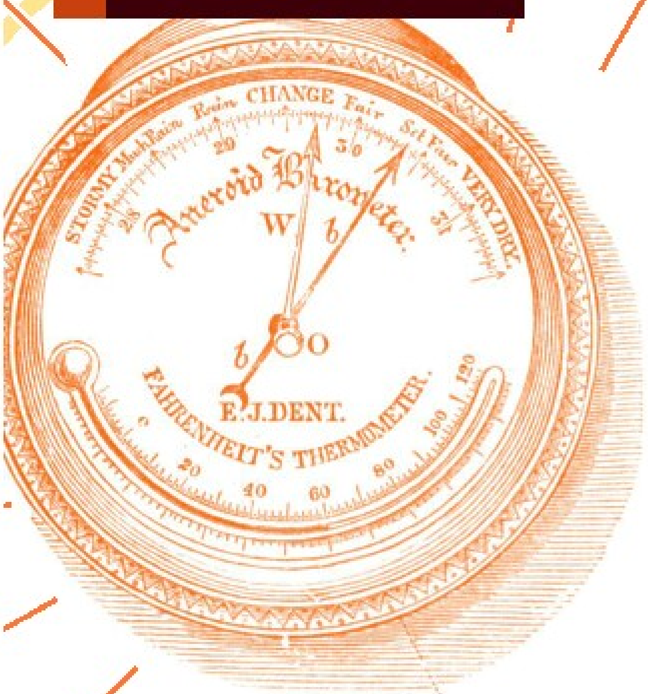
Climate Change &
Disaster Risk Reduction



CANARI

Caribbean Natural Resources Institute

Technical Report
No. 381

CLIMATE TRENDS AND SCENARIOS FOR CLIMATE CHANGE IN THE INSULAR CARIBBEAN

Report of Working Group I, Climate Change and Biodiversity in the Insular Caribbean

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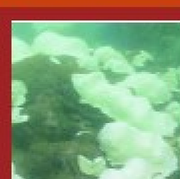
December 2008



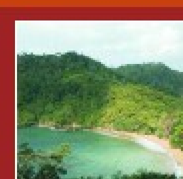


Table of Contents

Executive Summary

In March 2007 The Caribbean Natural Resources Institute (CANARI) launched the Climate Change and Biodiversity in the Caribbean (CCBIC) Project, which is funded by the John D. and Catherine T. MacArthur Foundation. The project focuses on increasing understanding and consensus on what is known, and perhaps more importantly what is not known, about the predicted climate change trends and their impact on biodiversity in Caribbean small island developing states. The goal is to develop a regional research agenda and capacity needs assessment to address identified gaps and to consider how protected area management, biodiversity protection, and conservation policy might address climate change in the region. Three working groups, focusing on coastal and marine biodiversity; terrestrial biodiversity; and the development of climate change scenarios and models, were convened to undertake the research required to assess the state of knowledge of the expected impacts of global climate change on Caribbean biodiversity, and to identify the gaps in our knowledge and the research required to fill these gaps. The findings of the climate change and scenario working group is given in this report.

The working group addressed 4 key problems outlined in Chapter 1:

- What baseline climate information, especially which included in climate databases, do we have for the Caribbean?
- What research has been done on climate variability and climate change in the Caribbean and what has been learnt?
- What is our present manpower and equipment capacity?
- What more do we need to know about climate change, especially as it relates to bio-diversity, and how can these needs be achieved?

Chapter 2 lists the datasets that exists for the Caribbean and provides information for accessing them. Chapter 5 points out the existing gaps and the need for putting in place ways of bridging the gaps. The gaps in this area include the need for increasing the density of meteorological stations, for daily station data of sufficient temporal length and for the measurement of climate variables other than the minimum dataset of precipitation, maximum and minimum temperature, all of which should be quality controlled. Additional variables could include sea surface temperature, soil moisture and concentration of atmospheric constituents. Derived information, such as, climate indices, should be store alongside these data. Furthermore legitimate users, such as researchers, should have easy access to these datasets. The report points to additional data in non-traditional archives (e.g. records of sugar plantations,

agricultural and hydrological bodies) and in non-digitised forms that are yet to be captured. There is also the need to acquire data from outside the region, e.g., detailed bathymetric maps of the Caribbean region. Mechanisms to fill these gaps include the introduction of protocol and agreements for the sharing and use of online facilities.

Chapter 3 outlines the present state of knowledge of climate and climate variability, and gives future climate scenarios, drawing from the 4th Assessment of the Intergovernmental Panel on Climate Change (IPCC) and the work of institutions within the region. A brief description of the methodologies of generating climate change scenarios and their limitations are given. These methodologies include General Circulation Models (GCMs), regional models and statistical downscaling. The latter offers potential for micro-scale biodiversity studies but require high quality daily data of long duration.

The range of temperature changes which can be expected over the present century is from just under 2º C to over 4º C. Under A1B Special Report Emission Scenario (SRES), a temperature rise of just below the global average of 2.8º C can be expected. It should be noted however that, if all the developed countries cut greenhouse gas emissions at the rate being proposed by the United Kingdom and France, then the temperature rise could be limited to just under 2º C. Under the A1B emission, precipitation can be expected to decrease in June, July and August by 2050's and sea level will continue rising, probably to the global average of about 0.21 to 0.48 meters by the end of the century, around the islands of the Caribbean. Globally, tropical cyclones will probably increase in intensity, but the distribution of the increase in intensity is uncertain.

The working group found that, although significant strides have been made in understanding Caribbean climate variability and change, and efforts have begun to generating region specific scenarios of future climate, gaps still remain (Chapter 5). These include:

- A need for further understanding of Caribbean climate variability, such as the low level jet, dry season dynamics, easterly wave dynamics and interactions.
- A need for investigation of local or sub regional climates and climate gradations.
- A need for further application of regional modelling techniques to downscaling climate change results for sub regions, territories, cities, towns, and station sites.
- A need for dialogue between climate researchers and scientists within the biodiversity sector, e.g., to quantify climatic variables, scales, and thresholds which would be needed for analysis of the impact of climate change on the sector.
- A need for a better understanding of sea level rise estimations due to global warming.

- A need for more region specific information/studies on deforestation, flooding, and the role of climate in determining such things as human settlements and international commerce.
- A need for a clearer understanding of the usefulness of the various types of climate data currently being archived for modelling biodiversity impacts, as well as the limitations and boundaries within which the data can/should be used.

Methods for filling the gaps include developing online mechanisms for storing and disseminating information, developing a Caribbean climate atlas, facilitating dialogue between climate researchers and scientists of other sectors such as biodiversity, supporting graduate student research and cross-disciplinary training.

Chapter 4 gives the existing manpower and technical capacity to undertake the generation of climate change scenarios and to assess and produce relevant climate analyses. The manpower is deemed to be adequate, but can be made more productive, while the technical capacity is inadequate but sufficient for many tasks. Chapter 5 lists the gaps in these areas. It notes the need for more interdisciplinary research. Presently there is a small, but growing, cadre of interdisciplinary researchers. The high cost of purchase, maintenance and calibration of meteorological instruments has resulted in a gradual deterioration of the meteorological network. The need for high performance computers and massive data storage systems makes it is difficult to give a detailed local forecast using currently installed capacity. To fill these gaps mechanisms are suggested, such as, investing in postgraduate training, supporting student exchanges within and outside of the region, support for staff education and training (e.g., at meteorological services), acquiring equipment and software to support climate research at existing organisations and institutions and updating meteorological infrastructure to ensure recording of quality data.

Chapter 1

Introduction

"At the global level, human activities have caused and will continue to cause a loss in biodiversity through, inter alia, land-use and land-cover change; soil and water pollution and degradation (including desertification), and air pollution; diversion of water to intensively managed ecosystems and urban systems; habitat fragmentation; selective exploitation of species; the introduction of non-native species; and stratospheric ozone depletion. The current rate of biodiversity loss is greater than the natural background rate of extinction. A critical question … is how much might climate change (natural or human-induced) enhance or inhibit these losses in biodiversity?" (Gitay et al, 2002.)

This question is being addressed by implementation of the *Climate Change and Biodiversity in the Insular Caribbean (CCBIC) Project.* One of the first steps, recognised by the CCBIC Steering Committee at its inaugural meeting in Trinidad in March 2007, was the establishment of Scenario and Modelling Working Group (WG I). The task of WGI was to provide "a summary of the state of knowledge and expertise for the development of climate change scenarios and models in support of the identification and assessment of expected impacts of global climate change on Caribbean on coastal and marine biodiversity, identifying the gaps in our knowledge, expertise, and capacities, and the measures that must be undertaken to fill these gaps" (CCBIC Guidance to Working Group Leaders). The members of WGI are:

- Prof. Anthony Chen, Climate Studies Group Mona (CSGM), Chairman
- Dr. Abel Centella, Instituto de Meteorologia (INSMET),
- Dr. David Farrell, Caribbean Institute of Meteorology and Hydrology (CIMH)
- Dr. Michael Taylor (CSGM)
- Mr. Arnoldo Benzanilla Morlot, Postgraduate Student (ISMET)
- Ms. Rhodene Watson, Postgraduate Student (CSGM)

CIMH, CSGM and ISMET and are leaders in climate variability and climate change studies in the Caribbean. CIMH (www.cimh.edu.bb), supported by sixteen Commonwealth Governments of the region, is a training and research organisation formed by the amalgamation of the Caribbean Meteorological Institute (CMI) and Caribbean Operational Hydrological Institute (COHI). CSGM (www.mona.uwi.edu/physics/Research/csg/intro.htm) was the first group in the English speaking Caribbean formed specifically to study climate variability and climate change in the region and has to its credit many publications on Caribbean climate in refereed journals. ISMET (www.met.inf.cu), founded in 1960's, is the foremost meteorological institute in the Spanish speaking Caribbean.

To address the task of WGI, 5 key problems were considered:

- What baseline climate information and existing climate databases do we have for the Caribbean? This is a necessary starting point in any climate study.
- What research has been done on climate variability and climate change in the Caribbean, and what has been learnt? How are climate change scenarios developed and what are the climate change scenarios for the Caribbean? To generate scenarios of future climate, it is necessary to know the climate processes at work and processes that change climate. Models that simulate climate and climate change have to be evaluated to determine if they capture actual climate processes and changes. This will assist in determining the validity of the scenarios generated.
- What is our present manpower and equipment capacity? This will determine our manpower and equipment needs.
- What more do we need to know about climate change, especially as it relates to bio-diversity and how can these needs be achieved?

These problems are respectively the subject of the following 4 chapters, Chapters 2 to 5, which will be followed by a concluding statement in Chapter 6. Appendix 1 gives a list of datasets with Caribbean data and Appendix 2 contains an extensive bibliography of English publications relating to climate. This is in addition to references which are given at the end of each chapter. CD's containing climatologies of some stations, listed in Chapter 2, have also been made available to CANARI.

The chapters are joint work of the 2 postgraduate students, who conducted the initial literature survey, and of the working group members, who amplified the submissions of the postgraduate students based on their expertise and experience. A working group meeting was held mid-way during the process to assess the work of the postgraduate students and to give additional guidance. The climatology and climate databases in Chapter 2 are based on the experience of the Heads of CIMH, which is the repository of all meteorological data in the English speaking Caribbean and of ISMET. The future climate scenarios from the Intergovernmental Panel on Climate Change (IPCC), which are discussed in chapter 3, are based on the experience of one of the working group member as one of the lead authors for Chapter 11, Regional Projections, of the IPCC 4th Assessment team. The remaining 3 chapters are based on the working knowledge of three of the working group members who are actively engaged in regional climate modelling and statistical downscaling for the Caribbean. Chapter 3, *Present Understanding, Future Scenarios of Caribbean Climate and Related Studies,* is the longest chapter. It discusses our knowledge of climate processes and climate variability, describes climate models, gives future scenarios and outlines the variety of work being done in Cuba on climate related issues. The sections marked with asterisks in this chapter can be considered supplemental material and are included for special interests.

Reference

Gitay, H., A. Suárez, R. Watson and D.J. Dokken (eds.) 2002: Climate Change and Biodiversity, IPCC Technical Paper V.

Chapter 2

<u>Baseline Data and Climate</u>

Introduction

Future climate change and climate variability are expected to have far-reaching effects on the economy, health, biodiversity and way of life in all nations. However, mid-latitude and tropical islands have characteristics which make them particularly vulnerable to changes in climate, sea-level rise and extreme events (IPCC, 2007). The Caribbean region with its small developing low-lying islands and in some cases climate dependent economies faces significant challenges with respect to climate change and climate variability. Current knowledge of climate change and climate variability and their potential effects in the Caribbean are limited due to the few studies and data available for the region. This situation has lead to considerable speculation.

Research on climate change and climate variability in the Caribbean focuses on (i) bounding the magnitude of change in key climatic variables such as daily and seasonal changes in precipitation characteristics, temperature, relative humidity, evaporation rates, sea-level rise, and changes in the characteristics of extreme events, and (ii) development and implementation of adaptation strategies to mitigate the impact of climate change and climate variability on socio-economic development at the local, national, and regional levels. Information from these studies is expected to inform local, national, and regional policies related to sustainable development.

Research as outlined above requires a significant amount of historical data and new data from existing and/or new networks. The focus of this chapter is to summarise the baseline climate information and databases for the Caribbean region. Note that particular emphasis will be paid to the English-speaking Caribbean and Cuba.

Baseline Data for Climate Studies

<u>Data set of climatology (rainfall, temperature, wind speed and direction, radiation, etc) Annual, Monthly, Max and Min Temp.</u>

Several sources of climate data [e.g., precipitation (intensity and duration), temperature (daily maximum and minimum), wind speed, direction, radiation, relative humidity among others] exist for the Caribbean region. The climate parameters contained in these data sets vary with some data sets containing more parameters than others. In addition, some data sets contain unprocessed data where as other data sets contain processed data. These data sets and their availability are summarised below and additional information is provided in Appendix 1.

- *Caribbean Institute for Meteorology & Hydrology (CIMH)*

CIMH maintains a climatology database that contains data recorded at stations maintained by National Meteorological Services (NMS) that are members of the Caribbean Meteorological Organisation (CMO) [Anguilla, Antigua & Barbuda, Barbados, St. Lucia, St. Vincent & the Grenadines, Dominica, Guyana, Grenada, Trinidad & Tobago, Jamaica, St. Kitts & Nevis, Belize, the British Virgin Islands, the Cayman Islands, Montserrat, and the Turks and Caicos Islands] as well as other stations in these countries deemed to provide data of good quality that meets WMO specified standards. CIMH performs quality assurance checks on the data prior to making it available to the public.

Parameters contained in the CIMH database include daily temperature, pressure, relative humidity, precipitation, cloud, and wind speed and direction. In several cases, the data sets are incomplete due to instrument failure and failure of the NHS to forward the data to CIMH. In some cases, the NMSs have a more comprehensive database than CIMH, however, much of this data is in notebooks and has not been converted to electronic form. The CIMH has developed a proposal to support rescuing much of the hard copy data from the various NMSs. The proposal is being circulated to various funding agencies.

Data contained in the database is available at no cost for academic applications, however, a fee is changed to commercial customers. Data contained in the CIMH monthly summaries is available directly from CIMH in hard copy form (1972-2004). These datasets are currently being scanned and posted to the CIMH webpage (http://www.cimh.edu.bb). A list of stations currently stored at CIMH is available at http://www.cimh.edu.bb/datainv.htm. In addition, data can be obtained directly from NMSs who may have data for stations not present in the CIMH database. Electronic data at most NMSs in the Caribbean are stored in CLICOM and/or CLIDATA.

- *Caribbean Climate Interactive Database (CCID)*

The CCID database consists of daily and monthly station data for various Caribbean islands in the period 1935 – 2000. The variables available are minimum temperature, maximum temperature and precipitation. The raw data or time series of monthly averages, climatologies, standard deviations, and anomalies may be viewed and saved. In addition correlations and scatter-plots of variables may also be obtained. The data is available free of cost and can be obtained by sending a request to Dr. Michael Taylor in the Department of Physics, University of the West Indies, Mona at michael.taylor@uwimona.edu.jm.

- *Universidad Nacional Autonoma de Mexico (UNAM):*

UNAM provides monthly temperature (maximum and minimum) and precipitation data on 0.5^o x 0.5^o grid that extends from 140^o W to 59^o W and from 4.75^o N to 45.25^o N. The data time series extends from 1901 to 2002. Sources of the data used to develop the gridded dataset are daily station precipitation and temperature from CLICOM (for Mexico) and the Global Historical Climatology Network (GHCN). Given the sizes of the islands of the eastern Caribbean, the grid resolution is quite coarse. In addition, the quality of the gridded data relies on the spatial locations of the sources of data, the interpolation methods used to develop the grid, and the quality assurance methods employed at the measurement locations.

More information is available at http://iridl.ldeo.columbia.edu/SOURCES/.UNAM/.gridded/.monthly/.v0705/.dataset_documentation.html

- *Climate Research Unit (CRU):*

The Climate Research Unit (CRU) at the University of East Anglia is one of the most popular sources of global climatic data and is often cited in major publications on climate. The CRU provides monthly data at several grid resolutions with the highest resolution being on a 0.5^o x 0.5^o grid that includes the Caribbean. The data time series extends from 1901 to 2000.

Climate parameters available from CRU include temperature (maximum, minimum, mean, and range), precipitation, wet days, water vapour, and cloud.

More information on CRU is available at http://www.cru.uea.ac.uk/

- *Climate Prediction Center (CPC) Global Climate Data and Maps*

The Climate Prediction Center Global Climate Data and Maps contains maps and time series for precipitation and surface temperatures for Africa, Asia, Europe, South and Central America, Mexico, Caribbean, Australia, and New Zealand.

Monitoring Weather and Climate

CPC monitors weather and climate in real time with the aid of satellite animations, conventional rain-gauge observations and global analyses of the atmospheric state. CPC also has available time series of accumulated actual daily precipitation and accumulated normal precipitation both of which are available on a daily basis and can be viewed on 5^o x 5^o grids over the Americas.

Global Regional Climate Maps

CPC also provides weekly maps of total precipitation and temperature (maximum and minimum) as well as departures from the norm. Monthly and 3 month maps are also available.

Global Precipitation Time Series

CPC provides observed precipitation time series showing observed versus actual for selected cities around the work for the last 30, 90 and 365 days.

Global Temperature Time Series

CPC provides observed temperature time series showing observed versus actual for selected cities around the work for the last 30, 90 and 365 days.

More information on CPC is available from http://www.cpc.noaa.gov/products/monitoring_and_data/restworld.shtml

- *International Research Institute for Climate and Society (IRI)*

IRI/LDEO Climate Data Library has available over 300 datasets from a range of earth science disciplines and climate related topics. The data includes the NCEP reanalysis database, outputs from IPCC assessment models, NCEP Climate Forecast System, and NCEP CPC constructed analogue sea surface temperature forecasts among others. Information summarising the contents of the IRI/LDEO Climate Library is available at http://iridl.ldeo.columbia.edu and http://iridl.ldeo.columbia.edu/SOURCES.

- *National Centers for Environmental Protection (NECP) Operational Analysis*

NCEP provides a range of climate data products to the public. The global products dataset includes precipitation and temperature which are updated twice daily. In addition to these products, NCEP also provides reanalysis data 4 times per day for a range of meteorology parameters.

- *Global Climate Observation System (GCOS)*

GCOS is intended to be a long-term operational system. GCOS addresses the total climate system including physical, chemical and biological properties as well as its atmospheric, oceanic, terrestrial, hydrologic, and cryospheric components. GCOS provides comprehensive operations required for:

- Monitoring the climate system
- Detecting and attributing climate change
- Assessing inputs of, and supporting adaptation to, climate variability and change

- Applications to national economic development
- Research to improve understanding, modelling and prediction of the climate system

More information on GCOS is available at http://www.wmo.ch/pages/prog/gcos/index.php

- *Cuba's Climate Data*

A database of precipitation, maximum and minimum temperature, relative humidity and wind speed and direction exists for 68 stations on Cuba. These stations have in general at least 30 years of daily and tri-hourly data with some stations having time series that go back 100 years. Most stations have not been moved from their original location and those that were moved have had correction factors applied to the data to account for the relocation. All of the meteorological data for Cuba has been digitised and a quality control process implemented to minimise errors.

In addition to the measurement of standard meteorological parameters, specialised meteorological stations exist that provide solar radiation, upper-air data, agro-meteorological and air quality and pollution.

The Center of Climate is in charge of storing and processing all the climate data and has the necessary software and hardware resources to deal with this task efficiently.

More information on climate data and climate studies in Cuba can be obtained at http://www.met.int.inf.cu

Climatologies

Excel worksheets containing tables and graphs of monthly average values of rainfall and minimum and maximum temperatures are provided in a CD at the back of this report[1] for the following countries:

Anguilla:	Wallblake Airport
Bahamas:	Freeport
Barbados:	CIMH, Grantley Adams Airport
Belize:	Central Farm, Pswgia
Cayman:	Owen Roberts Airport
Dominican Republic:	Santo Domingo
Dominica:	Canefield and Melville
Grenada:	PSIA

[1] The CD is provided only in the reports submitted to CANARI.

Jamaica:	Sangsters Airport, Norman Manley Airport, Worthy Park
Monsterrat:	WH Bramble Airport
St. Lucia:	Hewanorra Airport
St. Vincent:	ET Joshua Airport
Trinidad:	Piarco Airport
US Virgin Island:	Coral Bay, Cruz Bay

Reference

IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate 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.

Chapter 3

Present Understanding, Future Scenarios of Caribbean Climate and Related Studies

Average Behaviour or Climatology

The Caribbean climate has been concisely described by Taylor and Alfaro (2005). It can be broadly characterised as dry winter/wet summer with orography and elevation being significant modifiers on the sub regional scale. The dominant synoptic influence is the North Atlantic subtropical high (NAH). During the winter, the NAH is southernmost with strong easterly trades on its equatorial flank. Coupled with a strong trade inversion, a cold sea surface temperature (SST) and reduced atmospheric humidity, the region generally is at its driest during the winter. Precipitation during this period is due to the passage of mid-latitude cold fronts. With the onset of the spring, the NAH moves northward, the trade wind intensity decreases, the sea becomes warmer and the southern flank of the NAH becomes convergent. Concurrently easterly waves traverse the Atlantic from the coast of Africa into the Caribbean. Easterly waves frequently mature into storms and hurricanes under warm sea surface temperatures and low vertical wind shear generally within a 10ºN-20ºN latitudinal band referred to as the *main development region*. They represent the primary rainfall source and their onset in June and demise in November roughly coincides with the mean Caribbean rainy season. Around July a temporary retreat of the NAH towards the equator is associated with diminished rainfall known as the mid-summer drought. Enhanced precipitation follows the return of the NAH and the passage of the Inter Tropical Convergent Zone (ITCZ) northward. The passage of cold front from mid-latitudes is responsible for much of the rainfall in the dry season (December to March). Air temperature tends to follow the sun, or more precisely the variation in solar insolation. Below about 15ºN, this variation results in a bi-modal temperature peak. The timing of the processes is illustrated graphically for Jamaica in Fig. 1, and for Trinidad and Tobago in Fig. 2.

Fig. 1 The timing of climatology processes for Jamaica (NAH refers to North Atlantic High pressure system; SST, Sea Surface Temperature; ITCZ, Inter-tropical Convergence Zone)

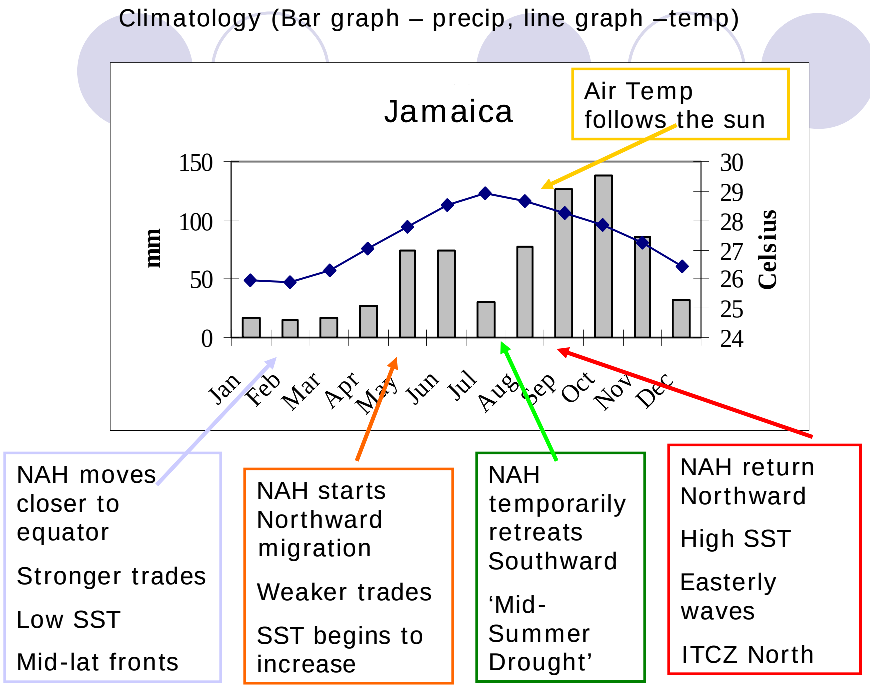
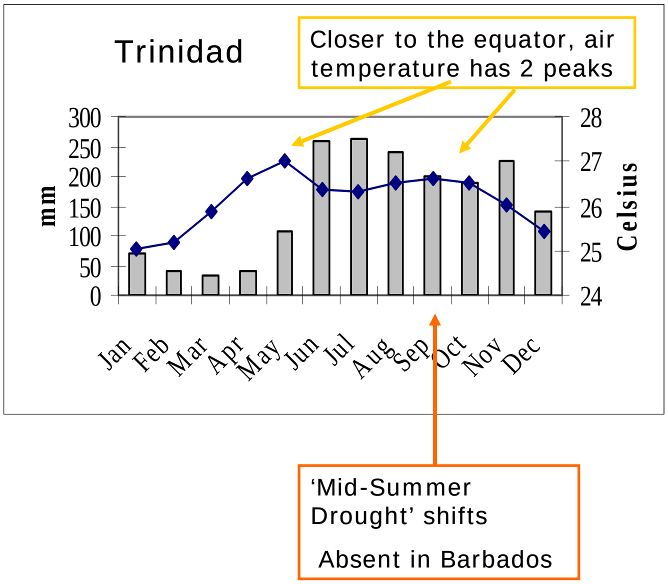


Fig. 2 The climatology for Trinidad, same as for Jamaica but the Mid-Summer Drought occurs later and 2 peaks in air temperature are evident.



'For small islands, differences in size, shape, topography and orientation with respect to the trade wind influence the amount of rainfall received by the various islands. Cuba, Jamaica, Hispaniola and Puerto Rico, the larger and more mountainous islands of the Greater Antilles, receive heavier rainfall at higher elevations, with a rain-shadow effect on their southern coasts which are distinctively arid. The smaller islands to the east tend to receive less rainfall, but are still well watered. For this region, rainfall totals generally increase going southward. The dry belt of the Caribbean is found over the southwestern islands of the Netherlands Antilles.'

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Climate Variability

The dominant mode of variability in precipitation in the dry season (December to March) is associated with the El Niño Southerly Oscillation[2] (ENSO) signal (Stephenson et al, 2007) with precipitation anomalies behaving oppositely in the north and south Caribbean. The south-eastern Caribbean becomes drier than normal in response to a warming ENSO (or El Niño) signal because a shift in atmospheric circulations (Hadley and Walker circulations).

[2] The term *El Niño* was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Perú, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation.

The early rainfall season (May to July) is anomalously wet during the year after an El Nino event, and anomalously drier during a La Nina event (Chen et al, 1997, Giannini et al., 2000, Chen and Taylor, 2002, Taylor et al, 2002, Spence et al., 2004, Ashby, 2005) due to warmer and colder than normal sea surface temperatures respectively. Again, the variation in sea surface temperature is due to shifts in atmospheric circulations during these events (Wang and Enfield, 2001). The warmer SST is referred to as 'warm pool' in the literature.

The late rainfall season (August, September, October, November) tends to be drier in El Niño years and wetter in La Niña years (Giannini et al., 2000, Martis et al., 2002, M. Taylor et al., 2002, Spence et al., 2004, Ashby et al., 2005, Jury et al., 2007) and tropical cyclone activity diminishes over the Caribbean during El Niño summers (Gray, 1984).

The phase of the North Atlantic Oscillation (NAO), which consists of opposing variations of barometric pressure near Iceland and near the Azores, modulates the behaviour of warm ENSO events mentioned above (Giannini et al., 2001). A positive NAO phase implies a stronger than normal NAH and amplifies the drying during a warm ENSO. On the other hand, a negative NAO phase amplifies the precipitation in the early rainfall season in the year after an El Niño.

Other works[*] on the climatology of the Caribbean include those of **Lecha et al., (1987**) and **González (1999),** which had the objective of making a statistical study of different climate phenomena and their influence on the general climate of the Caribbean**.** Climatologies of cold fronts, extreme events like heavy rain and tornadoes and phenomena such as drought have been studied by **Alvarez et al., (2006), Centella et al., (1997) and Björn and Amos (1999)**. Studies on choosing the right properties of the time series and the implications for describing the climatologic conditions for forecasting have been made by **Gay et al., (2007**).

Climate Trends

Global temperatures have increased by about 0.74˚C (0.56˚C to 0.92˚C) since the 19th century (IPCC, 2007). There has been a warming trend globally with minimum temperatures increasing at a higher rate than maximum from 1950-2001 (Alexander et al., 2006). An increasing trend in both variables is also observed for the Caribbean region by Peterson et al., (2002). They used ten globate climate indices to examine changes in extremes in Caribbean climate from 1950 to 2000. They found that the difference between the highest and lowest

[*] Supplemental Material

temperature for the year is decreasing but is not significant at the 10% significant level. Temperatures falling at or above the 90th percentile are increasing while those at or below the 10th percentile are decreasing (both significant at the 1% significant level). These results indicate that the region has experienced some warming over the past fifty years. Thus, there is a general warming trend with the number of very warm days and nights increasing while the number of very cool days and nights has been steadily decreasing over the same time period.

Two of the precipitation indices used by (Peterson et al. 2002) showed significant changes, the greatest 5 day rainfall total is increasing (10% significance level) while the number of consecutive dry days has decreased (1% significant level). However, the results may not take into account differing behaviour in precipitation in the North and South Caribbean. Using several observed data sets, Neelin et al., (2006) noted a modest but statistically significant drying trend for the Caribbean's summer period in recent decades.

Studies carried out in Cuba have demonstrated the existence of important climate variations in the country and in the region (**Naranjo and Centella, 1998; Lapinel et al, 2002 and Álvarez, 2006**). Major trends of the increase of the annual mean temperature in 0.5 C, an increase in the frequency of impact of extreme climate events, such as, intense rains and severe local storms, characterise the climate of the second half of the 20th century in Cuba**.** The frequency of drought events has also increased significantly, while the hurricanes that affect Cuba show a secular tendency to reduction. It has been demonstrated that these variations are consistent with the increase in the atmospheric circulation in the region and with the increase in the influence of El Niño Southern Oscillation (ENSO) event, which plays an important role as a forcing element of climate variability in Cuba. Cuba's climate behaviour during the last 4 decades is consistent and suggests the existence of an important variation in the decade of the 70's.

Climate Models, Generation of Climate Scenarios

A climate change scenario is a coherent and internally consistent description of the change in climate by a certain time in the future, using specific modelling techniques and under specific assumptions about greenhouse gas emissions and other factors that may influence climate in the future. The future time refers to longer periods than that considered when looking at climate variability, which refers to changes in patterns (e.g. precipitation patterns) from one season or one year to another. However, a climate change scenario cannot be regarded as a forecast of what the climate will be in the future, as we cannot forecast so far into the future what the emissions will be. Such a scenario simply tells us what the climate may look like in the future under certain conditions.

Scenarios can be generated using Atmospheric Global Climate Models (GCM), Coupled Atmospheric-Ocean Global Climate Models (AOGCM) which give coarse results over a large grid (~ 4° lat x 4° long), and Regional Models, which have a smaller scale of approximately 50km. These models are referred to as dynamic models since they consider the dynamic processes mentioned in the previous section. Current temperature, pressure, relative humidity and winds are used as inputs into these models and many projections for atmospheric parameters, stepped in time (e.g. for 2025 2050, 2080 and 2100), are generated as outputs. Another technique used for generating the scenarios is referred to as statistical downscaling. The aim of statistical downscaling is to generate the climate scenarios for a small region or even a point such as a weather station, using the output of a dynamic model for a larger region; hence the term downscaling. The process consists of generating and validating regression equations for the climate parameters to be downscaled. The regression equations are called predictands. Climate predictors, such as surface temperatures, pressure and vertical velocity, are available from data sets, such as the National Centre for Environmental Prediction (NCEP) re-analysis dataset. These regression equations are then employed to find scenarios of future climate for the small region by using future values of the predictors generated by the dynamic model[3]. All models must be validated by comparing their simulation of current or past climate with current or past climate data.

General Circulation models can be used to study climate change in the Caribbean region as a whole. For finer resolution, e.g., studying an individual island, a region model with resolutions of 25 to 50 km would be required. For studies of smaller areas, e.g., biodiversity around a station, statistical downscaling would have to be used. The statistical method however requires an input of a long time series of daily data, preferably of at least 30 years duration. This method however is versatile in terms of the parameters that can be related to climate. For example, if vegetation growth rate were related to relative humidity and a dataset of daily relative humidity were available, it would be possible to use the statistical method to generate scenarios of growth rate.

Future Climate Scenarios - IPCC Projections[*]

IPCC Scenarios of temperature change and percentage precipitation change between 1980 to 1999 and 2080 to 2099 for the Caribbean are based on the coordinated set of climate model simulations archived at the Program for Climate Model Diagnosis and Intercomparison[4]

[3] Reproduced from Chen et al (2006).
[*] Supplemental Material
[4] See http://www-pcmdi.llnl.gov/

(PCMDI); subsequently called the multi-model data set or MMD. The results of the analysis using A1B Special Report Emission Scenario - SRES (Nakićenović and Swart, 2000) are summarised in Table 1 (Christensen et al., 2007). A small value of T (column 8 for temperature and column 14 for precipitation) implies a large signal-to-noise ratio and it can be seen that, in general, the signal-to-noise ratio is greater for temperature than for precipitation change, so that the temperature results are more significant. The probability of extreme warm seasons is 100% (column 15) in all cases and the scenarios of warming are all very significant by the end of the century.

Table 1. *Regional averages of temperature and precipitation projections from a set of 21 global models in the MMD for the A1B scenario. The mean temperature and precipitation responses are first averaged for each model over all available realisations of the 1980 to 1999 period from the 20th Century Climate in Coupled Models (20C3M) simulations and the 2080 to 2099 period of A1B. Computing the difference between these two periods, the table shows the minimum, maximum, median (50%), and 25 and 75% quartile values among the 21 models, for temperature (°C) and precipitation (%) change. Regions in which the middle half (25–75%) of this distribution is all of the same sign in the precipitation response are coloured light brown for decreasing precipitation. T years (yrs) are measures of the signal-to-noise ratios for these 20-year mean responses. They are estimates of the times for emergence of a clearly discernible signal. The frequency (%) of extremely warm, wet and dry seasons, averaged over the models, is also presented. Values are only shown when at least 14 out of the 21 models agree on an increase (bold) or a decrease in the extremes. A value of 5% indicates no change, as this is the nominal value for the control period by construction.*

	Temperature Response (°C)							Precipitation Response (%)						Extreme Seasons (%)		
Region[a]	Season	Min	25	50	75	Max	T yrs	Min	25	50	75	Max	T yrs	Warm	Wet	Dry
CAR	DJF	1.4	1.8	2.1	2.4	3.2	10	-21	-11	-6	0	10		100	2	
	MAM	1.3	1.8	2.2	2.4	3.2	10	-28	-20	-13	-6	6	>100	100	3	18
10N,85W	JJA	1.3	1.8	2.0	2.4	3.2	10	-57	-35	-20	-6	8	60	100	2	40
to	SON	1.6	1.9	2.0	2.5	3.4	10	-38	-18	-6	1	19		100		22
25N,60W	Annual	1.4	1.8	2.0	2.4	3.2	10	-39	-19	-12	-3	11	60	100	3	39

Temperature

Table 1 shows that the MMD-simulated annual temperature increases at the end of the 21st century range from 1.4°C to 3.2°C with a median of 2.0°C, somewhat below the global average. Fifty percent of the models give values differing from the median by only ±0.4°C. The results are represented graphically in Fig. 3 which gives monthly changes in temperature. There were no noticeable differences in monthly changes.

The temporal evolution of temperature as simulated by the MMD models for the 20th and 21st centuries is also shown in Fig. 4 for the Caribbean (CAR). In general, it can be seen, by comparison with Box 11.1, Figure 1 of Christensen et al., (2007) that the temperature increases for the Caribbean are less than for the continental regions. The almost linear nature of the evolution is also apparent in the figure.

Statistical downscaling of a global model, HadCM3, results using the A2 and B2 SRES emission scenarios gives around a 2°C rise in temperature by the 2080s, approximately the same as the HadCM3 model. The agreement between the global model and the downscaling analysis gives a high level of confidence in the temperature simulations. The downscaling was performed with the use of the Statistical Down Scaling Model (SDSM) developed by Wily et al. (2002) as part of an Assessments of Impacts and Adaptations to Climate Change in Multiple Regions and Sector (AIACC) Small Island States SIS06 project (http://www.aiaccproject.org and Chen et al., 2006). Angeles et al. (2007) also simulate an approximately 1°C rise in SST up to the 2050s using the IS92a scenario.

Fig. 3 Monthly temperature change (º C) from 1980-1999 to 2080-2099 obtained from MMD models using the SRES A1B scenario for the Caribbean (CAR). The distribution gives the median (dark line), half the model values between the 25% and 75% quartile (dark shading) and the remaining up to the maximum and minimum values (light shading).

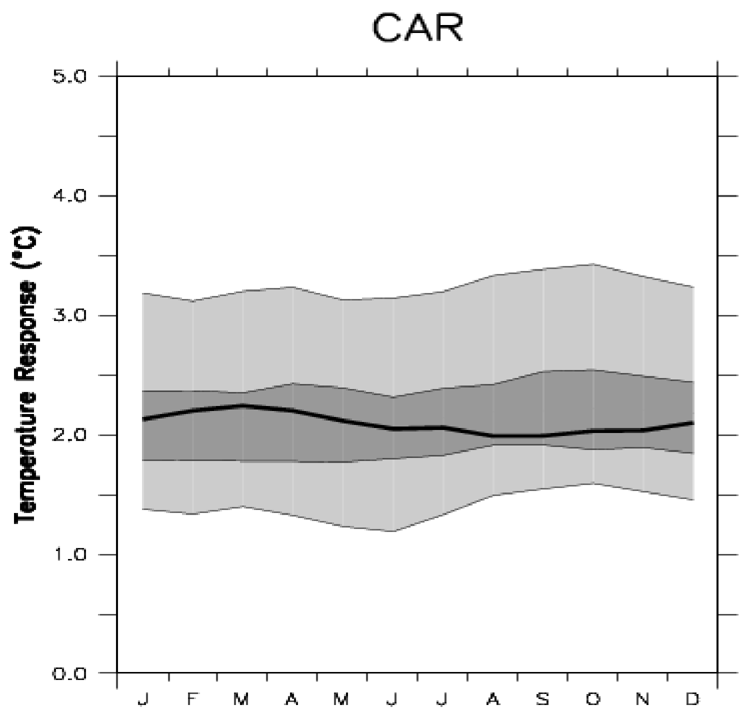
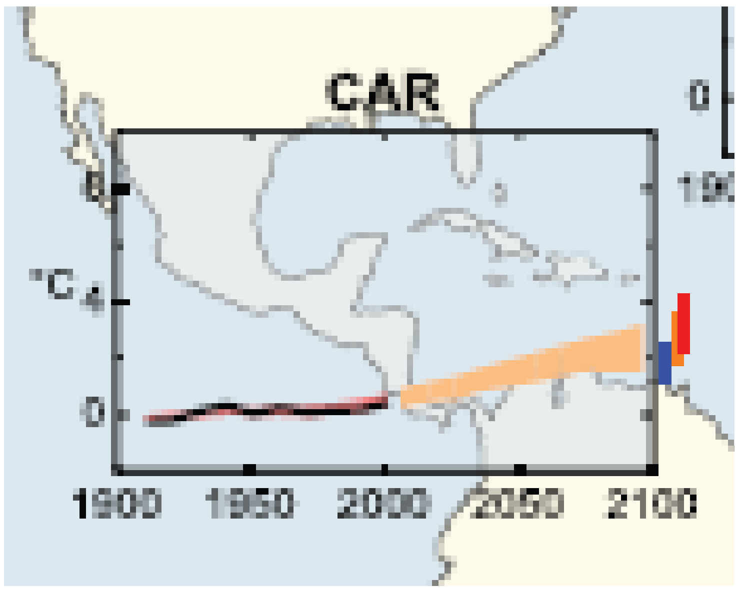


Fig. 4. Temperature anomalies with respect to 1901 to 1950 for the Caribbean region for 1906 to 2005 (black line) and as simulated (red envelope) by MMD models incorporating known temperature forcings; and as projected for 2001 to 2100 by MMD models for the A1B scenario (orange envelope). The bars at the end of the orange envelope represent the range of projected changes for 2091 to 2100 for the B1 scenario (blue), the A1B scenario (orange) and the A2 scenario (red).



Precipitation

According to Table 1, most models project decreases in annual precipitation and a few increases, varying from –39 to +11%, with a median of –12%. Figure 5 shows that the annual mean decrease is spread across the entire region (left panels). In December, January and February (DJF), some areas of increases are noted (middle panels) and in June, July and August (JJA), the region-wide decrease is enhanced, especially in the region of the Greater Antilles, where the model consensus is also strong (right panels).

Monthly changes in the Caribbean are shown in Fig. 6. Results from HadCM3 downscaled for the A2 and B2 emission scenarios using the SDSM also show a near-linear decrease in summer precipitation to the 2080s for a station in Jamaica (Chen et al., 2006). Downscaled results from the SDSM for stations in Barbados and Trinidad, however, show increases rather than decreases. Thus, there is consensus between the MMD results and the downscaled results for the Greater Antilles in JJA but not for the other islands, and also not on an annual basis. Angeles et al. (2007) also simulate decreases up to the middle of the century in the vicinity of the

Greater Antilles but not in the other islands in the late rainfall season. Table 1 shows that the decrease in JJA has the largest signal-to-noise ratio. The decrease is in agreement with the expected drying in the subtropics due to moisture in these regions being pulled into the convergent regions of the ITCZ (Held & Soden, 2006, Neelin et al., 2006, Chou & Neelin, 2004).).

Fig. 5 Precipitation changes over the Caribbean from the MMD-A1B simulations. Top row: Annual mean, DJF and JJA fractional precipitation change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Bottom row: number of models out of 21 that project increases in precipitation.

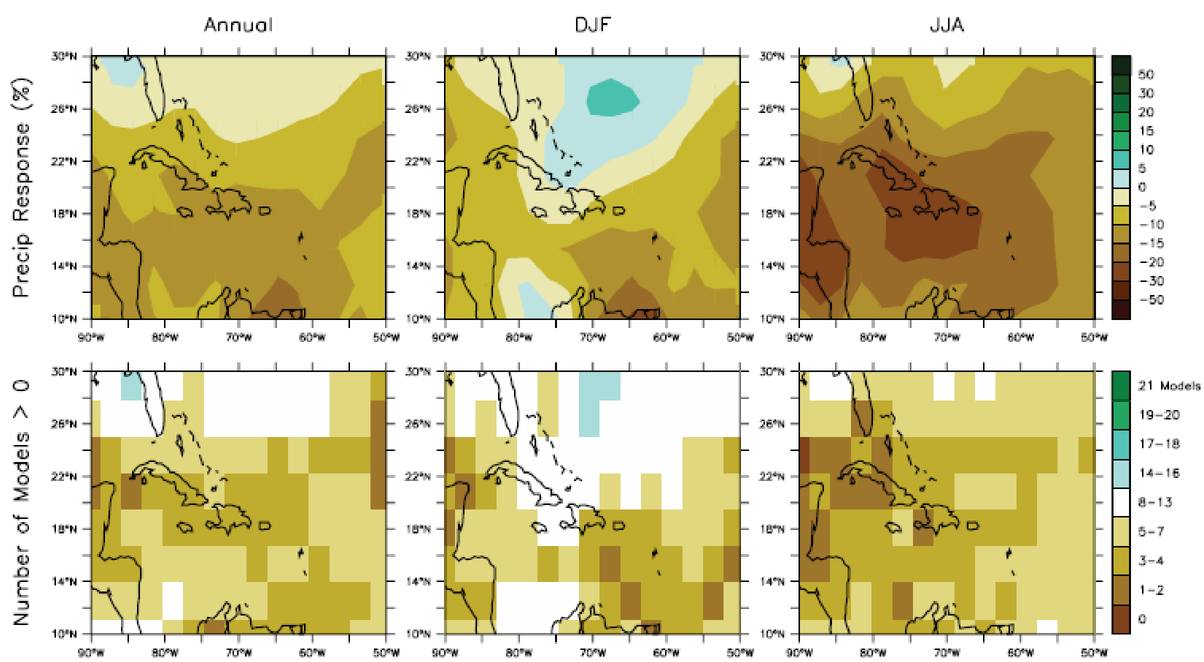
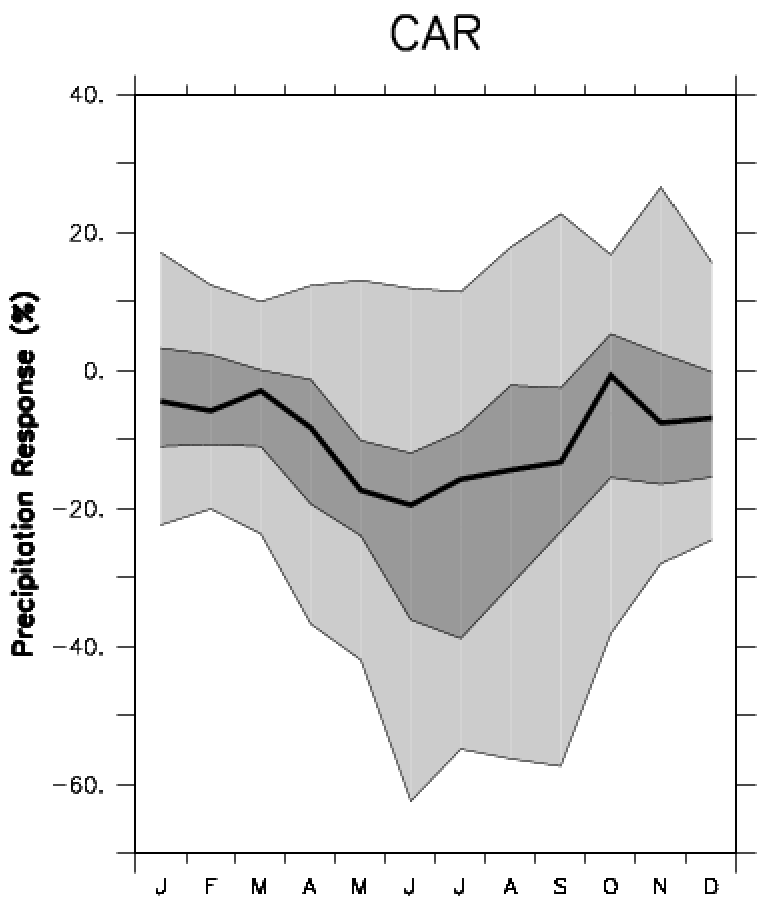


Fig. 6 As for Fig. 3 but for precipitation change (%).

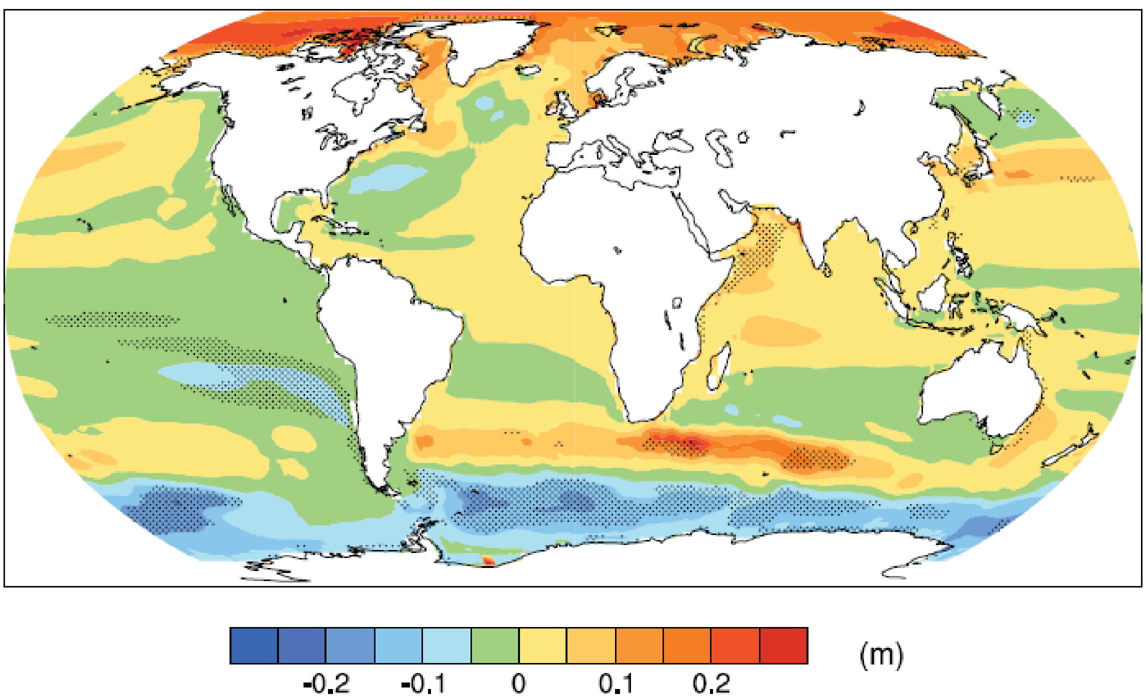


In the multi-model analysis, most models show shift to a more positive phase of the NAO, and consensus on temperature changes in the Pacific indicates an El Niño-like pattern with higher temperatures in the eastern Pacific (Meehl et al, 2007). These conditions are associated with drying in the Caribbean. Observed trends in precipitation are unclear. While Peterson et al. (2002) find no statistically significant trends in mean precipitation amounts from the 1950s to 2000, Neelin et al. (2006) note a modest but statistically significant summer drying trend over recent decades in the Caribbean in several observational data sets.

<u>Sea Level Rise</u>

Global sea level is projected to rise between the present (1980–1999) and the end of this century (2090–2099) by 0.35 m (0.23 to 0.47 m) for the A1B scenario (IPCC, 2007). Due to ocean density and circulation changes, the distribution will not be uniform. However, large deviations among models make estimates of distribution across the Caribbean uncertain. The range of uncertainty cannot be reliably quantified due to the limited set of models addressing the problem. Figure 7 gives the local sea level change in meters due to ocean density and circulation change relative to the global average during the 21st century (Meehl et al, 2007). The changes in the Caribbean are expected to be near the global mean. This is in agreement with observed trends in sea level rise from 1950 to 2000, when the rise in the Caribbean appeared to be near the global mean (Church et al., 2004),

Figure 7. Local sea level change (m) due to ocean density and circulation change relative to the global average (i.e., positive values indicate greater local sea level change than global) during the 21st century, calculated as the difference between averages for 2080 to 2099 and 1980 to 1999, as an ensemble mean over 16 AOGCMs forced with the SRES A1B scenario. Stippling denotes regions where the magnitude of the multi-model ensemble mean divided by the multi-model standard deviation exceeds 1.0.



Hurricanes

Fewer models have simulated tropical cyclones in the context of climate change than those simulating temperature and precipitation changes and sea level rise, mainly because of the computational burden associated with the high resolution needed to capture the characteristics of tropical cyclones. Accordingly, there is less certainty about the changes in frequency and intensity of tropical cyclones on a regional basis than for temperature and precipitation changes. A synthesis of the model results to date indicates that, for a future warmer climate, coarse-resolution models show few consistent changes in tropical cyclones, with results dependent on the model, although those models do show a consistent increase in precipitation intensity in future storms. Higher-resolution models that more credibly simulate tropical cyclones project some consistent increase in peak wind intensities, but a more consistent projected increase in mean and peak precipitation intensities in future tropical cyclones. There is also a less certain possibility of a decrease in the number of relatively weak tropical cyclones, increased numbers of intense tropical cyclones and a global decrease in total numbers of tropical cyclones (Meehl et al, 2007).

In an experiment with a high resolution global 20-km grid atmospheric model, Oouchi et al., (2006). was able to generate tropical cyclones that begin to approximate real storms. The model was run in time slice experiments for a present-day 10-year period and a 10-year period at the end of the 21st century for the A1B scenario to examine changes in tropical cyclones. In that study, tropical cyclone frequency decreased 30% globally, but increased about 34% in the North Atlantic. The strongest tropical cyclones with extreme surface winds increased in number while weaker storms decreased. The tracks were not appreciably altered, and maximum peak wind speeds in future simulated tropical cyclones increased by about 14% in that model, although statistically significant increases were not found in all basins. The competing effects of greater stabilisation of the tropical troposphere (less storms) and greater SSTs (the storms that form are more intense) likely contribute to these changes except for the tropical North Atlantic where there are greater SST increases than in the other basins in that model. Therefore, the SST warming has a greater effect than the vertical stabilisation in the Atlantic and produces not only more storms but also more intense storms there. However, these regional changes are largely dependent on the spatial pattern of future simulated SST changes (Yoshimura et al., 2006).

Analysis of observed Tropical cyclones in the Caribbean and wider north Atlantic Basin show a dramatic increase since 1995. This increase however has been attributed to the region being in the positive (warm) phase of a multi-decadal signal and not necessarily due to global warming

(Goldenburg et al., 2001). Results per year obtained from Goldenburg et al. have shown that during the negative (cold) phase of the oscillation the average number of hurricanes in the Caribbean Sea was 0.5 per year with a dramatic increase to 1.7 per year during the positive phase. While attempts have been made to link warmer SSTs with this increase in numbers, these have proven to be inconclusive, (Peilke et al., 2005). In a study to further examine the proposed link between global warming and tropical cyclone frequency, Webster et al., (2005) found that while SSTs in tropical oceans have increased by approximately 0.5˚C between 1970 and 2004 only the North Atlantic Ocean (NATL) shows a statistically significant increase in the total number of hurricanes experienced which began in 1995. In an analysis of the frequency and duration for the same time period no significant trends were noted for ocean basins except for the NATL which showed an increasing trend significant at the 99% confidence level. Webster et al. also noted an almost doubling of the category 4 and 5 hurricanes in the same time period for all ocean basins. While the number of intense hurricanes has been rising the maximum intensity of hurricanes has remained fairly constant over the 35year period examined.

IPCC 4th Assessment Summary

The summary below is based on the SRES A1B scenario which give an average global increase in temperature of 2.8º C over the present century. If all developed countries were to cut greenhouse gas emissions at the rate now proposed by the United Kingdom and France[5], then the global temperature increase would be limited to just under 2º C.

Sea levels are likely[6] to continue to rise on average during the century around the small islands of the Caribbean Sea. Models indicate that the rise will not be geographically uniform. Large deviations among models make regional estimates across the Caribbean uncertain.

Note: Based on the personal judgement of the CANARI Working Group I, the increase will probably follow the global average.

All Caribbean islands are very likely to warm during this century. The warming is likely to be somewhat less than the global annual mean warming in all seasons.

Summer rainfall in the Caribbean is likely to decrease in the vicinity of the Greater Antilles but changes elsewhere and in winter are uncertain.

Note: On going analysis of precipitation changes by the Climate Studies Group Mona warrants upgrading the 'likely' decrease of precipitation in the Greater Antilles to 'very likely'.

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[5] The proposed reduction are approximately 50% by 2050 and 80% thereafter.

[6] In the IPCC Summary for Policymakers, the following terms have been used to indicate the assessed likelihood, using expert judgement, of an outcome or a result: *Virtually certain* > 99% probability of occurrence, *Extremely likely* > 95%, *Very likely* > 90%, *Likely* > 66%, *More likely than not* > 50%, *Unlikely* < 33%, *Very unlikely* < 10%, *Extremely unlikely* < 5%

It is likely that intense tropical cyclone activity will increase (but tracks and the global distribution are uncertain).

Regional Efforts in modelling

Global, Regional and Statistical Downscaling Modelling

The generation of future climate change scenarios has been approached by means of statistical, global and regional models. The initial efforts at climate change modeling in Cuba were designed to generate local scenarios of climate change using simpler models than the global circulation models (GCMs), like MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) and a regional climate scenario generator called SCENGEN (A Regional Climate SCENario GENerator) that uses statistical methods as downscaling techniques (**Centella et al, 1999)**. Recently there has been increased use of regional climate models throughout the Caribbean region (**Taylor et al, 2007).** These models use dynamical downscaling and provide more accurate representation of the physical processes. Thanks to the combined efforts of a number of Caribbean institutions, namely, the Climate Studies Group Mona (CSGM), The University of the West Indies, the Instituto de Meteorologia de la Republic de Cuba (INSMET) and the Caribbean Community Climate Change Centre (CCCCC) regional projections of climate change are being produced that can be used by researchers and policy makers to asses potential climate change impacts and develop adaptation plans. Considerable effort is being made to ensure that the outputs of this work (climate change scenarios) can be made available to the widest possible audience and not only to the university and research centers. CSGM also uses statistical downscaling (SDSM) to downscale global projections to specific observational stations (Chen et al, 2006). Statistical downscaling of temperature and precipitation from global models to station sites in Barbados, Jamaica and Trinidad was undertaken in an Assessments of Impacts and Adaptations to Climate Change in Multiple Regions and Sector (AIACC) Small Island States SIS06 project. Agreements between global, regional and downscaling results allow expert judgments to be made concerning the likelihood of a given climate change scenario.

Early work by Singh (1997) using a GCM with the doubling of CO_2 scenario projected temperature increases near 2˚C by mid-century (2030-2050). This value is high in comparison to the study done by Angeles et al (2007) and compared to statistical downscaling results.

Climate variability and human health

Several studies have been undertaken for the purpose of identifying relationships between different kind of diseases (mainly respiratory diseases), and the climate variability. These studies have demonstrated the existence of a direct relationship between acute respiratory diseases such as bronchial asthma and meteorological variables such as temperature and moisture (**Guevara et al, 1999).** A relationship has been found between the daily values of the Ap geomagnetic index (http://www.nwra-az.com/spawx/ap.html) and the daily rate of adult patients receiving treatment for asthma crises, showing a complex non-linear effect of solar variability on asthmatic patients (**Del-Pozo et al, 2000)**. Based on statistical techniques and using autoregressive moving averages models, it has been possible to forecast, more than one month in advance, the pattern of bronchial asthma behaviour at a pre-determined location (health area) using the expected climatic variations as input data with an effectiveness of 70%. This type of modelling provides the decision makers with a tool to intervene before the health incident occurs (**Bultó and Morgado 2003)**. Some work has been done establishing some relationship between solar activity and myocardial infarctions due to a decrease in the Forbush index (**Mendoza and Díaz-Sandoval 2000)**. Studies of the health risk to a population of exposure to toxic air emissions from industrial sources undertaken in order to identify mitigation strategies appropriate for to the various social and economic circumstances of the study populations. The chronic non-cancer risk due to SO_2 emissions was estimated using the EPA-validated Health Risk Assessment methodology. The assessment identified the number of risk groups in terms of the age and exposure to the contaminant source (**Melgar et al, 2003)**.

A study of the relationships between dengue fever, temperature, and the projected effect of climate change on the transmission of dengue fever were undertaken for the English speaking Caribbean by Chen et al (2006). A temperature index based on a moving average of temperature (MAT) was devised to estimate the potential for the occurrence of a dengue epidemic.

Inter-annual Atmospheric Fluctuations: Quasi biennial Oscillation, the El Niño Southern Oscillation and their impact upon agricultural and meteorological drought

Most of the studies undertaken in Caribbean highlight the relation of our climate with three global reaching atmospheric fluctuations, El Niño Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and the Quasi biennial Oscillation (QBO)[7] (**Sánchez-Santillán, 2007 and Enfield and Alfaro, 1999)**. Their influence on agricultural and meteorological drought has

[7] The **QBO** (**quasi-biennial oscillation**) is a quasi-periodic oscillation of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere with a mean period of 28 to 29 months.

been specifically studied. In this regard, evaluations have been made of the timing of the different phases of these phenomena and the occurrence of significant deficits in total seasonal rainfall in the Caribbean and Mexico (**Bravo et al, 2005, Conde et al, 2006).** Results obtained reveal important correspondence between the timing of the atmospheric oscillations and significant seasonal droughts. These were observed to occur mainly during the rainy season, with notable correlations between rainfall and the direction and speed of the zonal wind components at 50 and 30 hPa, (**Lapinel et al, 2001)**. **Giannini et al, 2000** introduced an index that facilitates the predictions of an ENOS (simultaneous occurrence of the oceanic and atmospheric phenomena), its value being based on the accuracy with which it predicts the ENSO event. The patterns of atmospheric convection and the relationship with the ENSO and drought events have been studied (**Magaña and Ambrizzi 2005 and Lapinel et al, 2002).** The studies characterised the types of atmospheric convection, the structure of the circulation anomalies and its relationships with significant drought process.

Meso-scale and Smaller Scale Modelling*

In the field of numeric modelling some advances have recently been made, mainly at the meso-scale, using models that range from simple models, like shallow water model used to simulate the circulation anomalies over the Intra American Seas – IAS (**Alfaro et al, 2007),** to more complex and sophisticated numerical three-dimensional meso-scale model such as the Pennsylvania State University / National Center for Atmospheric Research numerical model (MM5) (**Mitrani et al, 2006 and Mitrani et al, 2005)**. Other models like Atmospheric Regional Prediction System (ARPS) have been used to study the structure and evolution of some convective storms in a tropical environment (**Pozo et al, 2006).** The model has also been used to determine the effect of an idealised cyclone vortex on the sea surface temperature, and the affect of the resulting decrease in sea surface temperature on the depth of the thermocline (**Villanueva et al, 2005). The ARPS model has also been used**to study saltwater intrusion in some of the regions coastal basins using geophysical, geological and geo-hydrological information to derive a geological model which was subsequently used in a two-dimensional numerical simulation of salt water intrusion (**Flores-Márquez et al, 1998)**. The International Centre for Theoretical Physics (ICTP) Regional Climate Model (RegCM) is a meso-scale climatic model that has been used to test effects of different resolution and parameterisations, and to establish the better model configuration for future studies (**Martínez et al, 2006)**

* Supplementary Material

Mid and long range climatic forecasts*

Forecasting systems have been developed for some meteorological variables that allow users to develop projections up to several months in into the future. Models for the conservation of thermal energy in the upper mixed layer of the ocean are used to predict sea surface temperature anomalies (SSTA) and their monthly changes for periods up to three months, and for seasonal prediction in the North Pacific and North Atlantic oceans. **Adem et al, (2000)** have demonstrated some success in predicting the large scale SSTA and monthly changes for periods of up to three months. In term of precipitation, which is extremely variable, it difficult to develop reliable forecasts. The most reliable forecasting methods, tend to be based on statistical multiple regression analysis (**Naranjo et al 1995 and Magaña et al, 2003).** Regression equations to forecast precipitation using climatic indices related to SSTs and atmospheric pressure have been studied **(Stephenson et al, 2007, Ashby et al, 2005 and Taylor et al 2002)**.

Tropical Cyclones and Storm Surge risk

For small island states and low lying coastal countries in the Caribbean region, tropical cyclones and coastal flooding are vitally important issues for risk management and economic development. A Chronologies of the of the occurrence of these phenomena have been produced by Pérez et al, 2000, Jáuregui 2003 and Romero et al, 2006. Some papers have been published on extreme hydrometeorological events such as storm surges and their relation to sea level rise caused by global warming. In a number of cases statistical determinations have been developed for the natural return period for these events. This information has been combined with the sea level rise projections produced global models under different scenarios (**Salas 2000)**. The studies indicates that in any future scenario, it's still the storm surge associated with tropical storms that is the most dangerous factor in the coastal zones areas assessed in Cuba (**Mitrani-Arenal et al, 2000)**.

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Chapter 4

Present Capacity

This chapter deals mainly with the manpower and equipment capacity of three institutions, Caribbean Institute of Meteorology and Hydrology (CIMH), Climate Studies Group Mona (CSGM) and Instituto de Meteorologia (INSMET). Other institutions involved in climate change research in the regions are the Caribbean Community Climate Change Centre (CCCCC) and the Joint Institute for Caribbean Climate Studies (JICCS).

<u>CCCCC</u>

CCCCC coordinates much of the Caribbean region's response to climate change. Officially opened in August 2005, the Centre is a key node for information on climate change issues and on the region's response to managing and adapting to climate change in the Caribbean. It is the official repository and clearing house for regional climate change data, providing climate change-related policy advice and guidelines to the Caribbean Community (CARICOM) Member States through the CARICOM Secretariat. In this role, the Centre is recognised by the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Environment Programme (UNEP), and other international agencies as the focal point for climate change issues in the Caribbean. It has also been recognised by the United Nations Institute for Training and Research (UNITAR) as a Centre of Excellence.

<u>JICCS</u>

JICCS is a newly-created organisation funded jointly by the University of Puerto Rico, and various local and federal government agencies. It is housed at the University of Puerto Rico, Mayaguez campus on the west coast of Puerto Rico. Its purpose is to provide an overarching infrastructure for researchers from university and federal agencies to work on problems concerning climate and environmental change in the Caribbean region, which is particularly vulnerable to changes in intensity and frequency of extreme weather events brought about by climate change. The mission of the JICCS will be fourfold. First, it will define the present climate and environment of the Caribbean. Second, it will predict the effects of future climate change scenarios on the region. Third, it will suggest ways by which the harmful effects of environmental change can be mitigated. Fourth, it will provide advice to policymakers on climate and environmental issues.

CIMH

CIMH is a training and research organisation formed by the amalgamation of the Caribbean Meteorological Institute (CMI) and Caribbean Operational Hydrological Institute (COHI). The Caribbean Meteorological Institute was established in 1967 by the member states of the Caribbean Meteorological Organisation (CMO) while the Caribbean Operational Hydrological Institute (COHI) was established in 1982. Even though the two Institutes were amalgamated since the mid 1980's, the organisation continued to be known as the Caribbean Meteorological Institute up until September 1999 when the name was officially changed to reflect the dual role of the Institute. Responsibility for the operation of the Institute rests with the sixteen Commonwealth Governments which comprise the CMO. The role and mission of the CIMH is to improve the meteorological and hydrological services and to assist in promoting the awareness of the benefits of these services for the economic well-being of the CMO countries. This is achieved through training, research and investigations, and the provision of specialised services and advice.

The Institute is located at Husbands, in the parish of St. James, Barbados, on the western side of the island. This location is about two kilometres from the Cave Hill Campus of the University of the West Indies, with which the Institute is affiliated. The Institute was designated as a Regional Meteorological Training Centre by the World Meteorological Organisation (WMO) in 1978 in recognition of the high standard of its training programmes. Students from all parts of the Caribbean, and sometimes beyond, are trained in such branches of meteorology as weather observing, forecasting, radar and satellite meteorology, instrument maintenance, agro-meteorology, and climatology, and in operational hydrology. CIMH maintains a staff complement of approximately 10 academic/research staff and 17 technical staff with expertise in weather forecasting, data mining, running and assessing climate models.

One of the primary functions of CIMH, and a carry over activity from CMI, is meteorological and hydrological data archiving. Currently, CIMH acts as a back up data repository for many CMO Member States, with only a few countries not taking advantage of the service. Data stored at CIMH is made available at no charge for academic research. However, a fee is charged to commercial entities requesting the data.

Numerical weather prediction models are increasingly being used to support weather forecasts. In recognition of this fact, the CIMH currently runs two numerical models [the Pennsylvania State University/ National Center for Atmospheric Research Meso-scale Model (MM5V3) and the Advance Weather Research Weather Forecasting (WRFV2)] twice daily to provide 48 hour weather predictions over the Caribbean region. Outputs from the models are used by National Meteorological Services in the Caribbean region to support local weather forecasts. Outputs from the models were also used to support weather predictions during the recently concluded 2007 Cricket World Cup.

CSGM

CSGM was formed within the Physics Department of the University of the West Indies in 1994. Its purpose is to:

- To investigate and understand the mechanisms responsible for a) the mean climate and b) extremes in climate in both Jamaica and the wider Caribbean;
- To use this understanding to predict climate on a seasonal and annual basis; To promote awareness of global change and renewable energy resources;
- To investigate and promote the advantageous uses of climate prediction in socio-economic sectors.

It has 3 academic staff attached to the Physics Department and 2 technical staff. Part of its strength lies in the ability to attract postgraduate students at the M.Phil., and Ph.D., levels, both of which are research based. It has capability in global, regional and statistical downscaling modelling. Computer facilities are adequate for computational purposes, but storage of model runs is an ongoing problem.

INSMET

- *Human Resources*:

  In the region INSMET have the demonstrated capacity for working on interdisciplinary and multinational projects.

- *Equipment and Data*:

At this moment ISMET can provide useful information for the entire Caribbean in terms of regional weather forecasting and some detailed meso-scale information, but is impossible to give a detailed local forecast using our currently installed capacity. Current equipment includes:

  - 4 PC's cluster running mm5 full operational for forecasting purpose.
  - 10 PC's running PRECIS and RegCM Experiments with storage capacity of 4 Tb
  - 4 Massive storage server total capacity 4 Tb.

In terms of scenarios and modelling ISMET have the following data:

- PRECIS Model. Source, INSMET Cuba, Contact, Abel Centella (http://precis.insmet.cu/Precis-Caribe.htm), All these data are storage in the CFA at the INSMET.
- Resolution and Domain 50x50 Km over the whole Caribbean, Antilles, Central-America, Mexico and part of the United States.
- ERA15 15 years of reanalysis runs with monthly outputs (1978-1993) Validation and research purpose
- Baseline (30 Years-Daily outputs) 1960-1990 using the Hadley Center global Model output.
- Future Scenarios (30 Years-Daily outputs) 2070-2100 for Hadley Center global Model output using A2 and B2 SRES scenarios
- Complete run (140 Years -Daily outputs) Using the ECHAM4 model 1960-2100
- ERA45 45 years of reanalysis runs with monthly outputs (1953-2001) Validation and research purpose.

CSGM has been collaborating on climate variability and climate change projects with CIMH since 1995, and with ISMET since 2000. Collaboration on climate change has strengthened with CCCCC as the facilitator. Taken together there is a core group of researchers and technical staff, backed up by research students capable of conducting climate change research in the region. However since these institutions deal mainly with atmospheric modelling, there is need for expertise in ocean and land surface interaction.

Chapter 5

Gaps and Bridging Them

Gaps

Significant strides have been made with respect to gaining an understanding of Caribbean climate variability and change, and efforts have begun with respect to generating region specific scenarios of future climate. Yet, gaps still remain which must be bridged, particularly if interdisciplinary efforts are to materialise. Some of the gaps are as identified below.

The Data Deficit

Determining the mechanisms that control Caribbean climate whether through statistical analyses or modelling requires good quality climate data of significant temporal length and from all territories across the Caribbean region. For example, statistical downscaling – a technique well suited for the development of scenarios for the biodiversity sector – requires long time series of daily station data for the location being studied.

The summary of chapter 2 suggests that datasets and data reserves exist for and within the Caribbean region. It however also highlights a number of deficits. Some of the identified gaps include:

- The need to increase the density of stations for which quality controlled historical data is available.
- The need for daily station data of sufficient temporal length (30 years or more) to enable scenario generation via statistical means.
- The need to expand the number of climatic variables captured by the historical data. The current emphasis is on a minimum dataset of precipitation, maximum and minimum temperature. This may not be sufficient for the generation of scenarios of relevance to other sectors e.g. the biodiversity sector.
- The need to ensure easy access to the existing data stores, for legitimate users e.g. researchers.
- The need to ensure that data currently being recorded meet adopted global and regional standards so that the identified data deficiencies with respect to present day historical data are not the deficiencies of the future generation.
- The need to capture secondary or derived information (e.g. climate indices or data ranges or deviations) for storage alongside the primary data.
- The need to expand data offerings to include SST and variables such as soil moisture, concentration of atmospheric constituents, etc.

Whereas some territories e.g. Cuba, have been successful at amassing reasonably long time series of station data for multiple variables and multiple stations this is not the case throughout the entire region. In many territories additional data exist which could supplement existing databases, but in non-traditional archives (e.g. records of sugar plantations, agricultural and hydrological bodies) and in non-digitised forms, and are therefore yet to be captured. There is at present no coordinated region-wide data capture effort, this, in spite of a growing sense of urgency about the deterioration of the media on which some the data is currently captured.

Capacity Constraints

Human Capacity

The Caribbean region is not devoid of the human capacity to undertake the tasks associated with generating climate change scenarios. Highly qualified meteorologists, and climate researchers with sufficient knowledge of methodologies to assess and produce relevant analyses exist within the region at institutions such as the CIMH, at a few meteorological offices and at regional and local universities. The number of interdisciplinary and multinational research projects carried out at these institutions and others within the region attest to this capacity.

Yet there are constraints. In particular, the very recent interdisciplinary emphasis of climate change research means that the pool professionals who can either straddle the disciplines being combined (e.g. meteorology and the biosciences), or with skills to effectively assess and/or examine vulnerability or adaptation, is small (though growing). Consequently there is often a need to hire consultants from outside the region to do such evaluations and assessments. Unfortunately, the experience of the region is that such experts leave their results but not their methodologies, and therefore do not facilitate a transfer of knowledge.

It is also to be noted that an aging cadre of professionals in the meteorological institutions of the region remains a problem.

Technical Constraints

Technical capacity varies across the region. The infrastructure to support meteorological measurements, climatic analysis, dynamical modelling, and scenario generation exists throughout the region, though not necessarily uniformly so. Institutions such as CIMH, IMSMET, UWI and UPR- Mayaguez are noteworthy for their technical infrastructure which, though not adequate, is sufficient for many tasks. Yet a survey of the region suggests some common constraints.

In spite of a growing awareness about the importance of data collection, the high cost of purchase, maintenance and calibration of meteorological instruments has resulted in a gradual deterioration of the meteorological network. When replacement instruments do not exist, or must wait on grant or government funding to be obtained, or inappropriate substitutions are made in the absence of the genuine instrument, the climate database suffers.

Additionally, the use that modern meteorology makes of new computer resources, means that the meteorological services and institutions conducting related meteorological activities, as well as research entities exploring climate variability and change, require high performance computers and massive data storage systems. These are necessary to generate useful and high quality information for forecasting purposes and for the research community. At this moment, most territories benefit from useful meteorological information from a variety of sources, including regional weather forecasting and some detailed meso-scale information. Outside of a few territories, however, (e.g. Puerto Rico) it is impossible to give a detailed local forecast using currently installed capacity.

Knowledge Needs

Finally, as previously suggested**,** the summary of Chapter 2 points to a vastly improved understanding of regional dynamics and a growing understanding of climate change and its likely manifestation in the Caribbean region. Yet the increased understanding highlights some knowledge gaps - pointing to areas that require better understanding. These include:

- A need for further understanding of Caribbean climate variability, particularly on the sub seasonal, seasonal, inter-annual (outside of El Nino variations) and decadal scales. Phenomena such as the low level jet, dry season dynamics, easterly wave dynamics and interactions require further examination. This is needed to provide context for examining future change within the region.
- A need for investigation of local or sub regional climates and climate gradations within individual territories and how these will likely be altered by climate change.
- A need for further application of regional modelling techniques (dynamical and statistical), particularly with respect to downscaling climate change results for sub regions, territories, cities, towns, and station sites.
- A need for dialogue between climate researchers and scientists within the biodiversity sector (for example) in order to jointly set foci, priorities, and an agenda of needs and deliverables. This would include the quantifying of climatic variables, scales, and thresholds which would be needed for analysis of the impact of climate change on the

- A need for a better understanding of sea level rise estimations due to global warming and the implications this will have for Caribbean coastlines especially during extreme events.
- A need for more region specific information/studies on deforestation, flooding, and the role of climate in determining such things as human settlements and international commerce.
- A need for a clearer understanding of the usefulness of the various types of climate data currently being archived for modelling biodiversity impacts, as well as the limitations and boundaries within which the data can/should be used.

Admittedly, some of this knowledge may already be in existence, particularly in the archives of governmental and non-governmental organisations, in the form of consultancy reports and commissioned studies done over the years. Their inaccessibility, the lack of knowledge about their whereabouts or existence, and the absence of central bibliographic databases do nothing to fill the knowledge needs of the region.

Filling the Gaps

The following represent steps which could/should be taken to fill the identified gaps. In some cases the steps represent major efforts which would involve multi-national collaboration, while in other cases the steps could be undertaken by a single territory or institution. Identification of funding to carry out the proposed solutions remains a vexing issue for the region as a whole.

Recommendations

<u>Data</u>

1. Putting in place mechanisms (protocols and agreements for sharing, online facilities, etc.) to facilitate the sharing of data located in existing archives and databases scattered throughout the Caribbean.
2. Putting in place structures/programmes to capture data that is not yet digitised and not yet available for use by researchers.
3. Putting in place programmes, infrastructure, and instrumentation to enable and/or support the capture of new data.
4. Subjecting existing data to rigorous quality control techniques in order to build a climate database for use by other sectors.

5. Acquiring useful datasets from sources outside the Caribbean e.g. detailed bathymetric maps of the Caribbean region.
6. Creating additional databases (where possible) of variables deemed necessary for interdisciplinary work e.g. soil moisture, SST, etc.

<u>Capacity – Human and Technical</u>

1. Investing in postgraduate training with an emphasis on Caribbean climate variability and change, numerical modelling of climate, and the modelling of climate change impact on various sectors including biodiversity, agriculture, tourism, water and coastal zones.
2. Supporting student exchanges within and outside of the region.
3. Support for staff education and training (especially for existing staff at meteorological services) in numeric and impact modelling, interpretation of results, analysis methods for climate change etc.
4. Acquiring equipment and software to support climate research at existing organisations and institutions with track records for doing the same. This would include massive storage devices, beowolf clusters (for numerical model runs), high speed intranet, radar networks, satellite images, software licenses and professional packages (e.g. Fortran, Matlab, GIS and professional Linux).
5. Updating meteorological infrastructure to ensure recording of quality data. This would include acquisition of automatic stations and calibration equipment for basic meteorological instruments e.g. thermometers, barometers, etc. as well as the acquisition of specific meteorological instruments e.g. buoys, mareographs, and gradient towers to study the turbulent layer and the wind properties near the ground level, solar radiometers and UV sensors, to study the solar potential of our region, etc.

<u>Knowledge</u>

1. Developing online mechanisms for storing and disseminating information e.g. a web-page compendium for use as a clearing house document for information.
2. Developing a Caribbean climate atlas.
3. Facilitating dialogue between climate researchers and scientists of other sectors such as biodiversity, in order to establish priorities, needs and deliverables for climate change studies.
4. Supporting graduate student research and cross disciplinary training.

Chapter 6
Concluding Remarks

This report has established that, although Caribbean Institutions are able to analyse and generate climate change scenarios, gaps in our ability to do so exist. Chapter 5 lists our needs and suggests pathways for bridging the gaps. Some solutions are not expensive, such as inter-disciplinary collaboration, exchange of personnel and training. Others require more funding, notably for computer accessories. Invariably the question will be asked whether or not the efforts to bridge the gaps are worthwhile.

As reported above, the scenarios generated by more affluent countries are global (and regional for their own needs). It will invariably be the task of Caribbean countries to produce their own regional scenarios, and the quality of the scenarios generated will depend on our national and regional capability, to the extent that gaps and deficiencies exist, efforts must be made to improve these capabilities and fill the identified gaps in capacity. There are questions and issues that were raised by working groups on Coastal and Marine Biodiversity and on Terrestrial Biodiversity in their meetings and reports, which will require more data gathering and climate change model runs.

The question will also be asked 'What if we can limit global warming and eventually reverse it, will our efforts be in vain?' In the first place, we are already committed to increases of at least 2ºC over the century due to the long life time of greenhouse gases in the atmosphere and the 'long' memory of the ocean even if conditions were stabilised. In the second place there are many advantages to be gained in the course of mitigating climate change, in addition to reducing global warming. Increased capacity in climate studies will lead to better forecasting of daily weather and of seasonal changes, such as drought and floods. Crop models and climate models could be combined to better predict crop yields. Models could be developed to determine the effects of deforestation, or better yet, the effects for re-forestation on future climates. So the efforts directed at filling the gaps in our knowledge and capability to study and better understand climatic phenomena and generate models and scenarios of future climate will not be in vain.

Appendix 1

List of Databases

Table showing Available datasets with Caribbean data

Dataset	UNAM	CRU	CMAP	CIMH	CCID
Data Type	gridded monthly	gridded monthly	gridded pentad &monthly	hourly & daily	daily & monthly
Resolution	0.5˚×0.5˚	0.5˚×0.5˚	2.5˚×2.5˚	station data	station data
Time Period	1901-2002	1901-2000	1979-present	1970-present	1935-2000
Domain	-140.25˚W - 59.75˚W	global	global	Caribbean	Caribbean
	4.75˚N - 45.25˚N				
Variables	T_{min}, T_{max}, Pcp	T_{min}, T_{max}, T_{mean}, T_{range}, Pcp,wetdays, vapour, cloud	Pcp	T_{min}, T_{max}, Pcp, pressure, cloud, wind speed & direction, humidity	T_{min}, T_{max}, Pcp,
Availability	free online	free online	free online	free to researchers but a fee for commercial entities	Free – contact Dr. Michael Taylor, UWI Mona, michael.taylor@uwimona.jm

Variables

T mean daily mean temperature (degrees Celsius)

T min   daily minimum temperature (degrees Celsius)

T max   daily maximum temperature (degrees Celsius)

T range daily temperature range (degrees Celsius)

frost   frost day frequency (days)

Pcp   precipitation

wetdays wet day frequency (days)

vapour vapour pressure

cloud   cloud cover

- UNAM - Universisda Nacional Autónoma de México : http://iridl.ldeo.columbia.edu/SOURCES/.UNAM/.gridded/.monthly/.v0705/
- CRU - Climate Research Unit: http://www.cru.uea.ac.uk/~timm/cty/obs/TYN_CY_1_1.html
- CIMH - Caribbean Institute for Meteorology and Hydrology: http://www.cimh.edu.bb/
- CMAP - Climate Prediction Center Merged Analysis of Precipitation: http://www.cpc.ncep.noaa.gov/products/global_precip/html/wpage.cmap.html
- CCID – Caribbean Climate Interactive Database

Contents of CCID Dataset

Station	Station Name	Long	Lat	Elev (m)	Start	End Date	Days of Data
BAH01	Free Port, Bahamas	26.4	-78.3	2	01-Jan-1968	31-Dec-2000	12055
BAR01	Barbados	13.09	-59.37	50	01-Jan-1969	31-Dec-1999	11013
BEL01	Central Farm, Belize	17.31	-88.12	61	01-Jan-1966	31-Dec-1970	1826
BEL02	Pswgia, Belize	17.53	-88.3	5	01-Jan-1960	31-Oct-2000	15078
CAY01	Cayman	19.17	-81.21	3	01-Jan-1976	31-Oct-2000	8979
CUR01	Curacao	12.2	-68.96	9	01-Apr-1935	31-Dec-1997	21239
DOR01	Dominican Republic	18.48	-69.91	14	01-Jan-1937	31-Dec-1999	22998
JAM01	Manley, Jamaica	17.56	-76.47	9	01-Jan-1992	31-Dec-2000	3162
JAM02	Sangster, Jamaica	18.3	-77.55	3	01-Jan-1992	31-Dec-2000	3048
	Worthy Park			365	01-Jan-1961	31-Dec-2000	
MON01	Montserrat	16.45	-62.12		01-Jun-1998	31-Dec-1999	498
STK02	Cunningham, St. Kitts	17.18	-62.42	63	01-Jan-1977	31-Dec-1999	8412
STK03	Fahies, St. Kitts			126	01-Jan-1977	31-Dec-1999	8412
STK04	Lynches, St. Kitts	17.18	-62.42	102	01-Jan-1977	31-Dec-1999	8412
STK05	Olivees, St. Kitts	17.18	-62.42	143	01-Jan-1977	31-Dec-1999	8409
STV01	St. Vincent	13.08	-61.12	13	01-Jan-1987	12-Dec-2000	5067
TRT01	Trinidad and Tobago	10.37	-61.21	15	01-Jan-1959	31-Dec-1999	14975
USV01	Coral Bay, U.S.V.I.	18.33	-64.7		01-Jan-1972	31-Dec-1999	23733
USV02	Cruz Bay, U.S.V.I.	18.33	-64.78	3	01-Jan-1972	31-Dec-1999	23733

Stations in CIMH Dataset

GUYANA	Ebini	X	X	X	X	X
GUYANA	Georgetown Bot. Gardens	06	48	58	08	2
GUYANA	Cheddi Jagan Airport	06	30	58	15	30
GUYANA	Lethem Airstrip	03	22	59	48	82
MONTSERRAT	Blackbourne	16	46	67	09	x
ST. KITTS	R.L. Bradshaw Airport	17	18	62	41	48
ST. KITTS	La Guerite	17	18	62	44	x
ST. KITTS	Nat. Agric. Station	17	18	62	43	x
ST. LUCIA	Hewanorra Airport	13	45	60	57	21
ST. LUCIA	Roseau Winban	13	56	61	02	x
ST. LUCIA	Union	14	01	60	08	x
ST. LUCIA	G.C. Charles Airport	14	01	61	00	2
ST. VINCENT	E.T. Joshua Airport	13	09	61	13	13
TOBAGO	Crown Point Airport	11	09	60	50	3
TOBAGO	Louis Dor	11	15	60	34	12
TRINIDAD	Piarco Airport	10	35	61	21	12
TRINIDAD	Centeno	10	35	61	20	15
TRINIDAD	Penal	10	10	61	28	8
TRINIDAD	St. Augustine	10	38	61	24	16
GRENADA	Grand Etang	12	06	61	36	x
GUYANA	Ebini	X	X	X	X	X
GUYANA	Georgetown Bot. Gardens	06	48	58	08	2

GUYANA	Cheddi Jagan Airport	06	30	58	15	30
GUYANA	Lethem Airstrip	03	22	59	48	82
MONTSERRAT	Blackbourne	16	46	67	09	x
ST. KITTS	R.L. Bradshaw Airport	17	18	62	41	48
ST. KITTS	La Guerite	17	18	62	44	x
ST. KITTS	Nat. Agric. Station	17	18	62	43	x
ST. LUCIA	Hewanorra Airport	13	45	60	57	21
ST. LUCIA	Roseau Winban	13	56	61	02	x
ST. LUCIA	Union	14	01	60	08	x
ST. LUCIA	G.C. Charles Airport	14	01	61	00	2
ST. VINCENT	E.T. Joshua Airport	13	09	61	13	13
TOBAGO	Crown Point Airport	11	09	60	50	3
TOBAGO	Louis Dor	11	15	60	34	12
TRINIDAD	Piarco Airport	10	35	61	21	12
TRINIDAD	Centeno	10	35	61	20	15
TRINIDAD	Penal	10	10	61	28	8
TRINIDAD	St. Augustine	10	38	61	24	16

Appendix 2

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Caribbean Natural Resources Institute

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This Technical Report was produced by the Caribbean Natural Resources Institute as an output of the project "Climate change and biodiversity in the insular Caribbean" funded by the John D. and Catherine T. MacArthur Foundation.

MACARTHUR
The John D. and Catherine T. MacArthur Foundation

Citation: Chen.A., M. Taylor, A. Centella, D. Farrell. 2008. Climate trends and scenarios for climate change in the insular Caribbean: Report of Working Group I, Climate Change and Biodiversity in the Insular Caribbean. CANARI Technical Report No.381: 63pp.