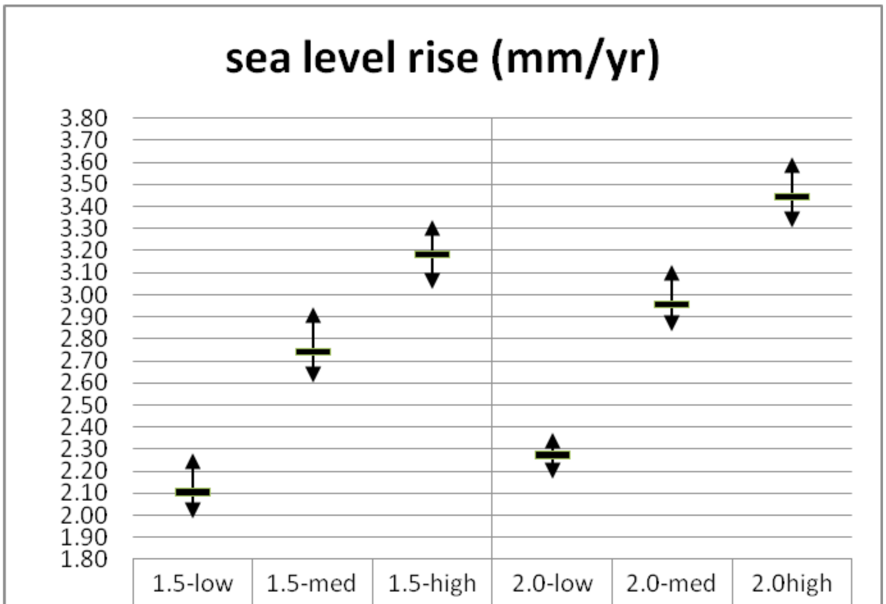
Overall, the differences for temperature, precipitation and wind between the 1.5°C and 2.0°C scenarios are small. In general, this is due to the buffering by the water mass from the Pacific Ocean, which protects the islands from amplified changes (in contrast to the big land masses). Moreover, from the global perspective many of the pronounced changes in climate tend to occur in the mid-to-high latitudes, particularly in the Northern Hemisphere, in contrast to the tropics and subtropics where the Pacific island countries are located. The exceptions could be changes in severe tropical storms and mean sea level.

4.2.2 PROJECTED CHANGES IN SEA LEVEL

For 1.5°C and 2.0°C global warming levels, there is potentially a wide range of estimates for sea-level rise, depending on the magnitude, rate and timing of the warming. Importantly, sea-level rise lags behind temperature increases as the oceans continue to expand (due to the thermal inertia of the oceans) and glaciers and ice sheets continue to lose mass. The faster the temperature increase, the bigger the lag. This means that, paradoxically, under a worst-case scenario in which the world warms very quickly, the parallel rise in sea level will, initially, be relatively minor. A substantial portion of the rise will be "in the pipeline" and occur many decades later (see also discussion in Section 2.1).

Moreover, sea level does not change uniformly due to different rates of oceanic thermal expansion around the world (most of the projected sea-level rise is the result of oceans expanding as they warm) and to changes in wind and ocean circulation patterns. These regional changes are simulated by a range of GCMs and can be shown for the Pacific region (see Figure 45). However, other contributions to sea level, for example, from glaciers and the ice sheets of Greenland and Antarctica, are not generally included in GCMs. Additional models and methods need to be used to derive the total change in sea level, which was the approach followed in the IPCC AR4.

In this section, the rates of sea-level rise (in mm/yr), as derived from IPCC AR4, are determined for the various future dates at which the world exceeds the 1.5°C and 2.0°C warming levels, which is a function of climate sensitivity and emission scenario. Figure 44 shows the range in sea-level rise rate for the two global warming scenarios in relation to the three climate sensitivities (low, medium, high) and the six IPCC emission scenarios (A1B, A1FI, A1T, A2, B1 and B2)[42]. The vertical arrows associated with each horizontal bar show the range of variation due to the emission scenarios. It is clear that the differences between the climate sensitivity values are more significant than the differences between emission scenarios (the length of the arrows).



	1.5-low	1.5-med	1.5-high	2.0-low	2.0-med	2.0high
max	2.28	2.94	3.34	2.38	3.13	3.63
min	1.99	2.60	3.02	2.17	2.83	3.31
– avg	2.11	2.74	3.18	2.27	2.96	3.44

Figure 44: Range of sea level rise rates for 6 IPCC emissions scenarios, 3 climate sensitivities over 2 global warming scenarios.

As the current observed rate of global warming suggests a medium to high range climate sensitivity (Cazenave et al., 2008), the best estimate of sea-level rise for 1.5°C warming is 2.60-3.34 mm/yr, while for 2.0°C warming it is 2.83-3.63 mm/yr. These future projections represent increases of 44-86% and 57-102% in the rate of sea-level rise under the 1.5°C and 2.0°C global warming scenarios, respectively.[43]

42 Scenarios that do not achieve 1.5 °C (A1Tlow, B1low, B2low) and/or 2.0 °C (A1Blow, A1Tlow, B1low, B2low, B1med) by 2100 were not included.

43 It should be noted that the IPCC AR4 report indicates that an additional increase of 2mm/yr from dynamic changes in ice sheet mass balance is possible during this century under the high climate sensitivity and under high temperature increases. As the global warming scenarios in this study are limited to 2.0 °C this has not been included.

It is important to note that, with increased global warming, the rate of sea level rise is likely to accelerate. Observations that the rate of sea-level rise has increased from 1.6mm/yr in the period 1961-2003 to 3.1mm/yr in the period 1993-2003, and that sea-level rise is currently tracking at or near the upper limit of the IPCC projections have led to concern that mid-range values of the IPCC projections could be significant underestimates (Steffen, 2009) (see also discussion in Section 2.1).

As mentioned above, changes in sea level are not expected to be uniform around the world. There are regional variations due largely to differential rates of oceanic thermal expansion and these variations are modelled by GCMs. Taking the median value of an ensemble of 11 GCMs, the regional pattern of change (relative to the global-mean change) for the Pacific region is shown in Figure 45: a value of less (more) than 1.0 indicates a rate of rise that is less (more) than the global-mean rate of thermal expansion. For most of the Pacific region, the multiplier is 0.95-1.05 (grey, less than 5% difference) or 0.85-0.95 (green, between 5-15% smaller). Some areas are just in the 1.05-1.15 range (5-15% bigger), with a given global sea level rise rate, these areas are experiencing up to 15% stronger increase. For the Kiribati case study in this chapter (Case Study 1), the multiplier for Tarawa is 1.03, or 3% above global mean.

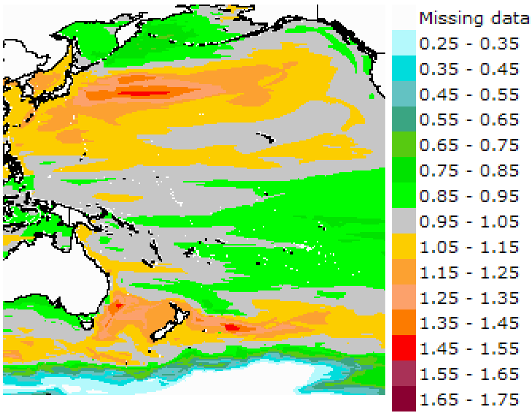


Figure 45: The pattern of oceanic thermal expansion in the Pacific region in relation to the global-mean value (in cm/cm), as derived from the median value of an ensemble of 11 GCMs

4.2.3 TROPICAL CYCLONES

Tropical cyclones are driven in large part by the surface temperature of seawater. Thus, in the first instance one might expect that global warming would result in more frequent and intense cyclones. Observational evidence does, in fact, show increases in numbers and intensities of severe tropical storms, but only for some regions (e.g. North Atlantic). In general, the IPCC AR4 concludes that:

A synthesis of the model results to date indicates, for a warmer future climate, increased peak wind intensities and increased mean and peak precipitation intensities in future tropical cyclones, with the possibility of a decrease in the number of relatively weak hurricanes, and an increase in the number of intense hurricanes (Solomon et al., 2007).

It is likely that maximum tropical cyclone wind intensities could increase by 5-10% by 2050, with peak precipitation rates of up to 25%, which in turn cause higher storm surge (Mimura et al., 2007)[44].

4.2.4 OCEAN ACIDIFICATION

Another important effect is the acidification of the oceans, which impacts on sea-life and especially coral reefs. However, given the modelling approach employed in this section, it is not possible to quantify the impact of the acidification with an additional 0.5°C of global warming. Recent research indicates that the effects of ~400ppm CO_2 on ocean acidification are very likely to cause reduction in live coral cover of 30-40%. Coral cover is expected to decrease by 75% due to bleaching and increased acidification of the ocean (Hoegh-Guldberg et al., 2007). As noted by Hoegh-Guldberg (cited in Steffen, 2009), business-as-usual trajectories of increasing acidity and SST will likely overwhelm even the most resilient of reefs sometime in the second half of the century (see also discussion in Section 3.1).

44 A more detailed study of the Pacific region that will track climate trends, investigate regional climate drivers, provide regional climate projections and improve understanding of ocean processes, ocean acidification and sea level rise is being undertaken by Australia through the Pacific Climate Change Science Program and will be available in 2011.

4.2.5 SUMMARY OF ANTICIPATED CLIMATE CHANGE IMPACTS FOR PACIFIC ISLANDS

A summary of climate change effects is outlined in Table 29. Overall, this section found that:

- Mean temperature change throughout the region is similar to that of the global average, but slightly less due to the moderating effects of the vast ocean area. Temperature increases of the order of 1.5°C would substantially extend the regions of very hot temperatures throughout the region and are very likely to increase the magnitude and frequency of extreme hot spells. An additional 0.5°C warming would likely cause a relatively large increase in the frequency of those extremes.

- For the 1.5°C warming level, mean annual rainfall is generally projected to increase on the order of 5-15% over most of the equatorial Pacific where rainfall is already high. Such increases are likely to significantly increase the magnitude and/or frequency of extreme rainfall events and increase flood risks. Other areas of the Pacific show lesser increases or even slight decreases in rainfall. With the additional 0.5°C warming, the rainfall changes proportionally.

- For most Pacific island countries in the southern hemisphere, annual mean wind speed is projected to increase by about 2-10% at the 1.5°C warming level, with small additional changes for the incremental warming. These increases could have significant implications for seasonal winds and extreme high winds and their associated risks, but the uncertainties are very large. There are considerable differences in the projections of changes in wind speed amongst the various climate models.

- The best estimate of the rate of mean sea-level rise at the 1.5°C warming level is 2.60-3.34 mm/yr, and 2.83-3.63 mm/yr at the 2.0°C level – an increase of 13-16% in the rate of mean sea-level rise from the additional 0.5°C warming. These estimates represent approximately a doubling of the rate of rise observed over the last 100 years.[45]

- Within the Pacific region, there are slight variations in the rate of sea-level rise as projected by the ensemble of GCMs due to differences in the rate of thermal expansion, ranging from ±15%.

45 Derived from IPCC AR4 projection, and assuming that the climate sensitivity lies in the mid-to-high range in accordance with recent observations. Possible contributions from dynamic changes in ice sheets are not included.

Table 29: Summary of effects of climate change in the Pacific region

Climate change effect	Change for 1.5°C global warming	Additional change for 2.0°C global warming
Temperature	≤1.5°C	≤0.5°C
Precipitation	-10% to +20%	-3% to +7%
Wind	-5% to +10%	-2% to +4%
Sea level rise rate	+44-86% (over 1990)	+13-16% [57-102% (over 1990) total]

4.3 PROJECTED IMPACTS ON VULNERABLE SECTORS, COMMUNITIES AND ENVIRONMENTS

The people of the Pacific have a long history of resilience to volatile climate conditions. However, changes in mean sea level, temperature and rainfall, and intensity of tropical storms increase the severity of climate change impacts, and the capacity of vulnerable countries to recover (Barnett & Campbell, in press).

The vulnerability of Pacific island countries and their ability to respond is inextricably linked to broader development challenges. The region's limited resources, concentration of population and infrastructure in coastal areas, susceptibility to natural disasters such as cyclones, sensitivity of fresh water supplies, isolation, small size and limited financial, technical and institutional capacities all exacerbate their vulnerability and limit their adaptive capacity.

Small economies are generally more exposed to external shocks, such as extreme events and climate change, than larger countries because many of them rely on one or few economic activities such as tourism and fisheries. The cost of adaptation relative to gross domestic product can be very high. The World Bank, Mimura et al., 2007 estimated that by 2050, in the absence of adaptation, a high island such as Fiji could experience damages of up to US $52 million (equivalent to 2-3% of Fiji's GDP in 1998) (Mimura et al., 2007). A group of low islands such as Tarawa in Kiribati could face average annual damages of US $8-16 million (or 17-18% of GDP in 1998) under A2 and B2 scenarios (Mimura et al., 2007).

Pacific island countries experience climate change impacts in a number of ways, as summarised by Hay (2000):

- land use changes, including settlement and use of marginal lands for agriculture, are decreasing the natural resilience of environmental systems and hence their ability to accommodate the added stresses arising from changes in climate and sea level;

- given the limited area and low elevation of the inhabitable lands, the most direct and severe effects of climate and sea-level changes will be increasing risks of coastal erosion, flooding and inundation; these effects are exacerbated by the combination of seasonal storms, high tides and storm surges;

- other direct consequences of anticipated climate and sea-level changes will likely include: reduction in subsistence and commercial agricultural production of such crops as taro, bananas and coconut; decreased security of potable and other water supplies; increased risk of dengue fever, malaria, cholera and diarrhoeal diseases; and decreased human comfort, especially in houses constructed in western style and materials (especially in the Pacific);

- groundwater resources of the lowlands of high islands and atolls may be affected by flooding and inundation from sea-level rise; water catchments of smaller, low-lying islands will be at risk from any changes in frequency of extreme events; and

- the overall impact of changes in climate and sea level will likely be cumulative and determined by the interactions and synergies between the stresses and their effects;

This section discusses the likely climate change impacts on vulnerable sectors, communities and environments, as well as the potential adaptation options open to the Pacific island countries.

4.3.1 WATER

Owing to factors of limited size, and geology and topography, water resources in small islands are extremely vulnerable to changes and variations in climate, especially rainfall. For example, a 10% reduction in average rainfall by 2050 is likely to correspond to a 20% reduction in the size of the freshwater lens on Tarawa atoll, Kiribati. Less rainfall coupled with land loss from sea level rise, is likely to reduce the thickness of the water lens on atolls by as much as 29% (Mimura et al., 2007).

Increased water demand related to population and economic development, combined with ongoing water pollution and unregulated use place serious stress on water resources. By mid-century, climate change is expected to reduce water resources in many small islands in the Pacific and Caribbean, to the point where they become insufficient to meet demand during low-rainfall periods (Parry et al., 2007). This is particularly the case for countries in the non-equatorial region of the Pacific.

Photo: Lorrie Graham, AusAID

Small islands' limited water storage capacity and groundwater reserves makes them vulnerable to prolonged or repeated extreme drought events, with impacts on local economies and health. For example, during the prolonged droughts of 1998-2000, boreholes yields in Fiji decreased by 40% during the dry period and export crops including sugar cane were severely affected (World Bank, 2000). Adaptation strategies such as demand management, integrated water resource management and increasing water storage and desalination plants (Tuvalu) are being explored in the Pacific region (Parry et al., 2007).

4.3.2 COASTS AND INFRASTRUCTURE

The coastlines of small islands are long relative to the island area. They are also diverse and resource rich, providing a range of goods and services, many of which are threatened by a combination of human pressures and climate change and variability resulting from sea level rise, increase in sea temperature, coastal erosion, salt intrusion into freshwater lenses and increased flooding from the sea. A large proportion of Pacific islands communities, both urban and rural live in coastal locations and coastal resources play an important part in subsistence and cash economies. Coastal areas also support a growing tourism industry, for example, in Fiji and Vanuatu. Sea-level rise will aggravate coastal problems such as inundation, storm surge during tropical cyclones, erosion and salinisation of soils and groundwater, threatening both local communities and industries dependent on coastal resources. These impacts are explored further in Case Studies 1 and 5.

The infrastructure base that supports island economies is located mostly in coastal areas, including ports, airports, roads and administrative and political infrastructure. The threat to infrastructure from sea-level rise including inundation, flooding and physical damage associated with land loss, could be amplified considerably by tropical cyclones. For example the port facilities in Suva, Fiji, and Apia, Samoa would experience overtopping, damage to wharves and flooding of the hinterland if there were a 0.5 metre rise in sea level combined with waves associated with a 1 in 50 year cyclone (Hay et al., 2003). Adaptation approaches based on integrated coastal zone management provide a framework to address existing threats and climate change-related impacts such as the location of key infrastructure, adaptations options to maintain coastlines and the protection of key habitats such as wetlands and coral reefs.

4.3.3 FOOD SECURITY – AGRICULTURE AND FISHERIES

Pacific Islands have traditionally enjoyed comparatively good food security, mainly because they have secured food in a variety of ways, including subsistence farming, trading and selling products, fishing and hunting. This historic food security is being eroded by urbanisation and a growing reliance on cheap and often poor quality imported foods (FAO, 2009).

Small islands have traditionally depended upon subsistence and cash crops for survival and economic development. While subsistence agriculture provides local food security, cash crops such as sugar cane, bananas and forest products are exported. The ecological dependence of Pacific island subsistence economies and societies is well documented (ADB, 2004). Projected impacts of climate change on agriculture include extended periods of drought on one hand, and on the other hand, a decline in soil fertility and erosion (due to increased precipitation) with loss of crops and reduced yields. Saltwater intrusion, groundwater contamination and loss of arable land will affect the growth of crops, particularly in coastal areas and on atoll islands. Climate change will favour the establishment and spread of new pests and disease vectors, further threatening the production of crops and livestock. A decline in agricultural production will have dramatic consequences for local economies and food security and reduce Pacific island countries' opportunities for trade and foreign exchange. Adaptation measures include initiatives to promote and support diversification of production systems, adopting integrated resource management approaches to food production, and building on traditional production systems to enhance resilience to climate change impacts (see Case Study 2).

Like other small island states, Pacific island countries have an extraordinary dependence on fish. The majority (60-90%) of this fish is derived from subsistence fishing in coastal waters. The contribution of tuna fishing to the economies of Pacific island countries exceeds US $535m per year (Gillett, 2009). Consequently the socio-economic implications of the impacts of climate change on fisheries are likely to be important and would exacerbate other anthropogenic stresses such as overfishing. On current projections, coastal fisheries will not be able to provide the fish needed by the rapidly increasing human populations for food security in 16 of the 22 Pacific island countries and Territories in the near future (SPC, 2008).

Projected impacts of climate change on fisheries arise from:

- Loss of coral reefs which underpin coastal fisheries as a result of coral bleaching under higher water temperatures, weaker coral skeletons and slower growth caused by ocean acidification, and increased physical damage by more intense tropical cyclones.

- The convergence of the western Pacific 'warm pool' and the 'cold tongue' of nutrient rich waters from the eastern Pacific equatorial upwelling that creates the prime feeding grounds for skipjack tuna is projected to move east as temperatures increase. In addition, the warm pool itself is expected to become less productive due to increased stratification of ocean surface waters in the tropics associated with higher temperatures, higher rainfall and reduced salinities.

Adaptation strategies to improve access to fish resources in urban and rural communities include improving fisheries and coastal management to address overfishing and existing threats to coastal habitats, providing access to tuna for subsistence and artisanal fishers in rural areas by establishing low-cost, inshore fish aggregating devices (FADs), providing incentives for better use by catch from industrial and pond aquaculture when feasible, such as in Melanesia (see Case Study 3).

4.3.4 ECOSYSTEMS

Photo: Lorrie Graham, AusAID

Oceanic islands have a unique biodiversity with high endemism because of their ecological isolation. Island ecosystems and the species they support provide essential services to island communities, including food, fibre, clean water, clean air and coastal protection as well as economic development opportunities such as tourism and fisheries.

Terrestrial habitats expected to be impacted most by climate change are mangrove and coastal systems, montane systems and dry land vegetation communities. Species that are naturally located in high elevation areas, in isolated or outlying mountain ranges, on smaller islands, or that are also exploited for human use are at greatest risk. Anthropogenic activities that are unrelated or only indirectly related to climate change, such as forest conversion for agriculture, over-logging and fire, will exacerbate the impacts of climate change and accelerate the rate of species extinction.

Marine ecosystems and in particular coral reefs are expected to be most affected by climate change. Coral bleaching (which is caused by increased SSTs), ocean acidification and marine invasive species will add to existing threats such as overharvesting and coral mining.

Ecosystem–based adaptation can enhance resilience to climate change, protect carbon stores and contribute to adaptation strategies (World Bank, 2009). Better protection and management of key habitats (wetlands, coral reefs, forests) through protected area networks, and natural resources through ecosystem based approaches will increase the resilience to climate change impacts and maintain ecosystems services and access to resources underpinning small islands economies (see Case Study 4).

4.3.5 HEALTH

Many small islands countries suffer from severe health burdens from climate sensitive diseases, including morbidity and mortality from extreme weather events, certain vector borne diseases and food and water borne diseases. Tropical cyclones, storm surge flooding and droughts have both short and long-term effects on human health, including increased diseases transmission and decreased agricultural production.

The spread of many climate sensitive diseases is increasing in small islands because of poor public health practices, inadequate infrastructure, poor water management practices and increasing global travel and changing climate conditions. Many Pacific island countries already depend on external health services and will be put under additional pressure from climate change.

Outbreaks of climate sensitive diseases can be costly in terms of lives and economic impacts. For example, an outbreak of dengue fever in Fiji coincided with the 1997-98 El Nino; out of a population of approximately 856,000, 24,000 were affected, with 13 deaths. The epidemic cost US $3-6 million (Mimura et al., 2007). Ciguatera fish poisoning is common in reef waters. Multiple factors contribute to outbreaks including pollution, and reef degradation (Hales, 1999).

4.4 CLIMATE CHANGE CASE STUDIES IN THE PACIFIC

Decisions and actions to reduce vulnerability in the Pacific must be taken now, but a number of scientific and economic uncertainties make this difficult. The scientific uncertainty begins with a lack of detailed observational data and climate modelling for the Pacific. This means that long-term projections include broad ranges for the likelihood, timing and extent of impacts. The diversity of Pacific geography means that local impacts will vary greatly across the region. Confronting uncertainty in decision making is not new. The challenge is to reduce the extent and causes of the unknown and build on existing expertise, institutions, community networks and infrastructure to allow positive outcomes in an unclear future.

This section presents five case studies that highlight issues and problems in the Pacific in relation to specific impacts of climate change. These case studies draw together insights from practitioners across the Pacific region. The case studies examine climate change impacts for sea level rise on the low-lying atoll environment of South Tarawa, Kiribati; agriculture and food security, fisheries across the Pacific; biodiversity in Melanesia; and coastal inundation in Honiara, Solomon Islands. The case studies discuss the implications of climate change impacts in each sector, and identify the potential for adaptation.

Case Study 1: Impacts of sea level rise in South Tarawa, Kiribati[46]

Kiribati is recognised as potentially at high risk from climate change impacts. Currently, this low-lying atoll nation is extremely vulnerable to storm surges and high tides, as well as being exposed to strong winds and to strong wave action (Government of Kiribati, 1999; 2007). These factors are further exacerbated in the capital of Kiribati, South Tarawa atoll, as the atoll is highly modified, mainly due to chronic overcrowding as a result of migration from the outer islands (Hay and Onorio 2006). This population is concentrated within a long and narrow 30km corridor of land, averaging only 450m in width, bounded on one side by the ocean and on the other side by the lagoon.

This case study, therefore, examines the potential impacts on South Tarawa from permanent inundation due to mean sea-level rise on South Tarawa, based on a 1.5°C and 2.0°C rise in global temperature. These impacts are contrasted with the higher IPCC A1FI emission scenario. The A1FI scenario serves as a useful comparison noting the implications for sea level rise identified in recent studies (The Copenhagen Diagnosis, 2009). This case study also reviews findings from an assessment undertaken of the joint occurrence of extreme waves and water levels, the impact of climate change on these processes, and what this means for wave conditions reaching the shoreline, wave run-up and overtopping in South Tarawa.

Findings are based on work undertaken for the Kiribati Adaptation Project Phase II (KAP II) (Kay, 2008; Elrick and Kay, in press), which was focused on delivering participatory climate change risk assessments and training with Government of Kiribati staff between 2007 and 2009.

The average of low and high model sensitivity results from the projected sea level rise rates for 1.5°C and 2.0°C global warming are shown in Figure 28 and Figure 46. Impacts were evaluated for 2070 and 2100.[47]

46 Lead Authors: Dr Robert Kay and Ms Carmen Elrick, Coastal Zone Management

47 Figures are based on modeling performed by CLIMsystems for the Pacific section. Modeling uses temperature increases of 1.5 and 2.0°C above the 'current day' baseline of 1961-1990 (2.2 and 2.7°C above pre-industrial temperatures).

Table 30: Mean sea-level rise used in the South Tarawa case study in cm above 1990 baseline

	2070	2100	2070	2100
	Low model sensitivity		High model sensitivity	
1.5 degrees (average of model results)	23.2	25.1	35.0	36.7
2.0 degrees (average of model results)	25.0	26.2	37.8	39.9
A1FI (high model sensitivity)			38.1	65.3

Findings presented here only consider permanent inundation impacts due to changes in mean sea level. There are additional climate change and impact assessment factors that will influence the vulnerability of South Tarawa. While not examined in this case study, they will impact significantly on the vulnerability of the islands. These factors include:

- Changes in offshore wave climate.
- Impacts on near shore reefs due to bleaching and/or acidification.
- Stresses to other factors that affect the viability of the atolls for human habitation, in particular the relationship between sea level rise and groundwater resources.
- Long term coastal change, including coastal erosion driven by climate change factors and human-induced change through construction of sea walls, causeways and other structures.
- Any change in climate variability related to seasonal, El Niño Southern Oscillation or Inter-decadal Pacific Oscillation characteristics.
- Changes in rainfall and drought patterns.

Primary impacts from mean sea level rise will be on the immediate coastal fringe and on low-lying land within the atoll (represented shaded blue in Figure 46). Low-lying land may become permanently swampy as sea levels, and consequently the water table, rise. Infrastructure and services situated in these areas will likely require increased maintenance, and certain areas of land may potentially become uninhabitable. In addition, ground water may become exposed to contaminants, as the boundaries between the freshwater interface and human activity decrease.

The assessment completed in South Tarawa demonstrates different villages along the atoll will experience differential impacts. This will affect properties, cultural services, roads and other infrastructure (electricity, telecommunications) in these areas. Importantly, the assessment demonstrates the extreme vulnerability of land designated for urban expansion in response to current overcrowding in the capital, acting as a major constraint on development and poverty alleviation options. As shown in Figure 46c, inundation under an A1FI scenario is greater than for the averaged model results (Figure 46a, b). This demonstrates that reducing emission from a business as usual trajectory will reduce sea level rise impacts in South Tarawa.

In the KAP II study, climate change impacts under the A1FI high sensitivity scenario were analysed using the NIWA coastal calculator, a tool developed to assess the impact of climate change on tide and extreme water levels, wave run-up levels and wave overtopping for specific locations in Tarawa (Ramsay et al., 2008). Workshop participants, consisting of key government stakeholders, analysed hazard maps that showed mean sea level rise impacts in South Tarawa, identified and then ranked potential risks. In order of priority, the highest priority risks identified were:

- Reduction in freshwater due to a decline in water quality (due to rising water table).
- Loss of land, leading to increased pressure on other areas due to migration, overcrowding and associated human health issues.
- Loss of cultural practices/identity through loss of historical sites and impacts on cultural facilities.
- Isolation of communities through damage and interruption to road networks.
- Biodiversity loss through increased coastal erosion and loss of marine habitats as mangrove systems are degraded.
- Economic loss through damage to major transport services such as the airport and ports.

Government of Kiribati stakeholders are currently finalising corresponding adaptation options to develop an Adaptation Action Plan. Adaptation options are being prioritised based on three criteria: an understanding of the risk level; current controls in place to manage the identified risk; and potential barriers and opportunities to implementation.

While Kiribati does not experience any significant storm surge because of its location close to the equator and outside the zone of direct tropical cyclone occurrence, when storm events coincide with high tides, significant areas of land can be inundated.

As part of the KAP project, a detailed assessment was undertaken of the joint occurrence of extreme waves and water levels, the impact of climate change on these processes, and what this means for wave conditions reaching the shoreline, wave run-up and overtopping (Ramsay et al., 2009).

Table 31 shows the potential changes in wave heights reaching the shoreline and wave run-up for a typical ocean side location in South Tarawa by 2100. In addition, the table shows the frequency of overtopping of the causeway separating two important islets (between Betio and Bairiki). This is based on offshore wave and water levels with a 10% chance of occurring in any one year.

Table 31: Example of possible changes by 2100 in shoreline wave height, run-up level and overtopping along the ocean side of South Tarawa for wave and water level conditions with a 10% chance of occurring in any one year.

	1.5 degrees		2 degrees		A1FI
	Low MS	High MS	Low MS	High MS	
Increase in mean sea level (cm)	25.1	36.7	26.2	39.9	65.3
Increase in significant wave height at the shoreline (cm)	0.09	0.13	0.09	0.14	0.23
Increase in beach wave run-up level (cm)	0.35	0.51	0.36	0.55	0.89
Increase in wave overtopping volume at Betio and Bairiki Causeway (%)	98	161	103	181	339

This demonstrates that overtopping will increase dramatically, particularly under the A1FI scenario. Any implications of short-term flooding experienced during storm events due to high tides and waves have not been considered in this case study.

Key findings from work undertaken as part of the KAP II project, using 1.5°C, 2°C and A1FI scenarios, demonstrate:

- Significant sensitivity of South Tarawa to mean sea level changes under the different scenarios.
- Increased frequency of wave-induced inundation affected by higher sea levels of the immediate coastal margins as one of the most obvious impacts of mean sea level rise.

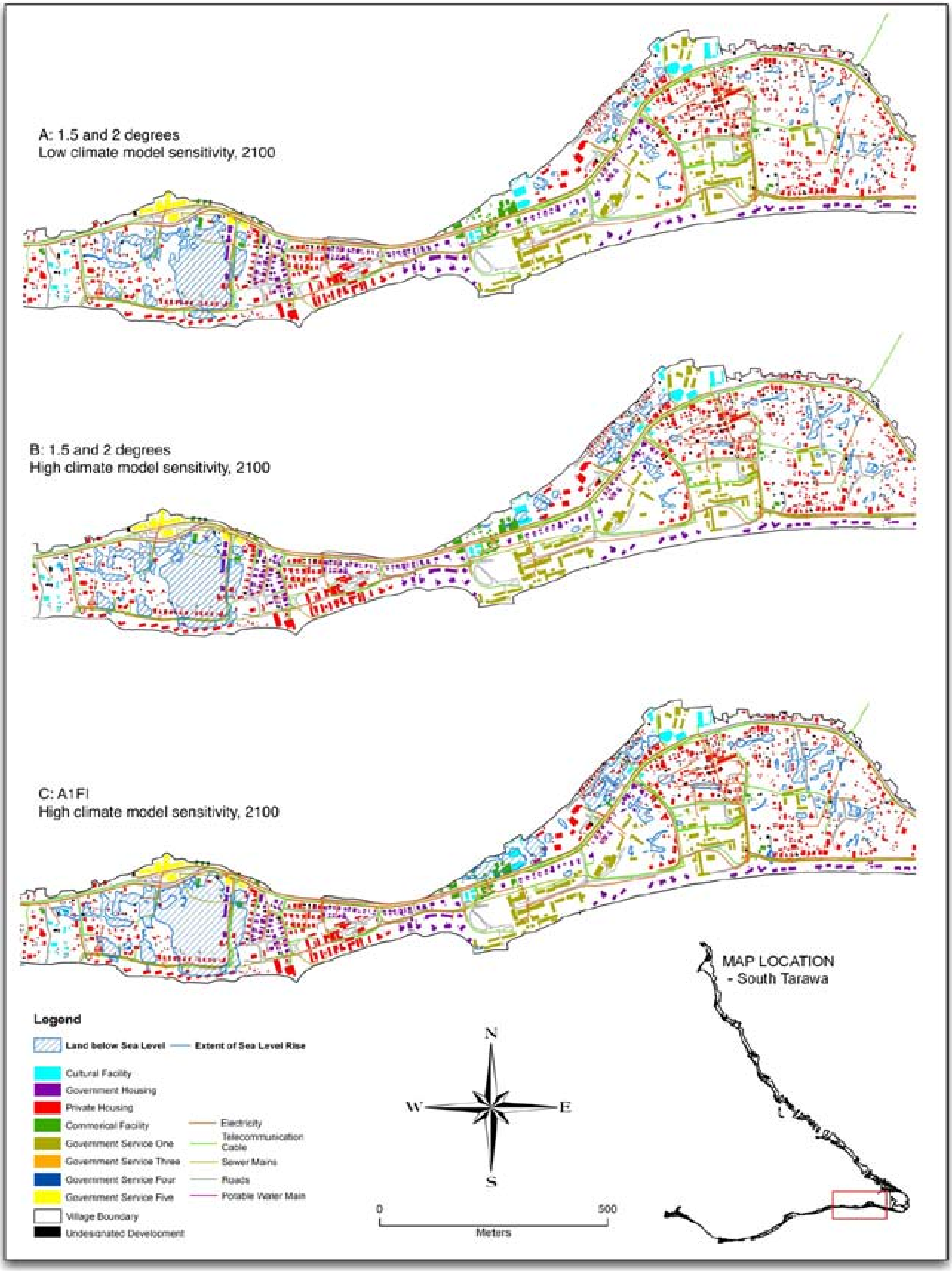


Figure 46: Land effected by sea-level rise in Bikeniebu village, South Tarawa, 2100, under three climate change scenarios (Kay, 2008; Elrick & Kay, in press)

Case Study 2: Agriculture and climate change in the Pacific[48]

The importance of agriculture is increasing globally with the recognition of the contribution it can make to development and therefore economic growth. Investment in agriculture reaps greater benefits than investment in any other sector. The Pacific is no exception. Agriculture is crucial to food and nutritional security in the Pacific. It provides food for the people of the Pacific and supports livelihoods through the sale of agricultural products on the domestic or export market. In Melanesia, up to 80% of the population is involved in agriculture and forestry on a subsistence or commercial basis. Up to 35% of GDP in resource rich countries such as Papua New Guinea is derived from agriculture and forestry.

Agriculture and local food production are also crucial for the health of the people of the Pacific. The alarming increase in non-communicable diseases is linked to the consumption of nutritionally-poor food, often imported. Increasingly there is more awareness as to the nutritional benefits of the traditional food crops of the Pacific and increased consumption of local food products are seen as key to tackling this serious health problem in the Pacific.

A recent report from Food and Agriculture Organization (FAO) (Climate change and food security in Pacific Island countries, 2008) highlighted some common themes drawn from studies conducted in Cook Islands, Republic of the Marshall Islands and Vanuatu. It was felt that these common themes apply to other Pacific islands. The potential for climate change to impact negatively on agriculture and food security in the Pacific is evident.

The overall trend will be unpredictability and intensity, which is already evident. For example, before 2005, Cook Islands was considered to lie outside the cyclone belt and likely to be hit by a severe cyclone only once every 20 years. Between February and March 2005, the country was affected by five tropical cyclones (three at category 5 level). The cyclones caused damage equal to 10% of the government's annual budget and destroyed 75% of homes on Pukapuka Island. In 2004, Niue was hit by Cyclone Heta, a category 5 cyclone that saw waves break over the island's 30-metre-high cliffs, causing two deaths, flattening 20% of buildings, destroying almost all of the country's agriculture, ruining

48 Lead Author: Dr Mary Taylor, Secretariat of the Pacific Community

90% of the country's museum artefacts and causing economic damage equivalent to 200 years of Niue's exports.

For the first time ever recorded in the region, in 2009 king tides struck several countries at the same time, including the Federated States of Micronesia, Republic of the Marshall Islands, Kiribati, Papua New Guinea, Solomon Islands and Tuvalu. In January 2009, Fiji was hit by the worst flooding in more than 50 years, resulting in at least 10 deaths. Flash floods also affected Solomon Islands with more than 13 people losing their lives in just one location.

Climate change will impact on agricultural production in the Pacific Islands in several ways. In coastal communities the effects of erosion, increased contamination of groundwater and estuaries by saltwater incursion, cyclones and storm surges, heat stress and drought may individually or in combination undermine food production. The availability and quality of land for production will also be affected through coastal erosion and contamination of groundwater by saltwater intrusion. Increased flooding of river catchment areas will exacerbate soil erosion. Climate change is projected to alter the function and species composition of forests, affecting their ability to provide important ecosystem services such as water cycle regulation, maintenance of soil fertility and conservation of biodiversity.

Crop productivity will be impacted because of floods, droughts, and salinisation. There is already evidence from the atolls that swamp taro is not responding well to saltwater intrusion, though there appear to be varietal differences. The predicted increase in extreme weather will damage crops at particular developmental stages and make timing of farming more difficult, reducing farmers' incentives to cultivate.

The impact of higher temperatures and increased carbon on tropical crops is not yet well understood. It is likely that the root and tuber crops will be able to manage the higher temperatures but in combination with drought especially at the time of establishment, could have an impact on yield. As the main staples of the Pacific are largely vegetatively propagated then flowering is not an issue, but this is not the case with fruit crops, for example mangoes.

There is also the issue of pests and diseases. The predictions are that climate change will favour the establishment and spread of new pests and disease vectors, further threatening the production of crops and livestock. Obviously extensive water-logging will favour "rot" problems, such as Pythium in taro. Anthracnose disease in yams is also favoured by a wet/wetter climate, as is taro leaf blight with taro.

The recent extreme flooding in Fiji highlighted the vulnerability of Pacific Island countries to these extreme events. Crops were wiped out, both those affecting food supply at the country level and also crops for export markets, such as papaya. There was an urgent need to access planting material for both purposes, highlighting the importance of robust planting material networks. Planting material networks are crucial, and ideally these should exist and be sustained at the national and community level.

Adaptation strategies must be diverse, combining the availability of crop and animal genetic diversity with the integrated management of natural resources needed to sustain their productivity and ensure they continue to provide the vital services needed by people and the environment. Diversifying production systems and building on traditional practices will be crucial in enhancing community resilience.

Diversity is central to managing climate change. The Pacific region is not well-placed to pursue targeted breeding as in other parts of the world, where resources support such an activity and where the crops are of more global importance. As a result the Pacific will have to rely on the genetic diversity that exists within the Pacific crop gene-pool but at the same time take advantage of the diversity that exists outside the region, in particular the diversity maintained by the International Agriculture Research Centres, such as Centro International de Papa (CIP), which has the mandate for sweet potato. As long as farmers have access to diversity they have options with which to manage climate change.

The SPC Centre for Pacific Crops and Trees (CePaCT) has established a climate ready collection, which includes crop diversity from within the region, mainly aroids. These aroids provide the ability to produce food in both water-logged and dry conditions. The development of this collection has been supported by several donors but its expansion and evaluation is a major component of Australia's International Climate Change Adaptation Initiative. The collection also consists of diversity from outside the region. A relatively recent acquisition has been salt and drought tolerant sweet potatoes imported from CIP, already in several countries undergoing evaluation. Sweet potato has the advantage of being an early maturing crop, and in fact, sweet potato material was distributed after the Fiji floods to farmers to ensure food security. This collection is very much a dynamic collection – with crop diversity being collected, distributed, evaluated and then conserved, or not, depending on its performance. Evaluation of the climate ready collection is essential so information can be obtained as to the performance of specific crops/varieties in varying conditions.

Photo: Rob Maccoll, AusAID

The CePaCT is linking with the taro breeding programme in Samoa, established in the early 1990s in response to the taro leaf blight which destroyed taro production. This programme, initially established with Australian Agency for International Development (AusAID) funding under the Taro Genetic Resources: Conservation and Utilization (TaroGen) project to generate breeding lines resistant to taro leaf blight has now extended the screening of the new breeding lines to look for climate-ready traits, such as drought tolerance.

The capacity to produce planting material also has to be strengthened at the community level, as highlighted by the Fiji floods in early 2009. Countries and communities must be less reliant on external sources for their planting material, requiring training in seed production, increased availability of open-pollinated varieties, and an understanding of seed storage and seed viability. At the community level there also needs to be an understanding of the importance of crop diversity.

Adaptation approaches must also include development and promotion of farming systems more suited to changing environmental conditions, such as traditional agro-forestry system, and the promotion of sustainable land and forestry management and land-use planning to minimise the projected impacts of climate change on agriculture and forestry, such as more regular inundation and soil erosion.

In summary, to reduce the impact of climate change on agriculture requires a holistic approach which works at the systems level but recognizes the importance of all components of the system. Diversity is the key - at all levels of the production system.

Case Study 3: Impacts of Climate Change on Fisheries in the Pacific[49]

Like other small island states, Pacific island countries have an extraordinary dependence on fish[50]. Throughout the region, subsistence and commercial fisheries, and aquaculture, contribute substantially to food security, livelihoods, economic growth and government revenue. Fish provides 51-94% of the animal protein in the diet of rural communities in the Pacific, with the exception of the inland population in Papua New Guinea (PNG). The majority (60-90%) of this fish is derived from subsistence fishing in coastal waters and per capita fish consumption by coastal communities often exceeds 75kg per person per year, more than four times the global average (Bell et al. 2009a).

Fish also commonly provides the people of the Pacific with a source of income – an average of 50% of coastal households from 17 Pacific Island countries and territories (PICTs) also earn either their first (30%) or second (20%) income from selling surplus fish caught from coastal and near shore waters (Kronan 2009). More than 12,000 people are employed on tuna vessels, or in industrial tuna canneries and loining operations, alone (Gillett 2009). Taken together, the value added to the economies of PICTs by coastal fishing, locally-based tuna fleets and aquaculture exceeds US $535 million per year (Gillett 2009). In addition, sales of licence fees to distant water fishing nations to catch tuna in the Exclusive Economic Zones (EEZs) of PICTs were valued at US $77 million in 2007, and contributed 4.4-41.7% of government revenue for seven PICTs (Gillett 2009).

Fish is a cornerstone of food security in the Pacific – there are few alternative sources of animal protein. However, the vital contribution of fish is under threat. Coastal fisheries will not be able to provide the fish needed by rapidly increasing human populations for food security (Figure 47) in 16 of the 22 PICTs in the near future (SPC 2008a, Bell et al. 2009a). The emerging gap between the fish required and the fish available from coastal fisheries will need to be filled largely by allocating more of the region's tuna resources for food security.

49 Lead Author: Dr Johann Bell, Secretariat of the Pacific Community

50 Fish is used here in the broad sense to include fish and invertebrates.

Improved access to tuna for subsistence and artisanal fishers in rural areas can be provided by establishing low-cost, inshore fish aggregating devices (FADs) as part of the national infrastructure for food security (SPC 2008a, Bell et al. 2009a). In urban areas, incentives need to be created for industrial fleets to land tuna of limited value for processing, and by-catch, at major ports throughout the region to increase the supply of fish. Production of fish both for rural communities and urban populations can also be increased through development of pond aquaculture, particularly in Melanesia (Bell et al. 2009a).

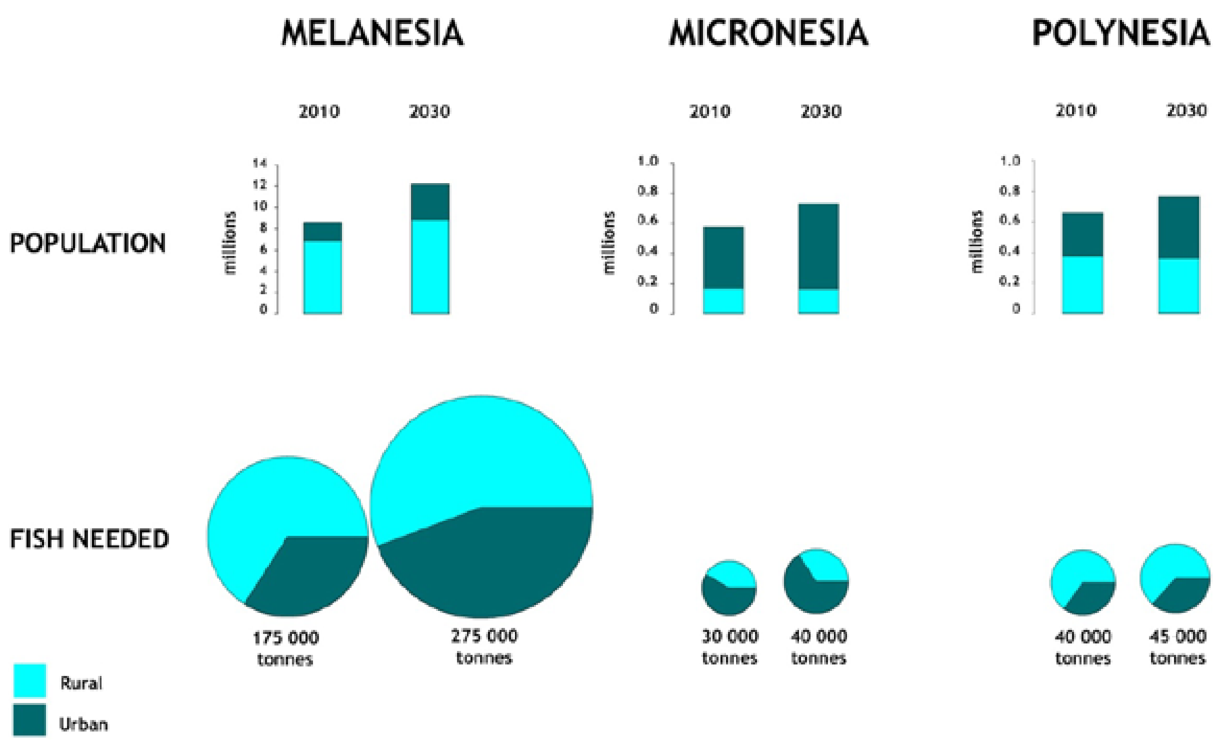


Figure 47: Forecasts of population growth, and the fish needed for to maintain per capita fish consumption at levels needed for good nutrition, in the three sub- regions of the Pacific in 2030 (Source: SPC 2008a).

Climate change threatens to derail the plans for continuing the vital contribution of fish to food security in the Pacific in several ways (SPC 2008b, Bell et al. 2009b):

1) The coral reefs that underpin much of the coastal fisheries production are projected to degrade due to the combined effects of: i) increased bleaching under higher water temperatures, ii) weaker coral skeletons and slower

of growth caused by reduced availability of carbonate ions through acidification of the ocean, and iii) increased physical damage by more intense tropical cyclones. The emerging gap between the production of fish from well managed coastal fisheries and the fish needed for food security will increase further as coral reefs degrade.

2) The convergence of the western Pacific 'warm pool' and the 'cold tongue' of nutrient rich waters from the eastern Pacific equatorial upwelling that creates the prime feeding grounds for skipjack tuna is projected to move east as temperatures increase. In addition, the warm pool itself is expected to become less productive due to increased stratification of ocean surface waters in the tropics associated with higher temperatures, higher rainfall and reduced salinities. This will weaken the transfer of nutrients from deeper waters to the photic zone, reducing the phytoplankton, zooplankton and micronekton that support oceanic (and coastal) fisheries production. Consequently, the success of measures to increase access to tuna will be influenced by the new patterns of distribution and abundance.

3) Greater risks of flooding associated with the projected increase in rainfall by 10-20% in the tropics is expected to dislocate the development of pond aquaculture by damaging infrastructure. The projected decreases in rainfall in the sub-tropics may reduce the scope for farming fish. Therefore, the potential for pond aquaculture to increase access to fish will be limited in some areas.

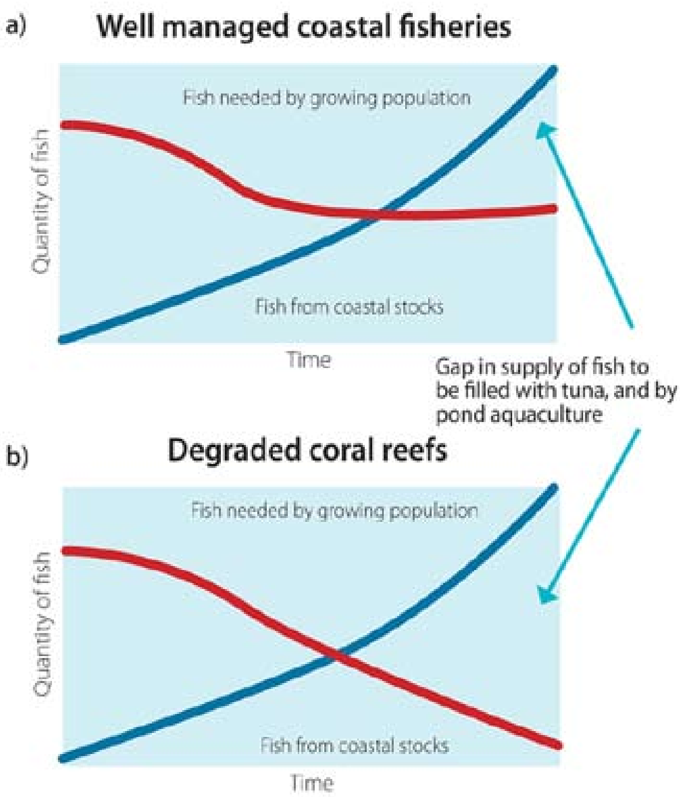


Figure 48: a) Emerging gap in the fish needed for food security and the fish available from well managed coastal fisheries in the Pacific; and b) the increased gap to be filled as coral reefs degrade due to climate change.[51]

The analyses being done for the comprehensive project underway in the Pacific to assess the vulnerability of fisheries and aquaculture in the region to climate change (SPC 2008b, Bell et al. 2009), indicate that limiting temperature rise to 1.5°C above pre-industrial levels is needed to implement the plans to increase access to fish for food security effectively. Projections for the SRES B1 scenario for 2035, equivalent to 1.2-1.5°C above pre-industrial temperatures, indicate that the increased frequency of coral bleaching and effects of >400 ppm CO_2 on ocean acidification are very likely to cause reductions in live coral cover of 30-40% (Table 26) (Hoegh-Guldberg et al. 2007). In particular, there is expected to be progressive loss of branching corals (*Acropora and Stylophora*). In turn, this is very likely to cause declines in abundance and diversity of coral-dependent fishes (Pratchett et al. 2008). However, few of these fish species are important to coastal fisheries. Thus, a 1.5°C increase in temperature is expected to have negligible (<1%) effects on coastal fisheries production (Table 26).

51 See SPC 2008a for Pacific island countries and territories where such gaps are expected to occur due to population growth alone.

Table 32: Projected effects of rises in temperature by 1.5 and 2.0°C on coral reefs, coastal fisheries, catches of skipjack tuna and rainfall for Pacific islands countries.[52]

Rise °C	Effects on coral reefs	Effects on coastal fisheries production	Changes in skipjack tuna catches within EEZ (%)				Rainfall
			Decrease	-%	Increase	+%	
1.5	30-40% decrease in coral cover, resulting in an average coral cover of 15%, branching corals no longer dominant ■■■■ ●●●●	Negligible (<1%) ■■■■ ●●●●			Cook Is Fiji FSM Kiribati Marshall Is Nauru New Cal. Palau PNG Samoa Solomon Is Tokelau Tonga Tuvalu Vanuatu ■■ ●●●	40.4 14.9 14.0 36.8 24.0 25.1 22.5 10.2 3.1 44.0 3.2 60.8 47.0 36.8 18.4	5-15% increase in equatorial regions; 5-10% decrease in SE Pacific; extremes more extreme ●●●● ■■■■
2.0	75% decrease in coral cover, resulting in an average coral cover of 5-10%, branching corals very rare ■■■■ ●●●●	20-50% decrease ■■ ●●●	PNG Solomon Is ■■ ●●●	10.6 5.5	Cook Is Fiji FSM Kiribati Marshall Is Nauru New Cal. Palau Samoa Tokelau Tonga Tuvalu Vanuatu ■■	50.2 24.0 4.8 43.1 24.4 19.7 18.7 1.7 49.2 69.0 50.2 40.9 15.1	10-20% increase throughout equatorial region; 5-20% decrease in SE Pacific; extremes more extreme ●●●● ■■■■

Likelihood:	Confidence:
■■■■ Very high 90-99% chance;	●●●●● Very High 95% of greater;
■■■ High 66-90% chance;	●●●● High 67-95%;
■■ Medium30-66% chance;	●●● Medium 33-67%;
■ Low 29% chance or less	●● Low 5-33%;
	● Very low 5% or less

52 Information derived from analyses led by O. Hoegh-Guldberg, M. Pratchett, P. Lehodey and J. Lough for the Secretariat of the Pacific Community based on model outputs from the Coupled Model Inter-comparison Project III (CMIP3) used by the IPCC Fourth Assessment Report.

The projected increases in catches of skipjack tuna within the EEZs of PICTS once temperatures have increased to 1.5°C above pre-industrial levels (Table 32), resulting from the preliminary modeling with SEAPODYM[53] (Lehodey et al. 2008, Senina et al. 2008), should make it easier to fill the emerging gaps in fish needed for food, particularly in Micronesia and Polynesia.

Development of small pond aquaculture in countries like PNG and Solomon Islands is likely to have to contend with more frequent and extreme flooding regimes (Table 32). However, such challenges are not insurmountable and concerted investment is now needed to implement this practical way of producing much-needed fish, particularly in inland areas.

Projected changes under SRES B1 in 2100 (equivalent to an increase of 1.7-2.2°C) to coral reefs, coastal fisheries and catches of skipjack tuna in some countries in the western Pacific pose severe problems for implementing the plans to increase access to fish for food security.

Once temperatures rise to 2°C above pre-industrial levels and atmospheric concentrations of CO_2 are 450-500 ppm, coral cover is expected to have decreased by 75% due to annual bleaching and increased acidification of the ocean (Ove Hoegh-Guldberg et al. 2007) (Table 32). Branching corals are expected to become virtually extinct. If this happens, many coral-dependent fish will disappear. Loss of structurally complex coral reef habitat is projected to lead to declines in abundance of up to 65% for virtually all reef-associated fish (Pratchett et al. 2008). There is moderate likelihood and confidence that declines in coastal fisheries production of 20-50% will also occur (Table 262), depending upon reliance of local coastal fisheries on strongly reef-associated fishes, and the as yet unknown capacity of some coral reef associated species, such as rabbitfishes and surgeonfishes, to use alternative hard substrata. There is also the prospect that increases of 2°C will affect the larval stages of many fish species and jeopardize regular replenishment of stocks, reducing yields and further widening the gap to be filled. However, considerable uncertainty still surrounds the projected effects on larval stages and our confidence in them occurring is currently low due to the difficulties associated with research in this area.

53 SEAPODYM is a spatial ecosystem and population dynamics model used to describe spatial dynamics of tuna at the Pacific basin scale, under the influence of both fishing and environmental effects. It is driven by environmental forcing (temperature, currents, oxygen and primary production) projected from the IPSL-CM4 global climate model.

Although there are prospects that it may be possible to offset the decline in coastal fish production through higher catches of skipjack tuna in the eastern Pacific (Table 32), the problems will be compounded for PNG and Solomon Islands where catches of skipjack are projected to decrease by around 5-10% (Table 32). This is of particular concern because PNG and Solomon Islands already have relatively large populations that are growing at some of the fastest rates in the region (SPC 2009).

Projections of increases in rainfall of 10-20%, and the concomitantly greater risks of more frequent and severe flooding (Table 32), may make it more difficult for small pond aquaculture to fulfil its potential role as a source of much-needed additional fish in PNG and Solomon Islands.

Given the extremely high dependence on subsistence fishing, the consequences of reduced per capita fish consumption in the western Pacific are malnutrition and loss of other opportunities as households use their labour and scarce financial resources to obtain alternative sources of protein. Where protein is derived from imports, incidence of non-communicable diseases (e.g., cardiovascular diseases, diabetes and hypertension) is expected to increase due to the low nutritional quality of such imports (SPC 2008c).

Projecting the changes to the sustainable production of coastal fisheries, the distribution and abundance of tuna, and the practicalities of implementing pond aquaculture, are essential to planning the use of fish for food security in the Pacific. The current uncertainty (low-medium confidence) about the production of coastal fisheries under a temperature rise of 2°C, and the preliminary nature of the modelling for tuna under a 1.5 and 2.0°C temperature rise (medium confidence), makes investment to improve the reliability of these projections imperative. In particular, Pacific island countries, and the institutions that support them, require urgent assistance to complete the science needed to inform effective adaptive management.

Priorities for research are:

1) High-quality observations of surface weather and oceanographic conditions in the Pacific combined with more realistic global climate models for the tropical ocean regions to provide more robust down-scaling of climate change and oceanographic modelling to the scales of islands. Such observations and modelling will allow more rigorous assessment of local sensitivity and vulnerability of the key fisheries resources to a changing climate and ocean.

2) Understanding the extent to which the direct effects of higher temperatures and increased acidification, and the indirect effects of reduced complexity of coral reef ecosystems, will affect the reproduction, recruitment, distribution, growth and abundance of commonly harvested coral reef fish.

3) Improved modelling of the effects of climate change on skipjack and big-eye tuna, and initial modelling for the other two species of tuna caught commonly in the Pacific (yellow-fin and albacore). Future models should be based on the most advanced coupled global climate models and incorporate projected fishing effort and interactions between tuna species. They will also require descriptions and long-term observations of the macrozooplankton and micronekton that provide food for tuna between a depth of 1200 metres and the surface to quantify accurately the link between production in the photic zone and tuna abundance.

4) Development of flexible systems for implementing small pond aquaculture under the constraints typical of the Pacific (e.g., limited availability of feeds, remote locations) that will be resilient to many of the risks associated with higher rainfall and more frequent and severe flooding.

Case Study 4: Impacts of Climate Change on Biodiversity in Melanesia[54]

Because climate change has happened in the Pacific over past millennia, it is clear that intact natural ecosystems possess some significant degree of inherent resilience to these changes. The main current and future threat to the Pacific region's terrestrial biodiversity from climate change is largely a factor of (1) the very rapid pace and degree of warming, which is faster and more intense than previous changes; and (2) the extent to which natural landscapes have been or will be modified or degraded by human activity. Human pressure on species and ecosystems reduces their resilience to environmental changes and makes extinction risks much more likely. A very possible result of this reduced natural resilience will be a corresponding decline in the ecosystem services (food resources, provision of rainfall and water supplies, pollination, storm protection) upon which human communities depend.

Even with the significant level of uncertainty that remains for regional climate projections, if the projected temperature and acidification are only close to accurate, corals and coral reefs will be severely stressed by 2100. Phase shifts to algal-dominated reefs are likely throughout the region. Over the long-term, it is likely that erosion of reefs from the combined impacts of coral beaching and acidification will exceed accretion rates. Loss of coral reef structure will decrease availability of fish habitat and shelter, with corresponding declines abundance and diversity in coral-dependent species, followed by species that are only dependent in part upon coral-dependent species, and further cascade effects would follow.

Physical factors driven by global-scale processes are likely to be significantly exacerbated by other extrinsic (pollution, poor land-use practices leading to sedimentation, and physical destruction such as coral mining, dredging) and intrinsic factors (exploitation or over-exploitation of the resource base, cyanide fishing). The interaction of these

54 Summary of conclusions for: Consensus Report: Climate change and biodiversity in Melanesia - what do we know? (2009). Stephen J. Leisz, J. Burke Burnett, Allen Allison (Eds). With contributions from: Axel Timmermann (International Pacific Research Center [IPRC]), Kelvin Richards (IPRC), Peter Brewer (Monterey Bay Aquarium Research Institute), Dan Polhemus (Bishop Museum), Steve Coles (Bishop Museum), Shelley James (Bishop Museum), Kris Helgen (National Museum of Natural History, Smithsonian Institution), Andy Mack (Carnegie Museum), Terry Donaldson (University of Guam Marine Laboratory), Geoffrey Hope (Australian National University). Bishop Museum Technical Report. Honolulu, HI: Bishop Museum.The research was funded by the John D. and Catherine T. MacArthur Foundation.

factors with climate change and acidification will increase extinction susceptibility, vulnerability and risk.

Ocean acidification may also negatively affect fishes in their larval stages, leading to greater impact upon fish assemblage structure and abundances on reefs and related systems. Fishers and fishing-based human communities in Melanesia are often heavily dependent upon reef resources associated directly or indirectly with corals. Thus, it is likely that significant aspects of reef ecosystem function and services will decline or even in some cases be lost to communities and other human users.

Certain areas are likely to have greater resilience than others, and dissimilar habitats may be connected in significant ways. While areas subject to cooler, deep water upwelling may seem, prima facie, to have greater capacity to resist thermal stress compared to shallow water areas, this is not necessarily the case. Some shallow water areas appear to have a wider natural temperature band than areas with more depth-diversity, and so some shallow water reef systems may be pre-adapted to thermal stress. Patterns of recovery following bleaching events are mixed both spatially, as well between and even among species in a given area. On the other hand, oceanic seawater may have higher total alkalinity relative to lagoonal waters, and thus may confer some buffer against acidification effects. Protection of algal turf and seagrass habitat may help mitigate acidification effects on reefs because photosynthetic activity in those habitats reduces CO_2 levels and thus raises the calcium/aragonite saturation state. These factors imply that resilience-maximizing approaches to marine conservation in Melanesia should emphasize the selection of large areas with a high degree of environmental heterogeneity (i.e. habitat diversity).

Terrestrial habitats that are expected to be most impacted by climate change (including sea-level rise) are mangrove and coastal systems, montane systems and dry land vegetation communities. Species that are naturally located in high elevation areas, in isolated or outlying mountain ranges, on smaller islands, or that are also exploited for human use are at greatest risk. However, a salient point of unanimous consensus is that anthropogenic activities that are unrelated or only indirectly related to climate change – such as forest conversion for agriculture, over-logging, and fire – may not only have greater impacts on biodiversity in the short-term, but will also exacerbate the impacts of climate change.

Photo: Rob Maccoll, AusAID

Many of the Pacific region's birds, mammals, reptiles and amphibians are potentially vulnerable to climate change in the region, especially those that are endemic and have limited ranges or distributions, are specifically adapted to distinct elevational gradients, or have specialized needs. Birds are a unique category since some are endemic to the region, but there are others which spend part of the year or part of their life outside the region. Thus these populations will also be affected by aspects of climate changes outside of the region and climate changes that are region- or area-specific. It seems clear that climate change, but our understanding of which species may be at particular risk will impact the full spectrum of faunal biodiversity, and which may actually benefit is inherently impeded by a serious dearth of scientific understanding about fundamental ecological processes, species requirements and physiologies.

Whether or not climate variability (ex. ENSO) will increase or decrease is undetermined based on global climate models. Drought conditions such as those associated with El Niño substantially increase the risk of forest fires, especially in disturbed forest (viz. open canopy secondary forest with dead wood supply). Increased climate variability, in tandem with anthropogenic forest disturbance (logging or forest conversion for agriculture) may therefore create conditions favourable for a serious increase in forest fires that would result in permanent alteration of forest habitat.

An additional key unresolved question is whether or not climate change will result in increased or decreased cloud cover and precipitation in particular areas of the Pacific. Increased precipitation regimes may play a role in mitigating some climate impacts. Clouds and rainfall tend to suppress temperature; synergistically they are believed to allow the possible compression of vegetation zones (i.e. Massenerhebung effect: the compression of altitudinal habitat zones). The extent to which this habitat compression will increase is a matter of speculation, but it would somewhat mitigate biodiversity impacts of climate change.

Whether or not ENSO events increase in frequency or intensity, even current high levels of anthropogenic forest disturbance combined with "normal" ENSO cycles and expected warming may be sufficient in themselves to result in long-term habitat alteration or loss. Logging and/or forest conversion alters or disrupts hydrological cycles. Terrestrial forests control air humidity, soil moisture, stream flows and water evaporation by regulating the hydrology through evapotranspiration, photosynthesis and regulation of rainfall runoff. Forests have a direct influence not only on the microclimate (i.e. within or immediately adjacent to the forest itself) but also at island-wide scales by sustaining higher precipitation levels compared to regions without a forest canopy. The persistence of relatively high proportions of intact (closed canopy) forest is therefore a fundamentally critical element in maintaining a degree of natural resilience to climate change impacts. Presumably there are thresholds in terms of how much closed forest cover is required to maintain basic hydrological functions, but what these may be in the Pacific is unknown and in serious need of immediate research. An essential corollary of this understanding is that maintaining forest resilience in protected areas will very likely require maintaining hydrological processes and habitat functionality outside of those protected areas as well.

Climate stresses are likely to vary spatially. For marine habitats in particular, refugia - areas where special environmental circumstances have enabled a species or a community of species to survive after extinction in surrounding areas - are likely to be very important, but what areas are the most promising candidates in this respect is not clear. For both marine and terrestrial conservation, it is critical to maximize habitat connectivity to allow species populations to move in response to their requirements and/or to allow dispersal/recruitment. Population movements are also likely to result in new ecological interactions among species, the properties of which are currently unknowable.

For terrestrial conservation, it is critical to maximize ecosystem resilience to climate change through the successful preservation of as much intact natural habitat and their accompanying ecological processes as possible. Large areas with high ecological diversity, particularly those with a wide range of elevations, probably have the greatest capacity to buffer the impacts of climate change. The presence of elevational gradients will be critical to facilitate the opportunities for habitat-sensitive species to relocate to new habitat as ecosystems shift over time. Larger protected areas are less susceptible to intrinsic and extrinsic perturbations relative to smaller protected areas. This strategy will not protect island endemics, which may require other types of conservation interventions.

Unfortunately, what ecosystem thresholds may exist is currently unknown. Given this uncertainty, sustainability principles and effective enforcement (in whatever forms are locally appropriate) should be prioritized at the community, island and regional levels. The overall conservation priority for climate change impacts on biodiversity in the Pacific should be to maximize ecosystem resilience to climate change. Operationalizing this principle at a variety of different scales in complex social and political contexts will require elements of pragmatism, experimentation and adaptive management.

In addition to specific impacts on species, general threats to biodiversity can be summarised as follows:

- Drier conditions can be expected to lead to increased fire risk and the subsequent expansion of grasslands; this will negatively impact forest species. Changes in temperature that require extra energy input (either for heating or cooling) can push species past their metabolic limits. This may be a special concern for birds, which have the highest thermo-metabolism (and limited thermo-regulation capacity) of all the warm-blooded animals.

- Changes in ocean currents may change the transport of food required by some shore and sea birds, which could have a particular impact on nesting sea-birds who rely on specific marine food resources at specific times of the year.

- Some bird species range over large areas as seasons change, tracking the availability of fruit, seed or nectar resources. For these populations to persist, their food resources over large spatial scales must be maintained, particularly through any bottlenecks of low food availability or "lean seasons." Climate change may alter the seasonal timing of food plants' flowering/fruiting, thus potentially disrupting keystone food resources for many species. Furthermore, keystone food resources for many species are not mobile and it is unknown whether or not preferred food plants will be able to move and/or adapt quickly enough in response to climate change.

- Increased storm intensity could lead to insufficient recovery time for species between extreme weather events, causing their populations to suffer accordingly. High elevation grassland and elfin forest are highly susceptible to loss due to fire, which is expected to increase with increasing temperatures.

- The response of forest trees to climate change will also depend upon the responses of, and interactions with, a wide variety of other organisms (e.g. pollinators and seed dispersers). Acute changes in climate during critical phases of a plant's life cycle such as flowering, seed development and seedling establishment may have much greater effects than the mean direct effects of climate change.

- Climate change may present enhanced opportunities for non-native species to become invasive, which would increase competition for food resources and/or introduce new predation pressures on native species. Similarly, new viral or other pathogens may exploit opportunities arising from thermal or precipitation changes, or existing diseases such as malaria may move into new areas. Combined with climate-stresses on organism physiology, this could increase disease risks and thus contribute to extinction pressure.

Case Study 5: Impacts of SLR in Honiara, Solomon Islands

Honiara is typical of the majority of urban centres in the Pacific situated on the coast and in potentially vulnerable low-lying areas. The exposure of Honiara to coastal hazards such as cyclone-driven storm surge, extreme high tides and future climate change is significant, and reinforced by increasing human settlement and degraded land conditions in certain areas. The coastal areas of Honiara that are mostly affected during the wet season are from Mataniko to Ranadi.

A SEAFRAME tide gauge has been operating at Honiara since 1994, where sea levels are shown to regularly exceed 1.2m and occasionally 1.3m due to the influence of meteorological effects in addition to high tides.[55] The mean higher high water relative to the zero of the tide gauge is 1.17m, or 0.479m relative to the datum used by the inundation study. Relative to the inundation study datum, the current highest astronomical tide prediction for Honiara is 0.523m. The highest astronomical tide is the highest sea level that can be predicted under any combination of astronomical conditions, that is, normal conditions and some seasonal effects (AusAID, 2007).

Modeling to map inundation at 1 to 3 metres along the Honiara coastline identified low-lying areas that are susceptible to flooding from high tides and storm surge when coupled with rising sea levels. The maps below provide a simple 'bucket fill' approach to determine areas that would be inundated at a certain mean sea level. Figure 49 shows mapping of one metre inundation and indicates the vulnerability of low-lying areas around the Point Cruz industrial area and around the mouth of the Mataniko River.

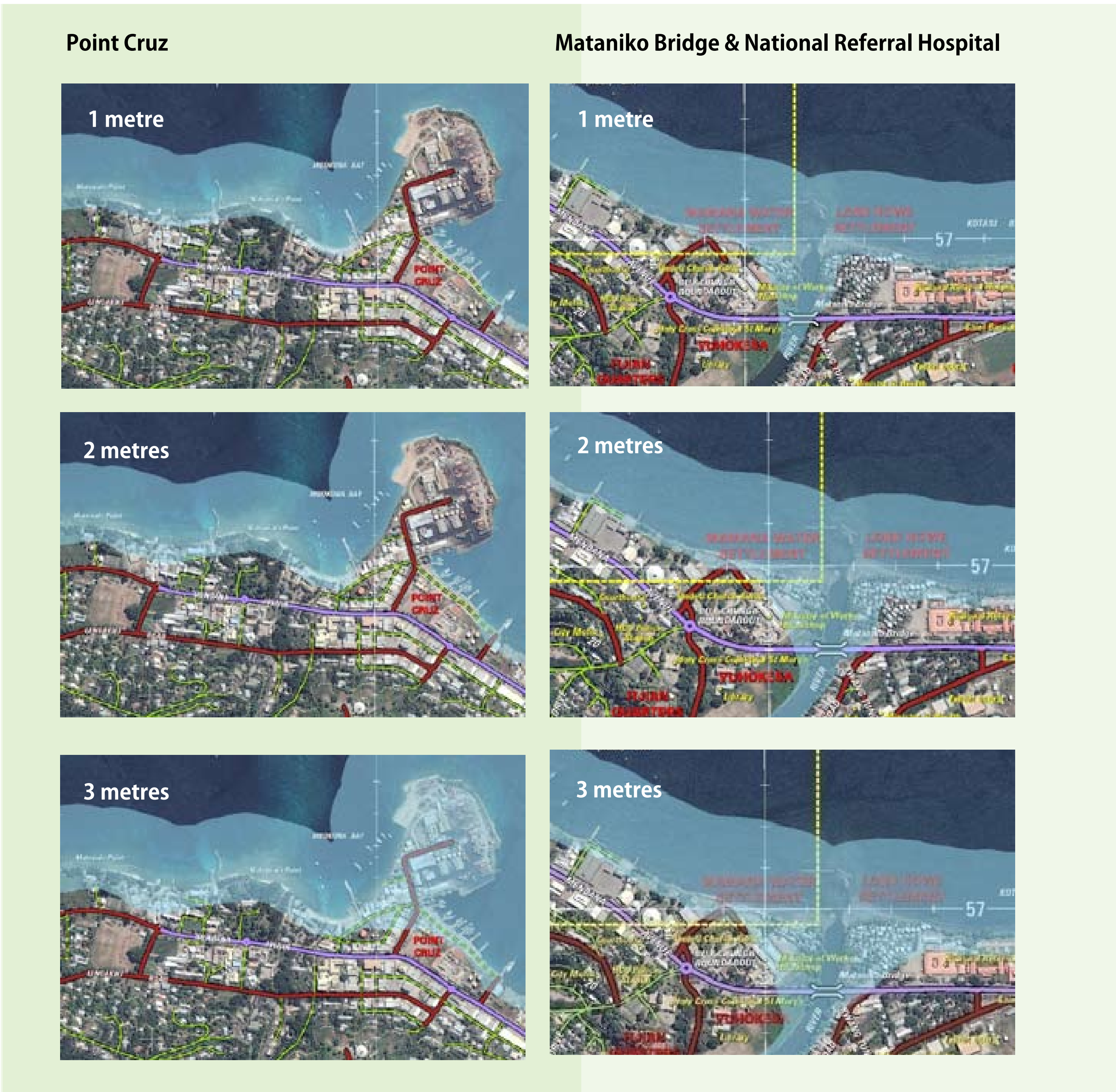
55 Relative to Lowest Astronomical Tide, the Mean Higher High Water at Honiara is 1.0m and Mean Sea Level is 0.6m (Australian National Tide Tables, 2009). See also: http://www.bom.gov.au/ntc/IDO70061/IDO70061SLI.png

Figure 49: Inundation modelling derived from high-resolution cartographic elevation data products (20m contour / spot heights) for Honiara at one metre inundation.

Storm surge events along the sea front of Honiara normally occur during the wet season/cyclone season from around November to April, peaking during the months of January and February. Observations from from Honiara indicate that Mamana Water (Lord Howe settlement) around the Mataniko Bridge and National Referral Hospital are continuously inundated especially during the wet season. With rising sea levels, coupled with high tides and increasing wind speeds, coastal inundation of between one and two metres is feasible. Considering the potential for storm surge and cyclone-driven impacts, inundation could occur at higher levels, as shown in the figures below. Inundation at these levels, and higher, has been modelled in other parts of the Pacific.[56]

56 Modeling of storm surge in Fiji has shown inundation of up to 3 metres. Source: http://www.bom.gov.au/pacificsealevel/pdf/AMSAT_climatemodel_factsht.pdf

Figure 50: Inundation modelling derived from high-resolution cartographic elevation data products (20m contour / spot heights) for Honiara, Solomon Islands: Point Cruz area (left) and Mataniko bridge area (right) at one, two and three metres inundation.



It is important to note the many limitations to this modelling, which should be treated as indicative of actual inundation impacts. The primary elevation data source (contours) is accurate to 10 metres vertical. Modeling is fixed to the coastline using a 'zero-point', making the littoral region relatively more accurate. Despite this, there are several data gaps in the maps, and therefore gaps in the modelling. The modelling does not account for the geomorphology of the coast, which would indicate how susceptible the coast would be to erosion, or how a changing wave climate and wind speed will impact on the infrastructure in the locations identified above. The modelling also does not take into account hydraulic processes, such as the width and depth of channels for flooding, which can be important when assessing inundation from storm events on top of a given sea-level rise. Finally, the modelling does not take into account the potential of riverine flooding or the hazard of coincident events, such as storm surge with a high rainfall event.

The limitations in this modelling demonstrate the importance for a concerted regional investment in high-resolution topographic data to facilitate detailed mapping of local areas, the extension of existing sea level monitoring programs, and efforts to improve understanding of wind and wave climate in the Pacific in the context of climate change. Inundation modelling can provide a strategic planning tool to assess risks to key assets, and guide further analyses, national planning efforts and investment decisions.

Inundation modelling can provide a strategic planning tool to assess risks to key assets, and guide further analyses, national planning efforts and investment decisions. Adaptation approaches based on integrated coastal zone management provide a framework to address existing threats and climate change related impacts such as the location of key infrastructure, adaptations options to maintain coastlines and the protection of key habitats such as coastal wetlands.

5. Conclusion

This report provides the first comprehensive assessment of the consequences of projected Sea Level Rise (SLR) and storm surge leading to coastal inundation (+1m to +6m) for the people and economies of the 15 CARICOM nations and provides evaluations of the differential impacts of +1.5°C and +2°C on coral reefs, water resources and agriculture in the Caribbean and an analysis of climate change impacts on the Pacific islands.

The Caribbean will be affected more seriously by SLR than most areas of the world; SLR in the northern Caribbean may exceed the global average by up to 25%. In addition, the impacts of tropical storms and hurricanes on coastal areas, even at present intensity and frequency, will be compounded by SLR. The impacts of SLR will not be uniform among the CARICOM nations, with some projected to experience severe impacts from a 1 metre SLR. In nations where low lying-land is extensive and who are therefore more exposed to the impacts of SLR and storm surge, concerns are of damage to agriculture, industry and infrastructure as well as salt water penetration into the groundwater reservoirs. For nations with a more complex topography and characterized by steep sloped coasts fronted by only a narrow strip of low lying land, the main concerns are landslides, beach erosion and disruption to infrastructure that is concentrated in limited flat land areas. In both cases, damage to mangroves and seagrass beds is of concern, especially since these areas are of importance in coastal protection as well as fishery resources. In the case of most of the countries, the tourism industry is of particular concern, since it is preferentially located very close to the coastal, often in low-lying areas with highly erodible sandy beaches. These impacts and changes mean that much more needs to be done in terms of coastal protection and in the planning of coastal development. It terms of protection, the importance of natural inhibitors to erosion, such as beaches and mangroves, needs to be emphasised. In terms of planning, attention needs to be paid to the location of industry, communication and of course housing. In addition, care will need to be taken in the 'siting' of tourist developments, which generally occur close to the coastline. In all these matters, the topographic and geologic setting of locations at risk must be taken into account. The most vulnerable CARICOM nations to SLR were found to be: Suriname, Guyana, The Bahamas, and Belize.

The key impacts of a 1 metre rise in SLR can be summarised as follows: over 2,700km^2 of Caribbean land area lost and

10% of The Bahamas land area; with the market value of undeveloped land lost across the CARICOM nations being over US $70 billion. Over 100,000 people will be displaced (8% of the population in Suriname, 5% of The Bahamas, 3% of Belize). The cost to rebuild basic housing, roads and services (water, electricity) for displaced population approximately US $1.8 billion. The annual GDP losses will be at least US $1.2 billion (over 6% in Suriname, 5% in The Bahamas, 3% in Guyana and Belize) not including hurricane and storm impacts on GDP. At least 16 multi-million dollar tourism resorts lost, with a replacement cost of over US $1.6 billion and the livelihoods of thousands of employees and communities affected. In addition to the impacts of increased temperature on agricultural yield over 1% agricultural land will be lost, with implications for food supply and rural livelihoods Transportation networks will be severely disrupted: 10% of CARICOM island airports will be lost at a cost of over US $715 million; lands surrounding 14 seaports will be inundated (out of a total of 50) at a cost of over US $320 million, the reconstruction cost of lost roads exceeds US $178 million (6% of road network in Guyana, 4% in Suriname, 2% in The Bahamas).

The total economic impact of 1 metre SLR in CARICOM nations includes a GDP loss of over US $1.2 billion per year, a permanent land lost value of US $70 billion and an initial reconstruction / relocation cost of $4.6 billion. These figures are based on SLR scientific evidence and do not include other major economic impacts, such as losses in agricultural production, losses in GDP from areas outside inundated regions, costs of changing energy needs, increased storm or hurricane damage and related insurance costs, necessary water supply construction, increased health care costs, or any non-market value impacts.

Sea level rise in the 21st century and beyond represents a serious and chronic impediment to sustainable development of some CARICOM nations and the impact estimates must be considered highly conservative for three reasons: a) population and GDP remain fixed at recent levels (estimates for 2010 and 2008 respectively) b) the coarse resolution of geospatial data available for this analysis masks the vulnerability of coastal infrastructure, natural areas and people to inundation from SLR in some areas c) the implications of SLR for accelerated coastal erosion could not be assessed in this study.

Regarding water resources the study found that water insecurity will increase in CARICOM nations; Precipitation levels will decline under climate change 1.5°C and 2°C increases and the severity of water resource problems for states which currently have insufficient water resources will have serious repercussions for the livelihoods of communities. For states that currently have sufficient water resources, a decline in precipitation will introduce new water resources issues. Reduced groundwater recharge will lead to a reduction in the amount of available water within aquifers, reduce the ability of states to cope with periods of drought and increased the risk of saltwater intrusion to aquifers, particularly in those close to the coast. Sea-level rise will increase the risk of saltwater intrusion into coastal aquifers, particularly those that are already at risk from over abstraction. As little as a 0.1m rise in sea level can substantially reduce the availability of fresh water in coastal aquifers. Most CARICOM nations have already experienced saltwater intrusion into aquifers. Sea-level rise threatens all coastal aquifers, and will also increase the effects of storm-surges that lead to aquifers becoming contaminated through coastal flooding. A 1.5°C temperature rise would impact water resources severely in a minority number of CARICOM states and be relatively manageable for most other states. A global mean temperature rise of 2.0°C or more will impact severely the water resources in the majority of CARICOM states. A reduction in precipitation for CARICOM states will reduce both the available surface water reserves and the level of groundwater recharge. These declines in precipitation would lead to an increase in the risk of periods of drought for the Caribbean region, which are likely to occur more frequently and be more severe.

On examination of the agriculture sector the report concludes that in developing countries and small island states, climate change will cause yield declines for the most important crops. Climate change will result in additional price increases for the most important agricultural crops – rice, wheat, maize, and soybeans and calorie availability in 2050 will not only be lower than in the no climate-change scenario—it will actually decline relative to 2000 levels. By 2050, the decline in calorie availability will increase child malnutrition by 20% relative to a world with no climate change. Climate change will eliminate much of the improvement in child malnourishment levels that would occur with no climate change. Average yields in CARICOM countries for three key crops (irrigated and rainfed rice, rainfed maize and rainfed cowpea) will be reduced – The declines range from about 3% to over 8%. Assuming these estimated yield effects apply to all crops, agricultural value in the CARICOM countries would fall by between US $85 million per year to US $243 million per year.

The ecosystem services provided to tourism and fisheries by Caribbean coral reefs are estimated to be worth between US $1.5 and $3.5 billion per year to the region. This economic valuation does not include the critical role played by coral reefs in the protection of coastal areas from storm surges and ocean swells - the environmental and economic importance of coral reefs to the Caribbean therefore should not be underestimated. The study examined the impacts of a 1.5°C and 2°C increase in temperature and found that the Caribbean is warming quickly: SST trends across the Caribbean basin over the past 22 years indicate current warming is occurring at 0.2 - 0.5°C per decade. Current SST trends over the Caribbean exceed, and at some locations nearly double, those being observed over the global tropical oceans and recent SST increases are greatest throughout the Windward Islands of the Lesser Antilles such as Grenada, St. Lucia, St Vincent and the Grenadines. In addition committed warming is inevitable: An increase in thermal stress on Caribbean coral reefs in the next 20-30 years is inevitable due to "committed" warming from GHG emissions already in the atmosphere and even more from those that will be emitted before emissions are eliminated. Coral bleaching frequency will exceed the rate of recovery: Under either the 1.5°C or 2°C warming scenarios, the accumulation of thermal stress on Caribbean coral reefs far exceeds current mass coral bleaching thresholds across the Caribbean and the frequency of bleaching events will exceed the rate of recovery. Clearly, 2.0°C will be worse than 1.5°C.

An additional and equally dangerous threat to coral reefs is ocean acidification from increasing atmospheric CO_2 which reduces coral reef growth. Conditions we are likely to see in the 21st century decade when we reach 1.5°C above pre-industrial levels (~490 ppm atmospheric CO_2) may prove adequate for reef growth, whereas at 2.0°C and 550 ppm Caribbean reefs are likely to be eroding. Even at equilibrium, corals across most of the Caribbean are in conditions that are in the upper half of the range adequate for reef growth at 1.5°C and 350 ppm, but near the bottom of that range at 2.0°C and 450 ppm. It is doubtful that corals can adapt to as much as 2.0°C warming: It is highly unlikely that adaptation through biological mechanisms and management will be sufficient to avoid severe degradation of Caribbean coral reefs from frequent bleaching events. More importantly, most known physiological mechanisms that allow corals to adapt to warmer conditions also cause slower growth, making the problems caused by acidification even more severe. Climate change and ocean acidification at 1.5°C are likely to have significant impacts on coral reef ecosystems and the ecosystem services they provide. This will be even more severe at 2.0°C.

In the Pacific islands, the high sensitivity of low-lying atolls to increases in SLR will threaten water and food security, settlements, health and infrastructure. Overall, although impacts of climate change will affect Pacific island countries differently, impacts on key sectors such as water resources, agriculture, fisheries and infrastructure are likely to be similar to those forecast for Caribbean countries.

In particular, an additional 0.5°C warming on 1.5°C would likely cause a relatively large increase in the frequency of extreme hot spells throughout the Pacific. Projected changes in rainfall, combined with salt intrusion and rises in water tables, will result in water scarcity in many Pacific island countries, in particular atoll countries outside the equatorial Pacific region, adding to existing stress from high water demand and compounded by limited storage capacity. In addition, storm surge and coastal erosion threaten coastal settlements and the transport, water and sanitation infrastructure that support them. Potential increases in peak wind speeds and the intensity of precipitation in tropical cyclones, coupled with SLR, could worsen impacts of storm surge and flooding. The consequences for coral reefs at 2°C warming are dire. A decrease of 75% in coral cover (compared with 30-40% under a 1.5°C scenario) will result in severe declines in the availability of reef-associated fish and coastal fisheries production, with significant implications for food security for many Pacific nations.

Economic impacts of climate change and the costs of adaption have yet to be assessed comprehensively at the regional and country level to inform national development strategies and investment decisions. Although the Pacific region has a strong subsistence heritage, many countries import food staples and are vulnerable to rising food and energy prices. Predicted impacts of climate change are likely to increase reliance on imported food, unless adaptation strategies are developed to diversify primary production and broaden countries' economic base (AusAID 2009).

As in the Caribbean, the lack of long-term datasets and high-resolution elevation data on all Pacific islands provides a fundamental barrier to improving and accurately quantifying the impacts that SLR will have on the Pacific region. There is a critical need for investment in high-resolution topographic data to facilitate detailed risk mapping of local areas. To enhance adaptive capacity in the Caribbean and the Pacific regions, further efforts are required to assess the practical outcomes of projects and ensure lessons are learned. Capacity building in vulnerability assessment and adaptive planning at the national and local levels are needed, building on Pacific institutions, knowledge and practices. Pacific islands have expressed their priorities for addressing climate change regionally through the Pacific Leaders' Call to Action on Climate Change, the Pacific Plan for Strengthening Regional Coordination and Integration, the Niue Declaration on Climate Change and the Pacific Islands Framework for Action on Climate Change 2006-2015.

5.1 RECOMMENDATIONS

The following selected recommendations based on the findings of this report should not be taken as exhaustive but are representative of a need for serious, comprehensive and urgent action to be taken to address the challenges of climate change in the islands and coastal states of the Caribbean Basin and the Pacific islands. Concerted global action will be needed to reduce the impacts of climate change on coastal areas of the Caribbean and the Pacific islands. Measures to contain the global temperature rise to 1.5°C by 2100 are an important objective and will reduce projected losses of land, infrastructure, resources and economies. The recommendations have been divided into two categories; 'improving climate change predictions for informed decisions' and 'predicting impacts on key sectors and implementing adaptation measures'.

5.1.1 IMPROVING CLIMATE CHANGE PREDICTIONS FOR INFORMED DECISIONS

Recommendation: In order to improve spatial detail and to examine uncertainties more closely, as well as to study changes in extreme climate events (e.g. heavy rainfall, tropical storms), further examination of the projections is recommended including downscaling; any such work would be consistent with the UNFCCC Nairobi Work Programme.

Recommendation: Detailed information on the vulnerability of coastal areas is needed. As the climate continues to change in the coming years, such information will be vital to inform coastal zone management and anticipate flood hazard. It seems likely that any continued global mean temperature increase will have serious consequences for the Caribbean and Pacific islands by 2100, but if the increase exceeds 1.5° C the consequences will be extremely serious in areas of high exposure. A strategy needs to be developed globally by which on the one hand, all nations would agree to curtail global emissions and address environmental degradation. On the other hand, the Caribbean and Pacific island communities themselves would agree to plan for the changes that will increasingly affect their coastlines as a result of increased warming and sea level rise that the world is already committed to from past emissions and climate feedbacks.

Recommendation: In both the Caribbean and the Pacific islands there is a critical need for: a) investment in high-resolution topographic data to facilitate detailed risk mapping of local areas; b) the extension of existing observational and sea-level monitoring programs, and efforts to improve understanding of wind and wave climate in the context of climate change; c) a detailed analysis of the capacity of adaptation options to cope with different levels of climate change and associated sea level rise; and d) more detailed costs assessments necessary to inform future negotiations regarding adaptation assistance from the international community.

5.2 PREDICTING IMPACTS ON KEY SECTORS AND IMPLEMENTING ADAPTATION MEASURES

Recommendation: Adaptation through biological mechanisms and management may allow some coral reefs to avoid severe degradation from frequent bleaching events and survive up to a 1.5°C warming. Such adaptation is uncertain and, if possible, would come with other costs such as reduced diversity and productivity. In summary, two sets of actions are required for the continued survival of coral reefs:

1) Rapid reduction of CO_2 emissions and eventual reduction of atmospheric CO_2 level, and

2) Management actions to help corals survive long enough for our actions to attempt to stabilize the climate system.

It is highly unlikely that adaptation through biological mechanisms and management will be sufficient to avoid severe degradation of coral reefs from frequent bleaching events if the temperature increase exceeds 1.5°C above pre-industrial levels. More importantly, most known physiological mechanisms that allow corals to adapt to warmer conditions also cause slower growth, making the problems caused by acidification even more severe. These impacts will be even more severe at 2.0°C.

Recommendation: To better address potential effects of climate change on agriculture, the following data and analyses are needed: a) improved downscaling of climate change scenarios b) better characterization of the crop varieties, including location specific information on agronomic environments, crop diversification and sustainability of production systems, and c) more detailed characterization of the agricultural sectors and their roles in economies and alternatives.

Recommendation: To address predicted impacts of climate changes on water resources, there is a need to improve water infrastructure and water management. In particular, states should a) improve water resource monitoring, including groundwater and precipitation; b) improve water distribution to increase access to clean water and reduce loss; c) increase water storage capacity to mitigate the effects of drought conditions; d) expand or initiate water metering and charging to encourage water conservation; and e) consider the implementation of desalination using renewable power sources to assist with periods of water shortages.

Recommendation: Adaptation to future SLR will require revisions to development plans and major investment decisions, based on impacts of climate change and SLR on coastal areas and vulnerability assessments. Caribbean and Pacific island countries need to develop a comprehensive understanding of their long-term risk to SLR to negotiate appropriate adaptation assistance. Future studies using high resolution Digital Elevation Models that account for erosion and not just inundation are essential to understand the true threat SLR poses to the people and economies of Caribbean and Pacific island countries and addressing this crucial knowledge gap should be a priority for Development Agencies.

References

Albright, R., B. Mason, and C. Langdon. (2008). Effect of aragonite saturation state on settlement and post-settlement growth of Porites astreoides larvae. Coral Reefs 27(3): 485-490.

Alvarez-Filip, L., N.K. Dulvy, J.A. Gill, I.M. Côté, and A.R. Watkinson. (2009). Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. Proceedings of the Royal Society B: Biological Sciences 276(1669): 3019-3025.

Alley, R.B., Clark, P.U., Huybrechts, P. and Joughlin, I. (2005). Ice-sheet and sea-level changes. Science, 310, 456-460.

Allison, M.A., Lee, M.T., Ogston, A.S., Aller, R.C. (2000). Origin of Amazon mudbanks along the northeastern coast of South America. Marine Geology 163: 241-256.

Anthony, K.R.N., M.O. Hoogenboom, J.A. Maynard, A.G. Grottoli, and R. Middlebrook. (2009). Energetics approach to predicting mortality risk from environmental stress: a case study of coral bleaching. Functional Ecology 23(5): 539-550.

AQUASTAT. (2009a). Summary Fact Sheet for Barbados, AQUASTAT Global Information System on Water and Agriculture, Food and Agriculture Organisation of the United Nations, available at: http://www.fao.org/nr/water/aquastat/data/factsheets/aquastat_fact_sheet_brb.pdf

AQUASTAT . (2009b). Summary Fact Sheet for Belize, AQUASTAT Global Information System on Water and Agriculture, Food and Agriculture Organisation of the United Nations, available at: http://www.fao.org/nr/water/aquastat/data/factsheets/aquastat_fact_sheet_blz.pdf

AQUASTAT. (2009c). Summary Fact Sheet for Saint Vincent and the Grenadines, AQUASTAT Global Information System on Water and Agriculture, Food and Agriculture Organisation of the United Nations, available at: http://www.fao.org/nr/water/aquastat/data/factsheets/aquastat_fact_sheet_vct.pdf

Arctic Climate Impact Assessment - Scientific Report. (2005). Cambridge University Press: 1024pp.

Arnell, NW. (2004). Climate change and global water resources: SRES emissions and socio-economic scenarios, Global Environmental Change 14: 31–52.

Asian Development Bank. (2004). Environmental Pacific Regional Strategy 2005-2009, Asian Development Bank, Manila, Philippines.

Atwood, D.K., J.C. Hendee, and A. Mendez. (1992). An assessment of global warming stress on Caribbean coral reef ecosystems. Bulletin of Marine Science 51(1): 118-130.

AusAID. (2007), Pacific Country Report Solomon Islands: Sea Level & Climate: Their Present State, South Pacific Sea Level and Climate Monitoring Project, http://www.bom.gov.au/pacificsealevel.

Australian Bureau of Meteorology –ABM. (2007). El Nino and La Nina: Important Ocean Phenomena, http://www.bom.gov.au/pacificsealevel/pdf/Elnino_and_La_Nina.pdf.

Bak, R.P.M., G. Nieuwland, and E.H. Meesters. (2009). Coral growth rates revisited after 31 years: What is causing lower extension rates in Acropora palmata? Bulletin of Marine Science 84(3): 287-294.

Baker, A.C., P.W. Glynn, and B. Riegl. (2008). Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook Estuarine, Coastal and Shelf Science 80(4): 435-471.

Baker, A.C., and A.M. Romanski. (2007). Multiple symbiotic partnerships are common in scleractinian corals, but not in octocorals: Comment on Goulet (2006). Marine Ecology Progress Series 335: 237-242.

Bamber, J. 2009. Recent Antarctic and Greenland ice-mass fluxes from satellite observations and their significance PAGES News, 17(2), 52-54.

Bamber, J., Riva, R.E.M., Vermeersen, B.L.A. and LeBrocq, A.M. (2009). Reassessment of the Potential Sea-Level Rise from a Collapse of the West Antarctic Ice Sheet. Science 324: 901-903.

Barnett, J, & Campbell, J (in press), Climate Change and Small States: Power, Knowledge and the South Pacific, Earthscan, London.

Baskett, M.L., S.D. Gaines, and R.M. Nisbet. (2009a). Symbiont diversity may help coral reefs survive moderate climate change. Ecological Applications 19(1): 3-17.

Baskett, M.L., R.M. Nisbet, C.V. Kappel, P.J. Mumby, and S.D. Gaines. (2009b). Conservation management approaches to protecting the capacity for corals to respond to climate change: a theoretical comparison. Global Change Biology: doi: 10.1111/j.1365-2486.2009.02062.x.

Bates BC, Kundzewicz ZW, Wu S and Palutikof JP, eds. (2008). Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

Bates, N.R., A. Amat, and A.J. Andersson. (2009). The interaction of ocean acidification and carbonate chemistry on coral reef calcification: evaluating the carbonate chemistry Coral Reef Ecosystem Feedback (CREF) hypothesis on the Bermuda coral reef, Biogeosciences Discussions 6: 7627-7672.

Bell JD, Kronen M, Vunisea A, Nash WJ, Keeble G, Demmke A, Pontifex S and Andréfouët S (2009a). 'Planning the use of fish for food security in the Pacific', Marine Policy, 33: 64-76.

Bell J, Batty M, Ganachaud A, Gehrke P, Hobday A, Hoegh-Guldberg O, Johnson J, Le Borgne R, Lehodey P, Lough J, Pickering T, Pratchett M, Sheaves M and Waycott M (2009b). 'Preliminary assessment of the effects of climate change on fisheries and aquaculture in the Pacific' in Gillett, R., (ed). Contribution of Fisheries to the Economies of Pacific Island Countries and Territories, Pacific Studies Series, Asian Development Bank (in press).

Bellwood, D.R., T.P. Hughes, C. Folke, and M. Nystrom. (2004). Confronting the coral reef crisis. Nature 429(6994): 827-833.

Berkelmans, R., and M.J.H. van Oppen. (2006). The role of zooxanthellae in the thermal tolerance of corals: a "nugget of hope" for coral reefs in an era of climate change. Proceedings of the Royal Society B: Biological Sciences 273(1599): 2305-2312.

Beyer, H. L. (2004). Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools.

Bhagooli, R., and I. Yakovleva. (2004). Differential bleaching susceptibility and mortality patterns among four corals in response to thermal stress. Symbiosis 37: 121-136.

Blanchon, P., A. Eisenhauer, J. Fietzke, and Z. Liebetrau. (2009). Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. Nature 458: 881-885.

Blanchon, P. and Shaw, J. (1995). Reef drowning during the last deglaciation: evidence for catastrophic sea-level rise and ice-sheet collapse. Geology 23: 4-8.

Blanchon, P. (2005). Comments on "Corrected western Atlantic sea level curve for the last 11,000 years based on calibrated ^{14}C dates from Acropora palmata framework and intertidal mangrove peat" by Toscano and Macintyre. Coral Reefs 24: 183-186.

Bobba A, Singh V, Berndtsson R and Bengtsson, L (2000), Numerical simulation of saltwater intrusion into Laccadive Island aquifers due to climate change. Journal of the Geological Society of India, 55, 589–612.

Bosch, W. (2002). The sea surface topography and its impact to global height system definition. In Drewes, H.A., Dodson, L.P., Fortes, L., Sanchez, P., Sandoval, P. (eds.) Vertical Reference Systems. IAG Symposia 124: 225-230.

Bosch, W., Acuila, G. and Kaniuth, R. (2009). Caribbean sea level variability from Topex/Poseidon Altimetry. Deutsches Geodätisches Forschungsinstitut. http://www.dgfi.badw.de

Bouchon, C., P. Portillo, Y. Bouchon-Navaro, L. Max, P. Hoetjes, A. Brathwaite, R. Roach, H. Oxenford, S. O'Farrell, and O. Day. (2008). Status of coral reefs of the Lesser Antilles after the 2005 coral bleaching event. In C. Wilkinson, and D. Souter [Eds.], Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Townsville, Australia, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre. 85-103 pp.

Braun, M., Humbert, A. and Moll, A. (2009). Changes of Wilkins Ice Shelf over the past 15 years and inferences on its stability. The Cryosphere, 3, 41–56.

Brewster, L. and Mwansa, J.B. (2000). Integrating Management of Watersheds and Coastal Areas in Small Island Developing States of the Caribbean: The Barbados National Report, prepared for the Caribbean Bruno, J.F., E.R. Selig, K.S. Casey, C.A. Page, B.L. Willis, C.D. Harvell, H. Sweatman, and A.M. Melendy. (2007). Thermal stress and coral cover as drivers of coral disease outbreaks. PLoS Biol 5(6): e124.

Burke, L., Maidens, J. et al. (2004). Reefs at Risk in the Caribbean. World Resources Institute. Washington, D.C. http://www.wri.org/publication/content/7863

Carton, J.A. (1999). Caribbean Sea eddies inferred from Topex/Poseidon altimetry and a 1/6˚ Atlantic Ocean model simulation. Journal of Geophysical Research 104: 7743-7752.

Casey, K.S., and P.A. Cornillon. (1999). Comparison of satellite and in situ based sea surface temperature climatologies. Journal of Climate 12: 1848-1863.

Causey, B. (2008). The history of massive coral bleaching and other perturbations in the Florida Keys. In C. Wilkinson, and D. Souter [Eds.], Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Townsville, Australia, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre. 61-67 pp.

Cayman Islands Government. (2004). The impact of Hurricane Ivan in the Cayman Islands. United Nations and Cayman Islands Government, 31pp.

Cazenave, A, Dominh, K, Guinehut, S, Berthier, E, Llovel, W, Ramillien, G, Ablain, M, & Larnicol G. (2008). 'Sea level budget over 2003–2008: A reevaluation from GRACE space gravimetry, satellite altimetry and Argo', Global and Planetary Change, ELSEVIER.

Caribbean Disaster Emergency Response Agency (CDERA). (2003). Status of hazard maps vulnerability assessments and digital maps: Barbados Country Report

Caribbean Disaster Emergency Response Agency (CDERA) 2003. Status of hazard maps vulnerability assessments and digital maps: Haiti Country Report.

Caribbean Disaster Emergency Response Agency (CDERA) (2004), Alternate water sources - a priority for the Montserrat Water Authority, press release of the Caribbean Disaster Emergency Response Agency, News Centre. Available at: http://www.cdera.org/cunews/news_releases/montserrat/article_654.php

CDERA .(2004), Alternate water sources - a priority for the Montserrat Water Authority, press release of the Caribbean Disaster Emergency Response Agency, News Centre. Available at: http://www.cdera.org/cunews/news_releases/montserrat/article_654.php

CDIAC. (2009). "Carbon Dioxide Information Analysis Center." Oak Ridge National Laboratory. Accessed from http://cdiac.ornl.gov/.

Challenger, B. (2004). Climate change technology transfer needs assessment for the Commonwealth of Dominica. Dominica's Initial National Communication Phase II Project Report. Roseau: Ministry of Agriculture.

Chen Z, Grasby S and Osadetz K (2004), Relation between climate variability and groundwater levels in the upper carbonate aquifer, southern Manitoba, Canada. Journal of Hydrology, 290, (1–2), 43–62.

Chen, J.L., Wilson, C.R. and Tapley, B.D. (2006). Satellite Gravity Measurements Confirm Accelerated Melting of Greenland Ice Sheet. Science DOI: 10.1126/science.1129007

Church, J. A., White, N. J., Coleman, R., Lambeck, K., Mitrovica, J. X. (2004). Estimates of the regional distribution of sea-level rise over the 1950-2000 period. J. Climate 17, 2609-2625.

Clark, P.U. and Weaver, A.J. (coordinating lead authors). (2008). Abrupt climate change. Report presented to the United States Congress by the U.S. Climate Change Science program and the Subcommittee on Global Change. U.S. Geological Survey, Reston, Virginia, USA, 459pp.

CLIMsystems. (2009). SIMCLIM, Climate Change Effect and Impacts Modeling Tool, http://www.climsystems.com/simclim/

Cohen, A.L., D.C. McCorkle, S. de Putron, G.A. Gaetani, and K.A. Rose. (2009). Morphological and compositional changes in the skeletons of new coral recruits reared in acidified seawater: Insights into the biomineralization response to ocean acidification. Geochemistry Geophysics Geosystems 10(1): doi: 10.1029/2009GC002411.

Connell, J.H. (1997). Disturbance and recovery of coral assemblages. Coral Reefs 16: S101-S113.

Cooper, B. and Bowen, V. (2001). National Report on Integrating Management of Watersheds and Coastal Areas in SIDS of the Caribbean: The Vincentian Perspective, report of the Environment Division, Ministry of Tourism and Environment, St. Vincent and the Grenadines, prepared for the Caribbean Environmental Health Institute, June 2001.

Crawley, A., D.I. Kline, S. Dunn, K. Anthony, and S. Dove. (2009). The effect of ocean acidification on symbiont photorespiration and productivity in Acropora formosa. Global Change Biology: doi: 10.1111/j.1365-2486.2009.01943.x.

CRW. (2009a). "Coral Reef Watch Satellite Monitoring " NOAA Coral Reef Watch. Accessed from http://coralreefwatch.noaa.gov/.

CRW. (2009b). "Ocean Acidification Product Suite." NOAA Coral Reef Watch. Accessed from http://coralreefwatch.noaa.gov/satellite/oa/index.html

Cumberbatch, J., Hutchinson, N., Robertson, A.A., Moore, W., Cashman, A., Walling, L. (2009), Climate change and tourism in Barbados: a vulnerability and capacity assessment of the tourism sector in Speightstown in response to climate change. 14pp. http://www.xcdtech.com/coastal2008/pdfs/WIE.pdf

Daniel, C.B., Maharaj, R. and De Souza, G. (2002). Tropical Cyclones affecting Trinidad and Tobago, 1725 to 2000. Trinidad and Tobago Meteorological Services.

Daniel, E.B. (2001). An assessment of beach erosion hazards in St Kitts and Nevis: summary report. http://www.oas.org/

PGDM/hazmap/cstlersn/sk_nev/kn_sum.htm

Das, S.B. Joughin, I., Behn, M.D., Howat, I.M., King, M.A., Lizarralde, D. and Bhatia, M.P. (2008). Fracture Propagation to the Base of the Greenland Ice Sheet during Supraglacial Lake Drainage Science DOI: 10.1126/science.1153360

Dasgupta, S., B. Laplante, C. Meisner, D. Wheeler, and J. Yan. (2007). The Impact of Sea Level Rise on Developing Countries: A Comparative Analysis. World Bank Policy Research Working Paper No. 4136. Washington, DC: World Bank.

Davidson, Phil. (2004). in Montserrat: After the eruption. http://www.independent.co.uk/news/world/americas/montserrat-after-the-eruption-498969.html. retrieved Dec. 21, 2009.

De Angelis, H. and Skvarca, P. (2003). Glacier surge after ice shelf collapse. Science, 299, 1560-1562.

De'ath, G., J.M. Lough, and K.E. Fabricius. (2009). Declining coral calcification on the Great Barrier Reef. Science 323(5910): 116-119.

De'ath, G., J.M. Lough, and K.E. Fabricius. (2009). Declining coral calcification on the Great Barrier Reef. Science 323(5910): 116-119.

Department of Economic Affairs (2001), National Report on Integrating Management of Watersheds and Coastal Areas in Grenada, report of the Department of Economic Affairs, Ministry of Finance, St. George's, prepared for the Caribbean Environmental Health Institute, July 2001.

Development Policy and Management Consultants. (2009). National adaptation strategy to address climate change in the agriculture sector of Guyana. Strategy and action plan. Belize: Caribbean Community Climate Change Centre.

Dietrich, R., Maas, H., Baessler, M., Ruelke, A., Schwalbe, E., 2005 Recent Flow Velocities at the Front of Jakobshavn Isbrae/Greenland from 2004 Field Observations American Geophysical Union, Fall Meeting 2005, abstract #C41A-05

Digerfeldt, G. and Hendry, M.D. (1987). An 8000 year Holocene sea-level record from Jamaica: implications for interpretation of Caribbean reef and coastal history. Coral Reefs 5, 165-169.

Dillon, W., ten Brink, U., Frankel, A., Rodriguez, R. Ad Mueller, C. (2001). Seismic and Tsunami Hazards in Northeast Caribbean Addressed at Meeting. U.S.Department of the Interior, U.S.Geological Survey. http://pubs.usgs.gov/of/2000/of00-006/htm/hazard.htm

Domack, E., Duran, D., Leventer, A., Ishman, S., Doane, S., McCallum, S., Amblas, S., Ring, J., Gilbert, R., & Prentice, M. (2005). Stability of the Larsen B ice shelf on the Antarctic Peninsula during the Holocene epoch. Nature, Vol. 436.

Domingues, C.M., Church, J.A., White, N.J., Glecker, P.J., Wijffels, S.E., Barker, P.M. and Dunn, J.R. (2008). Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 453, 1090-1093.

Donnelly, J.P. and Woodruff, J.D. (2007). Intense hurricane activity over the past 5000 years controlled by El Niño and the West African monsoon. Nature 447, 465-468.

Donner, S.D. (2009). Coping with commitment: Projected thermal stress on coral reefs under different future scenarios. PLoS ONE 4(6): e5712.

Donner, S.D., T.R. Knutson, and M. Oppenheimer. (2007). Model-based assessment of the role of human-induced climate change in the 2005 Caribbean coral bleaching event. Proceedings of the National Academy of Sciences 104(13): 5483-5488.

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

Dowdeswell, J. A. (2006). The Greenland Ice Sheet and Global sea-level rise. Science, 311, 963-964.

Dowdeswell, J.A. and Hagen, J.O., (2004). Arctic glaciers and ice caps. In Bamber, J.L. and Payne, A.J., (Eds.), Mass Balance of the Cryosphere, p. 527-557, Cambridge University Press.

Drigo A (2001), Integrating Management of Watersheds and Coastal Areas in Small Developing States of the Caribbean, National Report Common Wealth of Dominica, March 2001. Available at: http://www.cehi.org.lc/water_resources/projects/iwcam/national_reports/dominica/dominica_national_report.pdf

Eakin, C.M., J.M. Lough, and S.F. Heron. (2009). Climate variability and change: Monitoring data and evidence for increased coral bleaching stress. In M.H. Van Oppen, and J.M. Lough [Eds.], Coral Bleaching: Patterns, Processes, Causes and Consequences. Berlin, Springer. 41-67 pp.

Easterling, W. E., P. K. Aggarwal, P. Batima, K. M. Brander, E. D. Lin, S. M. Howden, A. P. Kirilenko, J. Morton, J. Soussana, J. Schmidhuber, and F. Tubiello. (2007). Food, fibre and forest products. 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. Ed. M. Parry, O. F. Canziani, J. Palutikof, P. J. van der Linden, and C. E. Hanson. Cambridge: Cambridge University Press.

Ellison, J. and Stoddart, D.R. (1991). Mangrove Ecosystem Collapse During Predicted Sea-Level Rise: Holocene Analogues and Implications. Journal of Coastal Research 7 (1), 151-165.

Elrick, C. & Kay, R. (in press) Adaptation Handbook: Undertaking Risk Treatment for Coastal Climate Change Risks in the Republic of Kiribati. Prepared for Kiribati Adaptation Project Phase II (KAP II), Government of Kiribati. Coastal Zone Management Pty Ltd, Perth.

Elsner, J.B., Kara, A.B. and Owens, M.A. (1999). Fluctuations in North Atlantic Hurricane Frequency. Journal of Climate 12 (2): 427-437.

Elsner, J.B., Kossin, J.P. and Jagger, T.H. (2008). The increasing intensity of the strongest tropical cyclones. Nature 455: 92-95.

Emanuel, K.A. (2005). Increasing destructiveness of tropical cyclones over the past 30 years, Nature, 436, 686-688.

Emanuel, K., Scudarajan, R.and Williams, J. (2008). Hurricanes and global warming. American Meteorological Society: 347-367.

Fabry, V.J., B.A. Seibel, R.A. Feely, and J.C. Orr. (2008). Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science 65: 414-432.

Fairbanks, R.G. (1989). A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342: 637-642.

Fairbanks, R.G. (2009). Lamont-Doherty Earth Observatory: current research. http://radiocarbon.1deo.columbia.edu/research/sealevel.htm

FAO (Food and Agricultural Organisation of the United Nations), (2009). Climate change and food security in the Pacific, FAO, SPC, USP Policy Brief, FAO, Rome.

Fernandez ,J., Rodrigues ,I., and Knuttle, W, (1997). Water Resource Sector of Antigua and Barbuda: United Nations Development Project, Saint John's, Antigua.

Fish, M.R., Côté, I.M., Gill, J.A., Jones, A.P., Renshoff, S. and Watkinson, A.R. 2005. Predicting the impact of sea-level rise on the Caribbean Sea turtle nesting habitat. Conservation Biology 19 (2), 482-491.

Fowler, HJ., Blenkinsop, S., and Tebaldi, C. (2007). Linking climate change modelling to impact studies: recent advances in downscaling techniques for hydrological modelling, International Journal of Climatology, 27: 1547-1578.

Frutos, R. (2003). Progress and Constraints in Developing Integrated Water Resources Management in Belize, Hydrology Unit, National Meteorological Service of Belize, available at: http://www.hydromet.gov.bz/Hydrological_Report.htm

García-Sais, J., R. Appeldoorn, T. Battista, L. Bauer, A. Bruckner, C. Caldow, L. Carrubba, J. Corredor, E. Diaz, C. Lilyestrom, G. García-Moliner, E. Hernández-Delgado, C. Menza, J. Morell, A. Pait, J. Sabater, E. Weil, E. Williams, and S. Williams. (2008). The state of coral reef ecosystems of Puerto Rico. In J.E. Waddell, and A.M. Clarke [Eds.], The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. Silver Spring, MD, NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. 75-116 pp.

Gardner, T.A., Côté, I.M., Gill, J.A., Grant, A. and Watkinson, A.R. (2003). Long-term region-wide declines in Caribbean corals. Science 301: 958-960.

Gardner, T.A., Côté, I.M., Gill, J.A., Grant, A. and Watkinson, A.R. (2005). Hurricanes and Caribbean coral reefs: impacts, recovery patterns and role in long-term decline. Ecology 86 (1): 174-184.

Gillett, R (ed.) (in press). The contribution of fisheries to the Economies of Pacific Island countries and Territories, Pacific Studies Series, Asian Development Bank , Manila, Philippines.

Gischler, E. (2006). Comment on "Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated 14C dates from Acropora palmata framework and intertidal mangrove peat" by Toscano and Macintyre. Coral Reefs 22, 257-270, and their response in Coral Reefs 24: 187-190.

Glasser, N.F. and Scambos, T.A. (2008). A structural glaciological analysis of the 2002 Larsen B ice shelf collapse Journal of Glaciology 54(184)": 3-15

Gledhill, D.K., R. Wanninkhof, and C.M. Eakin. (in press). Observing ocean acidification from space. Oceanography.

Gledhill, D.K., R. Wanninkhof, F.J. Millero, and M. Eakin. (2008). Ocean acidification of the Greater Caribbean Region 1996-2006. Journal of Geophysical Research 113: C10031.

Glynn, P.W. (1990). Coral mortality and disturbances to coral reefs in the tropical eastern Pacific. In P.W. Glynn [Ed.], Global Ecological Consequences of the 1982-83 El Niño-Southern Oscillation. Amsterdam, Elsevier. 55-126 pp.

Glynn, P.W., and L. D'Croz. (1990). Experimental evidence for high temperature stress as the cause of El Niño - coincident coral mortality. Coral Reefs 8: 181-191.

Goreau, T.J., Hayes, R. Ad Strong, A. (1997). Caribbean Sea Surface Temperatures and Coral Bleaching. Coral Reef Alliance http://www.globalcoral.org/caribbean_sea_surface_temperatur.htm

Goulet, T.L. (2006). Most corals may not change their symbionts. Marine Ecology Progress Series 321: 1-7.

Goulet, T.L. (2007). Most scleractinian corals and octocorals host a single symbiotic zooxanthella clade. Marine Ecology Progress Series 335: 243-248.

Government of Commonwealth of Dominica (2000), The Commonwealth of Dominica's First National Report on the Implementation of the United Nations Convention to Combat Desertification (UNCCD). Environmental Coordinating Unit, Ministry of Agriculture, Planning and Environment, Roseau, Commonwealth of Dominica, 20 pp.

Government of Kiribati. (1999). First National Communication to the United Nations Framework Convention on Climate

Change. Available: http://unfccc.int/essential_background/library/items/3599.php?rec=j&priref=2437#beg

Government of Kiribati. (2007). National Adaptation Program of Action. Available: http://unfccc.int/resource/docs/napa/kir01.pdf

Gregory, J.M., Huybrechts, P. and Raper, S.B. (2004). Threatened loss of the Greenland ice-sheet. Nature, 428, 616.

Grinsted, A., Moore, J.C. and Jevrejeva, S. (2009). Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. Climate Dynamics 10.1007/s00382-008-0507-2

Grottoli, A.G., L.J. Rodrigues, and J.E. Palardy. (2006). Heterotrophic plasticity and resilience in bleached corals. Nature 440(7088): 1186-1189.

Haites, E., D. Pantin, M. Attzs, B. James. (2002). Assessment of the Economic Impact of Climate Change on CARICOM Countries. Washington, DC: World Bank.

Intergovernmental Panel on Climate Change (IPCC). (2001). Climate Change 2001: Working Group II: Impacts, Adaptation and Vulnerability. Cambridge: Cambridge University Press.

Hales, SP et al (1999), 'Ciguatera, El Nino and Sea Surface Temperature', Ecosyst.Health, Vol 5, pp.20-25.

Hansen J (2005), A slippery slope. How much global warming constitutes "dangerous anthropogenic interference"? Climatic Change, 68: 269-279.

Hansen, J.E. (2007a). Climate catastrophe. New Scientist July 2007: 30-34.

Hansen, J.E. (2007b). Scientific reticence and sea level rise. Environmental Research Letters 2: 1-6.

Harrison, S. (2006). Destabilisation of Parts of the Greenland and West Antarctic Ice Sheet, in Rapid Climate Change, Lloyd's of London. Available at: http://www.lloyds.com/News_Centre/360_risk_insight/Research_and_reports.htm

Harvell, C., K. Kim, J. Burkholder, R. Colwell, P. Epstein, D. Grimes, E. Hofmann, E. Lipp, A. Osterhaus, R. Overstreet, J. Porter, G. Smith, and G. Vasta. (1999). Emerging marine diseases - climatic links and anthropogenic factors. Science 285: 1505-1510.

Hay, J. (2000). 'Climate change and small island states', Tiempo, Issue 36-37, September: 1-4.

Hay, J, Mimura G, et al.(2003), Climate Variability and Change and Sea Level Rise in the Pacific Island Region: A resource book for policy and decision makers, educators, and other stakeholders, Secretariat of the Pacific Regional Environment Programme (SPREP) Apia, Samoa.

Hay, E. and Onorio, K, (2006). Kiribati Country Environmental Analysis: Integrating environmental considerations in economic and development planning processes, report prepared for the Asian Development Bank.

Heron, S., J. Morgan, M. Eakin, and W. Skirving. (2008). Hurricanes and their effects on coral reefs. In C. Wilkinson, and D. Souter [Eds.], Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Townsville, Australia, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre. 31-36 pp.

Heron, S.F., B.L. Willis, W.J. Skirving, C.A. Page, C.M. Eakin, I.R. Miller, T.R. Christensen, D.K. Gledhill, G. Liu, J.A. Morgan, B.A. Parker, and A.E. Strong. (2009). Predicting the risk of coral disease outbreak using satellite SST. EOS Transactions AGU 90(22): Jt. Assem. Suppl., Abstract OS32A-07.

Hickerson, E.L., G.P. Schmahl, M. Robbart, W.F. Precht, and C. Caldow. (2008). The state of coral reef ecosystems of the Flower Garden Banks, Stetson Bank, and other banks in the northwestern Gulf of Mexico. In J.E. Waddell, and A.M. Clarke [Eds.], The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. Silver

Spring, MD, NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. 189-217 pp.

Hoegh-Guldberg, O. (1999). Climate change, coral bleaching and the future of the world's coral reefs. Marine and Freshwater Research 50: 839-866.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, and M.E. Hatziolos. (2007). Coral reefs under rapid climate change and ocean acidification. Science 318(5857): 1737-1742.

Holgate, S., Jevrejeva, S., Woodworth, P. and Brewer, S. 2007. Comment on "A semi-empirical approach to projecting future sea-level rise". Science 317: 1866.

Holland, M.M. and Bitz, C.M. (2003). Polar amplification of climate change in coupled models. Climate Dynamics, 21: 221-232.

Howat, I.M., Joughin, I.R. and Scambos, T.A. 2007. Rapid Changes in Ice Discharge from Greenland Outlet Glaciers. Science Express. DOI: 10.1126/science.1138478

Hughes, T.P. (1994). Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. Science 265(5178): 1547-1551.

Hughes, T.P., A.H. Baird, D.R. Bellwood, M. Card, S.R. Connolly, C. Folke, R. Grosberg, O. Hoegh-Guldberg, J.B.C. Jackson, J. Kleypas, J.M. Lough, P. Marshall, M. Nyström, S.R. Palumbi, J.M. Pandolfi, B. Rosen, and J. Roughgarden. (2003). Climate change, human impacts, and the resilience of coral reefs. Science 301: 929-933.

Hughes, T.P., and J.H. Connell. (1999). Multiple stressors on coral reefs: A long-term perspective. Limnology and Oceanography 44: 932-940.

IOP, (2009): Climate Change: Global Risks, Challenges and Decisions, Copenhagen 10.-12. March 2009. All sessions. IOP Conference Series: Earth and Environmental Series. Available online at: http://www.iop.org/EJ/volume/1755-1315/6

Intergovernmental Panel on Climate Change - IPCC. (2000): Special Report on Emissions Scenarios [N. Nakicenovic, J. Alcamo, G. Davis, B de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grübler, Tae Yong Jung, T. Kram, E. Lebre La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H-H Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor and Z. Dadi]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 599 pp.

IPCC. (2007a). 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, 996 pp.

IPCC. (2007b). Summary for Policymakers. In Climate Change 2007: the physical science basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, K.B., Avery, T., Tignor, M. and Miller, H.L. (eds.). Cambridge University Press, Cambridge.

IPCC. (2001). The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change (Houghton, J.T, Ding, Y., Giggs, D.J., Noguer, P.J, van der Linden, J, Dai, X, Maskell, C.A. and Johnson, C.A. (eds.). Cambridge University Press, Cambridge.

IOC. (2006). Intergovernmental co-ordination group for the tsunami and other coastal hazards warning system for the Caribbean Sea and adjacent regions. First session, Bridgetown, Barbados.

Jokiel, P.L., K.S. Rodgers, I.B. Kuffner, A.J. Andersson, E.F. Cox, and F.T. Mackenzie. (2008). Ocean acidification and calcifying reef organisms: a mesocosm investigation. Coral Reefs 27(38): 473-483.

Jones, A.M., R. Berkelmans, M.J.H. van Oppen, J.C. Mieog, and W. Sinclair. (2008a). A community change in the algal endosymbionts of a scleractinian coral following a natural bleaching event: field evidence of acclimatization. Proceedings of the Royal Society B: Biological Sciences 275(1641): 1359-1365.

Jones, L., P.M. Alcolado, Y. Cala, D. Cobian, V. Coelho, A. Hernandez, R. Jones, J. Mallela, and C. Manfrino. (2008b). The effects of coral bleaching in the northern Caribbean and western Atlantic. In C. Wilkinson, and D. Souter [Eds.], Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Townsville, Australia, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre. 73-83 pp.

Kaufman, D.S., Schneider, D.P., McKay, N.P., [3] Ammann, C.M., Bradley, R.S., Briffa, K.R., Miller, G.H., Otto-Bliesner, B.L., Overpeck, J.T., Vinther, B.O., (2009). Arctic Lakes 2k Project Members. Recent Warming Reverses Long-Term Arctic Cooling Science, 325 (5945): 1236 – 1239

Kay, R. (2008). Development of an Integrated Climate Change Adaptation Risk Diagnosis and Planning Process: Final Report. Report prepared for the KAP Project, Phase II. Tarawa, Kiribati. Coastal Zone Management Pty Ltd, Perth.

Kilpatrick, K.A., G.P. Podesta, and R. Evans. (2001). Overview of the NOAA/NASA Advanced Very High Resolution Radiometer Pathfinder algorithm for sea surface temperature and associated matchup database. Journal of Geophysical Research 106: 9179-9197.

Kleypas, J.A., J.W. McManus, and L.A. Meñez. (1999). Environmental limits to coral reef development: Where do we draw the line? American Zoologist 39: 146-159.

Knutson, T.R., J.J. Sirutis, S.T. Garner, G.A. Vecchi, and I.M. Held. (2008). Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions Nature Geoscience (6): 359-364.

Knutson, TR, Tuleya, RE (2004) Impact of CO2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective paramaterization, Journal of Climate, 17, 3477-3495.

Kubatzki, C., Montoya M., Rahmstorf, S., Ganopolski, A., Claussen, M. (2000). Comparison of the last interglacial climate simulated by a coupled global model of intermediate complexity and an AOGCM. Climate Dynamics, 16: 799-814.

Kuffner, I.B., A.J. Andersson, P.L. Jokiel, K.S. Rodgers, and F.T. Mackenzie. (2008). Decreased abundance of crustose coralline algae due to ocean acidification. Nature Geoscience 1(2): 114-117.

Kundzewicz, Z. W., Mata, L., Arnell, N., Döoll, P., Kabat, P., Jim_enez, B., Miller, K., Oki, T., Sen, Z., and Shiklomanov, I. (2007). Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, chapter Freshwater resources and their management. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Lander, J.F., Whiteside, L.S. and Lockeridge, P.A. (2002). A brief history of tsunamis in the Caribbean Sea. Science of Tsunami Hazards 20 (1): 57 – 94.

Langdon, C., and M.J. Atkinson. (2005). Effect of elevated pCO_2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. Journal of Geophysical Research 110(C09S07).

Lasker, H.R., and M.A. Coffroth. (1999). Responses of clonal reef taxa to environmental change. American Zoologist 39(1): 92-103.

Lehodey, P., Senina, I., and Murtugudde, R. (2008), 'A spatial ecosystem and populations dynamics model (SEAPODYM) – modeling of tuna and tuna-like populations', Progress in Oceanography, 78: 304-318.

Lewsey, C., Cid, G., Kruse, E. (2004). Assessing climate change impacts on coastal infrastructure in the Eastern Caribbean, Marine Policy 28: 393–409

Lighty, R.G., Macintyre, I.G. and Stuckenrath, R. (1982). Acropora palmata reef framework: a reliable indicator of sea level in the western Atlantic for the past 10,000 years. Coral Reefs 1: 125-130.

Little, A.F., M.J.H. van Oppen, and B.L. Willis. (2004). Flexibility in algal endosymbioses shapes growth in reef corals. Science 304(5676): 1492-1494.

Liu, G., L.E. Matrosova, C. Penland, D.K. Gledhill, C.M. Eakin, R.S. Webb, T.R.L. Christensen, S.F. Heron, J.A. Morgan, W.J. Skirving, and A.E. Strong. (in press). NOAA Coral Reef Watch Coral Bleaching Outlook system. Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, 7-11 July 2008.

Liu, G., W. Skirving, and A.E. Strong. (2003). Potential for expansion of coral reefs into higher latitudes due to climate change. OCEANS 2003 5: P2745 - P2747.

Liu, G., A.E. Strong, W.J. Skirving, and L.F. Arzayus. (2006). Overview of NOAA Coral Reef Watch program's near-real-time satellite global coral bleaching monitoring activities. Proceedings of the 10th International Coral Reef Symposium, Okinawa: 1783-1793.

Loya, Y., K. Sakai, K. Yamazato, Y. Nakano, H. Sambali, and R. vanWoesik. (2001). Coral bleaching: the winners and the losers. Ecology Letters 4: 122-131.

Lund, R. (in press). Tropical cyclone frequency. Journal of the American Statistical Association.

Lundgren, I., and Z. Hillis-Starr. (2008). Variation in Acropora palmata bleaching across benthic zones at Buck Island Reef National Monument (St. Croix, USVI) during the 2005 thermal stress event. Bulletin of Marine Science 83(3): 441-

451.

Lynch, M. (1996). A quantitative-genetic perspective on conservation issues. In J.C. Avise, and J.L. Hamrick [Eds.], Conservation Genetics. New York, USA, Chapman and Hall. 471-501 pp.

Lynch, M., W. Gabriel, and A.M. Wood. (1991). Adaptive and demographic responses of plankton populations to environmental change. Limnology and Oceanography 36(7): 1301-1312.

Mageney, A., Heinrich, P.H., Roche, R., Boudon. G. and Cheminée, J.L. (2000). Modeling of debris avalanche and generated water waves: application to real and potential events in Montserrat. Physics and Chemistry of the Earth, series A 25: 741-745.

Mallela, J., and M.J.C. Crabbe. (2009). Hurricanes and coral bleaching linked to changes in coral recruitment in Tobago. Marine Environmental Research 68(4): 158-162.

Manabe, S., and Stouffer, R.J. (1980). Sensitivity of a global climate model to an increase of CO_2 concentration in the atmosphere. Journal of Geophysical Research, 85(C10): 5529-5554.

Mann, M.E., Woodruff, J.D., Donnelly, J.P. and Zhang, Z. (2009). Atlantic hurricanes and climate over the past 1,500 years. Nature 460: 880-883.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78: 1069-1079.

Manzello, D.P., M. Brandt, T.B. Smith, D. Lirman, J.C. Hendee, and R.S. Nemeth. (2007). Hurricanes benefit bleached corals. Proceedings of the National Academy of Sciences 104(29): 12035-12039.

Manzello, D.P., J.A. Kleypas, D.A. Budd, C.M. Eakin, P.W. Glynn, and C. Langdon. (2008). Poorly cemented coral reefs of the eastern tropical Pacific: Possible insights into reef development in a high-CO_2 world. Proceedings of the National Academy of Sciences 105(30): 10450-10455.

Martinez, Andres R. and Rothman L. Haiti Earthquake to Cost Economy at least 15% of GDP (Update 2). http://www.bloomberg.com/apps/news?pid=newsarchive&sid=aSMTe1TZFBUQ. Retrieved Jan 15, 2010.

Marshall, P., and H. Schuttenberg. (2006). A Reef Manager's Guide to Coral Bleaching. Townsville, Australia, Great Barrier Reef Marine Park Authority. 163 p.

Marshall, P.A., and A.H. Baird. (2000). Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. Coral Reefs 19(2): 155-163.

Mayer, H. and Herzfeld, U.C. (2005). The Rapid Retreat of Jakobshavns Isbrae, West Greenland: New Field Observations of 2005 and Structural Analysis of its Evolution. Eos Trans. AGU, 86(52): Fall Meet. Suppl., Abstract C41A-06

McClanahan, T.R. (2007). Response of the coral reef benthos and herbivory to fishery closure management and the 1998 ENSO disturbance. Oceologia 155: 169-177.

McClanahan, T.R., M. Ateweberhan, C.A. Muhando, J. Maina, and M.S. Mohammed. (2007). Effects of climate and seawater temperature variation on coral bleaching and mortality. Ecological Monographs 77: 503-525.

McCook, L.J., J. Jompa, and G. Diaz-Pulido. (2001). Competition between corals and algae on coral reefs: a review of evidence and mechanisms. Coral Reefs 19(4): 400-417.

McField, M., N. Bood, A. Fonseca, A. Arrivillaga, A.F. Rinos, and R.M. Loreto Viruel. (2008). Status of the Mesoamerican reef after the 2005 coral bleaching event. In C. Wilkinson, and D. Souter [Eds.], Status of Caribbean Coral Reefs after

Bleaching and Hurricanes in 2005. Townsville, Australia, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre: 45-60.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, (2007). Global Climate Projections. 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.

Mercer, J. (1978). West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster Nature 271: 321-325.

Metz, B., O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer [Eds.]. (2007). Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK, Cambridge University Press. 851 pp.

Middlebrook, R., O. Hoegh-Guldberg, and W. Leggat. (2008). The effect of thermal history on the susceptibility of reef-building corals to thermal stress. Journal of Experimental Biology 211(7): 1050-1056.

Miller, K.P. (2007). Variations in sea level on the West Trinidad coast. Marine Geology 28: 219-229.

Miller, J., E. Muller, C. Rogers, R. Waara, A. Atkinson, K. Whelan, M. Patterson, and B. Witcher. (2009). Coral disease following massive bleaching in 2005 causes 60% decline in coral cover on reefs in the US Virgin Islands. Coral Reefs 28(4): 925-937.

Mills, A.P. (2001). St Vincent and the Grenadines. Marine Pollution Bulletin 42: 1208-1228.

Milne, G.A., Gehrels, W.R., Hughes, C.W. and Tamisiea, M.E. (2009). Identifying the causes of sea-level change. Nature

Geoscience 2: 471 – 478.

Mimura, N., Nurse, L., McLean, R.F., Agard, J., Briguglio, P., Payet, R. and Sern, G. (2007). Small Islands. 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.: 687-716.

Mitrovica, J.X., Tamisiea, M.E., Davis, J.L. and Milne, G.A. (2001). Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. Nature 409: 1026-1029.

Mitrovica, J.X., Gomez, N., Clark, P.U. 2009. The sea-level fingerprint of West Antarctic collapse. Science 323, 753.

Moises E.Angeles, Jorge E.Gonzalez, J. E. David, and L. H. José. 2007. Predictions of future climate change in the caribbean region using global general circulation models. International Journal of Climatology 27 (5): 555-569.

Morgan, J., S. Heron, and M. Eakin. (2008). The 2005 bleaching event: Coral-List log. In C. Wilkinson, and D. Souter [Eds.], Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Townsville, Australia, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre: 37-44.

Muller, E., C. Rogers, A. Spitzack, and R. van Woesik. (2008). Bleaching increases likelihood of disease on Acropora palmata (Lamarck) in Hawksnest Bay, St John, US Virgin Islands. Coral Reefs 27(1): 191-195.

Mumby, P.J. (2006). The impact of exploiting grazers (Scaridae) on the dynamics of Caribbean coral reefs. Ecological Applications 16: 747-769.

Mumby, P.J., A. Hastings, and H.J. Edwards. (2007). Thresholds and the resilience of Caribbean coral reefs. Nature 450(7166): 98-101.

Murty, T.S. (1977). Seismic Sea Waves: Tsunamis. Bulletin of the Fisheries Research Board of Canada 198: 337.

Myles, D. (1985). The Great Waves. Robert Hale, London.

Nakićenović N and Swart R, Eds. (2000), Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, 599 pp.

National Climate Committee. (2002). Guyana Initial National Communication. Georgetown: National Climate Committee, Natural Resources and Environment Advisory Committee, United Nations Development Programme (UNDP).

National Oceanographic and Atmospheric Administration. (2007). Atlantic Oceanographic and Meteorological Laboratory. Hurricane Research Division Report.

NCDC. (2009). "NOAA Extended Reconstructed Sea Surface Temperature (ERSST.v3b)." NOAA National Climatic Data Center. Accessed from http://www.ncdc.noaa.gov/oa/climate/research/sst/ersstv3.php.

Nelson, G. C., M. W. Rosegrant, et al. (2009). "Climate Change: Impact on Agriculture and Costs of Adaptation." IFPRI, September 2009.

NODC. (2009). "NODC 4km Pathfinder Version 5." NOAA National Oceanographic Data Center. Accessed from http://www.nodc.noaa.gov/sog/pathfinder4km/.

Nurse, L.A., Graham, SEM., Hay, JE., Suarez, AG, Wong, PP, Briguglio, L, Ragoonaden, S. (2001). Small Island States, in Climate Change 2001:Impacts, Adaptation and Vulnerability, contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, McCarthy JJ, Canziani OF, Leary NA, Dokken DJ, White KS (Eds.), GRID Arendal, available at: http://www.grida.no/publications/other/ipcc_tar/

Nyberg, J., Malmgren, B.A., Winter, A., Jury, M.R., K H. Kilbourne and Quinn, T.M. (2007). Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. Nature 447: 698-701.

Nystrom, M., C. Folke, and F. Moberg. (2000). Coral reef disturbance and resilience in a human-dominated environment. Trends in Ecology & Evolution 15: 413-417.

O'Brien, K. (2000). Developing Strategies for Climate Change: The UNEP Country Studies on Climate Change Impacts and Adaptations Assessment. CICERO Report 2000:2. Olso: Center for International Climate and Environmental Research.

O'Loughlin, K.E. and Lander, J.F. (2003). Caribbean tsunamis: a 500 year history from 1498 – 1998. Advances in Natural and Technology Hazards Research. Kluwer Academic Publishers, the Netherlands.

Oppenheimer, M., and Alley, R.B. (2004). The West Antarctic Ice Sheet and Long Term Climate Policy. Climatic Change, 64(1-2): 1-10.

Oppenheimer, M and Alley, RB. (2005). Ice sheet, global warming and Article 2 of the UNFCCC. Climatic Change, 68: 257-267.

Oppenheimer, M. (1998). Global warming and the stability of the West Antarctic Ice Sheet. Nature, 393: 325-332.

Overpeck, J.T., Otto-Bliesner, B.L., Miller, G.H., Muhs, D.R., Alley, R.B. and Kiehl, J.T. (2006). Paleoclimatic evidence for future ice-sheet instability and rapid sea-level rise. Science 311: 1747-1750.

Oxenford, H., R. Roach, A. Brathwaite, L. Nurse, R. Goodridge, F. Hinds, K. Baldwin, and C. Finney. (2008). Quantitative observations of a major coral bleaching event in Barbados, Southeastern Caribbean. Climatic Change 87(3): 435-449.

Pandolfi, J.M., and J.B.C. Jackson. (2006). Ecological persistence interrupted in Caribbean coral reefs. Ecology Letters 9(7): 818-826.

Paras-Carayannis, G. (2004). Volcanic tsunami generating source mechanisms in the eastern Caribbean region. Science of Tsunami Hazards 22 (2): 74.

Parkinson, R.W., de Laune, R.D. and White, J.R. (1994). Holocene Sea-Level Rise and the Fate of Mangrove Forests Within the Wider Caribbean Region. Journal of Coastal Research 10 (4): 1077-1086.

Parry, ML, Canziani, OF, Palutikof, JP, van der Linden, PJ & Hanson, CE (Eds). (2007). Summary for Policymakers, Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.:23-78.

Patterson, K.L., J.W. Porter, K.B. Ritchie, S.W. Polson, E. Mueller, E.C. Peters, D.L. Santavy, and G.W. Smith. (2002). The etiology of white pox, a lethal disease of the Caribbean elkhorn coral, Acropora palmata. Proceedings of the National Academy of Science, USA 99: 8725-8730.

Payne, A.J., Vieli, A., Shephard, A., Wingham, D.J., and Rignot, E. (2004). Recent dramatic thinning of largest West Antarctic ice stream triggered by oceans. Geophysical Research Letters, 31: L23401

Peltier, W.R., Fairbanks, R.G. (2006). Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. Quaternary Science Reviews 25 (23-24): 3322-3337.

Pratchett,MS, Munday, PL, Wilson, SK, Graham, NAJ, Cinner, JE, Bellwood, DR, Jones, GP, Polunin, NVC and McClanahan, TR. (2008), 'Effects of climate-induced coral bleaching on coral-reef fishes: ecological and economic consequences'. Oceanography and Marine Biology: An Annual Review, 46: 251-296.

Precht, W.F., K. Deslarzes, E. Hickerson, G.P. Schmahl, J. Sinclair, and R. Aronson. (in press). Holocene reef development at the Flower Garden Banks: Recent surprises. Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, 7-11 July 2008.

Rahmstorf, S. (2003). Timing of abrupt climate change: A precise clock. Geophysical Research Letters, 30(101510), doi: 10.1029/2003GL017115.

Rahmsdorf, S. (2007). A semi-empirical approach to projecting future sea-level rise. Science 315: 368-370.

Rahmsdorf, S. (2007a). Response to comments on "A semi-empirical approach to projecting future sea-level rise" Science 317: 1866.

Rahmsdorf, S. (2009). Address to the Oxford University Climate Conference, 2009.

Rahmstorf, S., Cazenave, A., Church, J.A., Hansen, J.E., Keeling, R.F., Parker, D.E. and Somerville, R.C.J. (2007). Recent Climate Observations Compared to Projections. Science Express, 10.1126/science.1136843

Ramsay, D.L., Stephens,S., Gorman, R., Oldman, J., and Bell, R. (2008), Kiribati Adaptation Program. Phase II. Information for Climate Risk Management: Sea-levels, waves, run-up and overtopping. NIWA Report: HAM 2008-022.

Randall, D.A., R.A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R.J. Stouffer, A. Sumi, and K.E. Taylor. (2007). Climate models and their evaluation. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller [Eds.], Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge, UK, Cambridge University Press: 590-662.

Renegar, D.A., and B.M. Riegl. (2005). Effect of nutrient enrichment and elevated CO_2 partial pressure on growth rate of Atlantic scleractinian coral Acropora cervicornis. Marine Ecology Progress Series 293: 69-76.

Rial, A., Pielke Sr., R.A., Beniston, M., Claussen, M., Canadell, J., Cox, P., Held, H., De Noblet-Ducoudré, N., Prinn, R., Reynolds, J.F. and Salas, J.D. (2004). Nonlinearities, feedbacks and critical thresholds within the Earth's climate system. Climatic Change 65: 11–38.

Rignot, E. (2001). Evidence for rapid retreat and mass loss of Thwaites Glacier, West Antarctica Journal of Glaciology 47(157),March: 213-222(10).

Rignot, E. Vaughan, D.G., Schmeltz, M., Dupont, T. MacAyeal, D. (2002). Acceleration of Pine Island and Thwaites Glaciers, West Antarctica Annals of Glaciology 34(1): 189-196.

Rignot, E. G. Casassa, P. Gogineni, W. Krabill, A. Rivera, and R. Thomas. (2004). Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf. Geophysical Research Letters, 31(18): L18401, doi:10.1029/2004GL020697.

Rignot, E., Box, J.E., Burgess, E. and Hanna, E. (2008). Mass balance of the Greenland ice sheet from 1958 to 2007. Geophysical Research Letters 35(L20502), doi:10.1029/2008GL035417

Roeleveld, W. and van Loon, A.J. (1979). The Holocene development of the young coastal plain of Suriname. Geologie en Mijnbouw 58: 21-28.

Ritchie, K.B. (2006). Regulation of microbial populations by coral surface mucus and mucus-associated bacteria. Marine Ecology Progress Series 322: 1-14.

Rodríguez-Ramírez, A., C. Bastidas, S. Rodríguez, Z. Leão, R. Kikuchi, M. Oliveira, D. Gil, J. Garzón-Ferreira, M.C. Reyes-Nivia, R. Navas-Camacho, N. Santodomingo, G. Díaz-Pulido, D. Venera-Ponton, L. Florez-Leiva, A. Rangel-Campo, C.

Orozco, J.C. Márquez, S. Zea, M. López-Victoria, J. Armando Sánchez, and M.C. Hurtado. (2008). The effects of coral bleaching in southern tropical America : Brazil, Colombia, and Venezuela. In C. Wilkinson, and D. Souter [Eds.], Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Townsville, Australia, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre. 105-114 pp.

Rogel, J., Hare, B., Nabel, J., Macey, K., Schaeffer, M., Markmann, K. and Meinshausen, M. (2009). Halfway to Copenhagen, no way to 2°C. Nature Reports 3: 81-83.

Sachs, J.D., Mellinger, A.D., and Gallup, J.L., (2001). The geography of poverty and wealth. Scientific American, 284(3), p.70-75.

Saunders, M. A., and A. S. Lea. (2008). Large contribution of sea surface warming to recent increase in Atlantic hurricane activity. Nature 451 (7178): 557-560

Scantlebury, M. (2009). The impact of climate change on Heritage Tourism in the Caribbean: a case study from Speightstown, Barbados, West Indies. The International Journal of Climate Change: Impacts and Responses 1 (2): 37-48.

Scambos, T. A., J. A. Bohlander, C.A. Shuman, and P. Skvarca. (2004). Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, Geophysical Research Letters, 31(18).

Schmith, T., Johansen, S. and Thejill, P. (2007). Comment on “A semi-empirical approach to projecting future sea-level rise”. Science 317: 1866.

Schwab, W.C., Danforth, W.W., Scanlon, K.M. and Masson, D.G. (1991). A giant submarine slope failure on the northern insular slope of Puerto Rico. Marine Geology 96: 237-246.

Senina I, Sibert J and Lehodey P (2008), 'Parameter estimation for basin-scale ecosystem-linked population models of large pelagic predators: application to skipjack tuna' Progress in Oceanography, 78: 319-335.

Serreze, M.C., Barrett, A.P., Stroeve, J.C., Kindig, D.N. and Holland, M.M. (2009). The emergence of surface-based Arctic amplification. The Cryosphere, 3: 11–19.

Shein, K.A. (2006). State of the climate in 2005. Bulletin of the American Meteorological Society 87(6): s1-s102.

Sheppard, C.R.C. (2003). Predicted recurrence of coral mass mortality in the Indian Ocean. Nature 425: 294-297.

Shepherd, A., Wingham, D., and Rignot, E. (2004). Warm ocean is eroding West Antarctic Ice Sheet. Geophysical Research Letters, 31(23): L23402, doi:10.1029/2004GL021106.

Shepherd, A., Wingham, D. Payne, A.J. and Skvarca, P. (2003). Larsen Ice Shelf Has Progressively Thinned Science, 302: 856-859.

Silverman, J., B. Lazar, L. Cao, K. Caldeira, and J. Erez. (2009). Coral reefs may start dissolving when atmospheric CO_2 doubles. Geophysical Research Letters 36: doi: 10.1029/2008gl036282.

Singh, B. and El Maayar, M. (1998). Potential impacts of greenhouse gas climate change scenarios on sugar cane yields in Trinidad. Tropical Agriculture (Trinidad) 75.

Smith, D (2006) Rapid Sea-level Rise, in Rapid Climate Change, Lloyd's of London. Available at: http://www.lloyds.com/News_Centre/360_risk_insight/Research_and_reports.htm

Smith, D.E. (2005). Tsunami: a research perspective. Geology Today, 21 (2): 64-68.

Smith, D.E., Wells, J.M., Mighall, T.M., Cullingford, R.A., Holloway, L.K., Dawson, S. and Brooks, C.L. (2003). Holocene relative sea levels and coastal changes in the lower Cree valley and estuary, SW Scotland, UK. Transactions of the Royal Society of Edinburgh: Earth Sciences 93: 301-331.

Smith, D.E., Shi, S., Cullingford, R.A., Dawson, A.G., Dawson, S., Firth, C.R., Foster, I.D.L., Fretwell, P.T., Haggart, B.A., Holloway, L.K. and Long, D. (2004). The Holocene Storegga Slide tsunami in the United Kingdom. Quaternary Science Reviews 23: 2291-2321.

Smith, T.M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore. (2008). Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880-2006). Journal of Climate 21: 2283-2296.

Sole, A., Payne, T., Bamber, J., Nienow, P. and Krabill, W. (2008). Testing hypotheses of the cause of peripheral thinning of the Greenland Ice Sheet: is land-terminating ice thinning at anomalously high rates? The Cryosphere Discussions, 2: 673–710.

Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood & Wratt D (2007). 'Technical Summary' 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, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M & Miller HL (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

SOPAC (Pacific Islands Applied Geoscience Commission)(2007)., Funding for renewable energy and energy efficiency projects under the Kyoto Protocol's Clean Development Mechanism, SOPAC Miscellaneous Report 630, Suva, Fiji.

SPC (Secretariat of the Pacific Community) (2008a), Fish and Food security, Policy Brief 1/2008, Secretariat of the Pacific Community, Nouméa, New Caledonia.

SPC (2008b). Fisheries and Climate Change, Policy Brief 5/2008, Secretariat of the Pacific Community, Nouméa, New Caledonia.

SPC (2008c). 'Food Security in the Pacific', Agenda Item 3.1, 38th Meeting of the Committee of Representatives of Governments and Administrations, 13–16 October 2008. Secretariat of the Pacific Community, Nouméa, New Caledonia.

SPC (2009a). Working Paper 5: Fish for Food Security in the Pacific, 6th SPC Heads of Fisheries Meeting, 9-13 February 2009, Secretariat of the Pacific Community, Nouméa, New Caledonia

SPC (2009b). SPC Statistics and Demography Programme (and its Pacific Regional Information System – PRISM), Secretariat of the Pacific Community, Nouméa, New Caledonia. www.spc.int/prism

Sotka, E.E., and R.W. Thacker. (2005). Do some corals like it hot? Trends In Ecology & Evolution 20(2): 59-62.

SPREP (Secretariat of the Pacific Regional Environment Programme) , (2009). http://www.sprep.org/members/map.htm

Stearns, L.A. and G.S. Hamilton. (2005). Rapid changes of large tidewater glaciers in SE Greenland, AGU meeting.

Steffen, W., (2009), Climate Change 2009: Faster Change and More Serious Risks, Department of Climate Change, http://www.climatechange.gov.au/en/publications/science/faster-change-more-risk.aspx

Steig, E.J., Schneider, D.P., Rutherford, S.D., Mann, M.E., Comiso, J.C., Shindell, D.T. (2008). Warming of the Antarctic ice sheet surface since the 1957 International Geophysical Year. Nature, 457: 459-462.

Stone, L., A. Huppert, B. Rajagopalan, and Y. Loya. (1999). Mass coral reef bleaching: a recent outcome of increased

El-Nino activity? Ecology Letters 2: 325-330.

Strong, A., G. Liu, C. Eakin, T. Christensen, W. Skirving, D. Gledhill, S. Heron, and J. Morgan. (in press). Implications for our coral reefs in a changing climate over the next few decades. Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, 7-11 July 2008.

Strong, A.E. (1989). Greater global warming revealed by satellite-derived sea surface temperature trends. Nature 338: 642-645.

Strong, A.E. (1991). Sea surface temperature signals from space. In W.A. Nierenberg [Ed.], Encyclopedia of Earth System Science. San Diego, CA, Academic Press. 4. 69-80 pp.

Strong, A.E., F. Arzayus, W. Skirving, and S.F. Heron. (2006). Identifying coral bleaching remotely via Coral Reef Watch - Improved integration and implications for changing climate. In J.T. Phinney, O. Hoegh-Guldburg, J. Kleypas, W. Skirving, and A. Strong [Eds.], Coral Reefs and Climate Change: Science and Management. Washington, DC, American Geophysical Union. 61: 163-180.

Sutherland, M., Dare, P., Miller, K. (2008). Monitoring sea level change in the Caribbean. Geomatica 62 (4): 428-436.

Tanzil, J.T.I., B.E. Brown, A.W. Tudhope, and R.P. Dunne. (2009). Decline in skeletal growth of the coral Porites lutea from the Andaman Sea, South Thailand between 1984 and 2005. Coral Reefs 28(2): 519-528.

Tartaglione, C.A., Smith, S.R. and Obrien, J.J. (2003). ENSO Impact on Hurricane landfall probabilities for the Caribbean. Journal of Climate 16: 2925-293.

The Copenhagen Diagnosis, (2009). Updating the World on the Latest Climate Science. I. Allison, N.L. Bindoff, R.A. Bindschadler, P.M. Cox, N. de Noblet, M.H. England, J.E. Francis, N. Gruber, A.M. Haywood, D.J. Karoly, G. Kaser, C. Le Quéré, T.M. Lenton, M.E. Mann, B.I. McNeil, A.J. Pitman, S. Rahmstorf, E. Rignot, H.J. Schellnhuber, S.H. Schneider, S.C. Sherwood, R.C.J. Somerville, K. Steffen, E.J. Steig, M. Visbeck, A.J. Weaver. The University of New South Wales. Climate Change Research Centre (CCRC), Sydney, Australia, 60pp. http://www.copenhagendiagnosis.org/

Thomas, R., E. Rignot, G. Casassa, P. Kanagaratnam, C. Acuña, T. Akins, H. Brecher, E. Frederick. (2004). Accelerated Sea-Level Rise from West Antarctica. Science, 306(5694): 255-258.

Tingstad, A.H. and Smith, D.E. (2007). El Niño and sea level anomalies: a global perspective. Geology Today 23 (6): 215-218.

Tollner E, Ed. (2007), Water profile of Belize. In: Encyclopedia of Earth. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). First published in the Encyclopedia of Earth March 21, 2007; Last revised June 28, 2007. Available at: http://www.eoearth.org/article/Water_profile_of_Belize

Toscano, M.A. and Macintyre, I.G. (2003). Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from Acropora palmata framework and intertidal peat. Coral Reefs 22: 257-270.

Toscano, M.A. and Macintyre, I.G. (2005). Response to Blanchon, P. comments on “Corrected western Atlantic sea-level curve for the last 11,000 years based on calibrated ^{14}C dates from Acropora palmata framework and intertidal mangrove peat” by Toscano and Macintyre. Coral Reefs 24: 187-190.

Trenberth, K (2005) Uncertainty in Hurricanes and Global Warming, Science, 308, 1753-1754.

Trenberth, K.E., and D.J. Shea. (2006). Atlantic hurricanes and natural variability in 2005. Geophysical Research Letters

33(12): L12704.

Tribollet, A., C. Godinot, M. Atkinson, and C. Langdon. (2009). Effects of elevated pCO_2 on dissolution of coral carbonates by microbial euendoliths. Global Biogeochemical Cycles 23: GB3008.

Trombley, R.B. (2008). Potential Caribbean area mega tsunami risk. 18th Geological Conference of the Caribbean, Santo Domingo, Dominican Republic.

Turner, J., Colwell, S.R., Marshall, G.J., Lachlan-Cope, T.A., Carleton, A.M., Jones, P.D., Lagun, V., Reid, P.A. and Lgovkina, S. (2005). Antarctic climate change during the last 50 years. International Journal of Climatology 25: 279-294.

UNESCO: Wise practices for coping with beach erosion:

Dominica: http://www.unesco.org/csi/act/cosalc/brochdom.htm

Grenada: http://www.unesco.org/csi/act/cosalc/brochgre.htm

Montserrat: http://www.unesco.org/csi/act/cosalc/brochmon.htm

St Lucia http://www.unesco.org/csi/act/cosalc/brochluc.htm

St Vincent and the Grenadines: http://www.unesco.org/csi/act/cosalc/brochvin.htm

United States Department of State. (2008). U.S. Ocean Agency to help build sea-level network in the Caribbean. http://www.america.gov/st/env-english/2008/August/200080819185526lcnirellep0.878978

Universteit Leuven. (2009). Coastal morphodynamics of Suriname. http://www.kuleuven.be/hydr/SurinameCoast/

SurinameCoast.htm

UN-OCHA (2010). Consolidated Appeals Process (CAP): Haiti Earthquake Flash Appeal 2010. http://www.reliefweb.int/rw/rwb.nsf/db900SID/SODA-7ZQPUC?OpenDocument. Retrieved from ReliefWeb Jan. 15, 2010.

USACE (1998), Water Resources Assessment of Guyana, report of the Mobile District & Topographic Engineering Center, United States Army Corps of Engineers, December 1998.

USACE (1999), Water Resources Assessment of Haiti, report of the Mobile District & Topographic Engineering Center, United States Army Corps of Engineers, August 1999.

USACE (2001a), Water Resources Assessment of Jamaica, report of the Mobile District & Topographic Engineering Center, United States Army Corps of Engineers, February 2001.

USACE (2001b), Water Resources Assessment of Suriname, report of the Mobile District & Topographic Engineering Center, United States Army Corps of Engineers, December 2001.

USACE (2004a), Water Resources Assessment of the Bahamas, report of the Mobile District & Topographic Engineering Center, United States Army Corps of Engineers, December 2004.

USACE (2004b), Water Resources Assessment of Dominica, Antigua, Barbuda, St. Kitts and Nevis, report of the Mobile District & Topographic Engineering Center, United States Army Corps of Engineers, December 2004.

van de Wal, R.S.W., Boot, W., van den Broeke, M.R., Smeets, C.J.P.P., Reijmer, C.H., Donker, J.J.A. and Oerlemans, J. (2008). Large and Rapid Melt-Induced Velocity Changes in the Ablation Zone of the Greenland Ice Sheet Science, 321: 111-113.

Velicogna, I. and Wahr, J. (2006). Measurements of Time-Variable Gravity Show Mass Loss in Antarctica Science 311(5768):1754 – 1756.

Velicogna, I. (2009). Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. Geophysical Research Letters 36: L19503.

Vieli, A., and Payne, A.J. (2005). Modeling the grounding line migration of marine ice sheets, Journal of Geophysical Research 110: F01003.

Ware, J.R. (1997). The effects of global warming on corals reefs: acclimate or die. Proceedings of the 8th International Coral Reef Symposium, Panama 1: 527-532.

Water Resources Agency (2001), Integrating the Management of Watersheds and Coastal Areas in Trinidad and Tobago, National Report of the Water Resources Agency of Trinidad & Tobago prepared for The Ministry of the Environment, March 2001.

Water Resources Management Unit (2001), Integrating the Management of Watersheds and Coastal Areas in St. Lucia, Report of the Water Resources Management Unit, Ministry of Agriculture, Forestry and Fisheries, Government of St. Lucia, prepared for the Caribbean Environmental Health Institute (CEHI), July 2001.

West, J.M., and R.V. Salm. (2003). Resistance and resilience to coral bleaching: implications for coral reef conservation and management. Conservation Biology 17: 956-967.

Whelan, K.R.T., J. Miller, O. Sanchez, and M. Patterson. (2007). Impact of the 2005 coral bleaching event on Porites porites and Colpophyllia natans at Tektite Reef, US Virgin Islands. Coral Reefs 26(3): 689-693.

Wigley, T. (2007). MAGICC/SCENGEN: Model for Assessing Greenhouse-gas Induced Climate Change/A Regional Scenario Generator,, http://www.cgd.ucar.edu/cas/wigley/magicc/about.html

Wilkinson, C., and D. Souter [Eds.]. (2008). Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Townsville, Australia, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre. 152 p.

Wilkinson, C.R. (2000). Status of Coral Reefs of the World: 2000. Townsville, Australia, Australian Institute of Marine Science. 363 p.

Woody, K., A. Atkinson, R. Clark, C. Jeffrey, I. Lundgren, J. Miller, M. Monaco, E. Muller, M. Patterson, C. Rogers, T. Smith, T. Spitzak, R. Waara, K. Whelan, B. Witcher, and A. Wright. (2008). Coral bleaching in the U.S. Virgin Islands in 2005 and 2006. In C. Wilkinson, and D. Souter [Eds.], Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005. Townsville, Australia, Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre: 68-72.

World Bank. (2009). Convenient Solutions to an Inconvenient Truth: Ecosystem-based approaches to climate change, World Bank, Washington DC.

World Bank. (2000). Cities, Seas and Storms: managing change in Pacific islands Economies, Vol IV, Adapting to Climate change, Wold Bank, Washington D.C.

World Resources Institute. www.wri.org/publication/content/7863.

World Travel and Tourism Council -WTTC. (2008). WTTC Supports CARICOM Prioritization on Tourism. PRNewwire 13 March 2008. www.hispanicprwire.com/news.php?l=in&id=10940.

Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J. and Steffen, K. (2002). Surface melt-induced acceleration of Greenland ice-sheet flow. Science, 297: 218-222.

NOTE: All photographs are credited to The CARIBSAVE Partnership and AusAID.

Please note that a DVD was distributed at Copenhagen COP15 December 2009 with the 'Key Points' of the report. The DVD contains copies of the following:

1. An Overview of Modeling Climate Change Impacts in the Caribbean Region with contribution from the Pacific Islands: KEY POINTS

2. An Overview of Modeling Climate Change Impacts in the Caribbean Region with contribution from the Pacific Islands: SUMMARY DOCUMENT

3. 'The Burning Agenda: The Climate Change Crisis in the Caribbean', Short Film (30 minutes) Commissioned by the British Foreign and Commonwealth Office

'1.5 To Stay Alive', Song written and performed by the Barbadian performance poet Adisa 'AJA' Andwele.

These items and copies of the report , Summary Document and Key Points can be obtained via free download at www.caribsave.org

An Overview of Modelling Climate Change Impacts in the Caribbean Region with contribution from the Pacific Islands:

FULL REPORT

This report was commissioned by the United Nations Development Programme (UNDP) Sub-Regional Office for Barbados and the OECS, and by the UK Department for International Development (DFID), with support from Australia's International Climate Change Adaptation Initiative. The report was produced by The CARIBSAVE Partnership and authored by members of 15 key institutions around the world dealing with climate change.

This Report provides an overview for all CARICOM member states of the risks from climate change and includes a section on the common threats of climate change for Pacific island countries. The report focuses on: climate change projections for the Caribbean region under +1.5°C and +2°C global warming scenarios; the implications of ice sheet melt for global sea level rise (SLR); the projections and implications of SLR for the Caribbean region; evaluation of the differential impacts of +1.5°C and +2°C on coral reefs, water resources and agriculture in the Caribbean, with additional analysis for the Pacific islands.

United Nations Development Programme
December 2009

UNDP Barbados and the OECS
Energy and Environment Programme
UN House
Marine Gardens, Hastings
Christ Church, Barbados

+ 1 246 467 6000
reynold.murray@undp.org
www.bb.undp.org

CARICOM · CARIBBEAN COMMUNITY CLIMATE CHANGE CENTRE · DFID Department for International Development · caribsave · UNDP