

Future climate of the Caribbean from a regional climate model

Jayaka D. Campbell, Michael A. Taylor,* Tannecia S. Stephenson, Rhodene A. Watson and Felicia S. Whyte

The Climate Studies Group Mona, The University of the West Indies, Mona, Kingston 7, Jamaica, West Indies

ABSTRACT: Scenarios of rainfall and temperature changes for the period 2071-2100 under the A2 and B2 Special Report on Emissions scenarios are examined using the Hadley Centre Providing Regional Climates for Impacts Studies regional climate model. The model simulates 'present-day' (1979–1990) rainfall and temperature climatologies reasonably well, capturing the characteristic bimodality of Caribbean rainfall and the boreal summer maximum and winter minimum temperatures. Seasonal spatial patterns are also reproduced, but rainfall amounts are underestimated over the northern Caribbean island masses, including Cuba, Jamaica, Hispaniola and Puerto Rico. Temperatures over the region are also overestimated by 1-3 °C. For the period 2071-2100, temperatures are projected to increase across the region by 1-4 °C for all months irrespective of the scenario. The rainfall response varies with season with one of the more robust changes being an intensification of a gradient pattern in November–January, in which the northern Caribbean (i.e. north of 22° N) gets wetter and the southern Caribbean gets drier. There is also a robust June–October drying signal. The results point to changes in the regional circulation patterns due to the human-induced climate change and warrants further investigation. Copyright © 2010 Royal Meteorological Society

KEY WORDS climate change; Caribbean; scenarios; rainfall; temperature

Received 23 February 2009; Revised 12 June 2010; Accepted 16 June 2010

1. Introduction

In recent times, due to both anthropogenic and natural effects, the earth's climate has been changing. Globally, mean surface temperatures have increased by approximately 0.74 ± 0.18 °C since the turn of the 19th century [Inter Governmental Panel on Climate Change (IPCC) Fourth Assessment Report] (Solomon *et al.*, 2007), with further increases projected through the end of the century. This will result in shifts in regional rainfall and temperature regimes and climate extremes (Solomon *et al.*, 2007).

Station observations in the Caribbean (Figure 1) show a statistically significant warming trend over the latter half of the 20th century (Peterson *et al.*, 2002). Future shifts in climate regimes will have implications for the developing states within the Caribbean given the climate sensitivity of their economies (Jury, 2009). Caribbean states largely rely on sectors such as tourism or agriculture for economic sustainability and growth. The generation of climate change projections and scenarios for the Caribbean at appropriate scales is therefore an important exercise particularly for long-term planning.

Global climate models (GCMs) are the most common tools for investigating climate change and making projections for the future. GCMs are mathematical representations of physical processes in the atmosphere, ocean, cryosphere and land surface. They represent the climate using a three-dimensional grid over the globe, typically with a horizontal resolution between 125 and 600 km, 10-20 vertical layers in the atmosphere and as many as 30 ocean layers. In recent decades, the evolution of GCMs has allowed for a much better scientific understanding of anthropogenic global climate change, much of which has been reported in the IPCC's Assessment Reports (Solomon et al., 2007). In the Caribbean, GCM realizations have been used to project a 1-2 °C temperature rise by the mid-2050s and increases in sea-surface temperatures and vertical windshear (Singh, 1997a, 1997b; Angeles et al., 2006) under a 'business as usual' scenario. Other GCM-based rainfall projections for the region suggest (1) a slight decline in annual rainfall $(-6.8 \pm 15.8\%)$ (Nurse and Sem, 2001); (2) a slight increase in December-February rainfall (Nurse and Sem, 2001); (3) a decrease in June-August rainfall (Nurse and Sem, 2001); (4) an increase in early and late season rainfall (Angeles et al., 2006); (5) a decrease in annual rainy days (Nurse and Sem, 2001; Solomon et al., 2007) and (6) an increase in the daily intensity of rainfall (Nurse and Sem, 2001; Solomon et al., 2007). Gamble and Curtis

^{*} Correspondence to: Michael A. Taylor, The Climate Studies Group Mona, The University of the West Indies, Mona, Kingston 7, Jamaica, West Indies. E-mail: michael.taylor@uwimona.edu.jm



Figure 1. Map showing PRECIS domain over the Caribbean and adjacent Caribbean region. The box shows the Caribbean rainfall index domain as defined by Chen and Taylor (2002).

(2008) present a review of Caribbean rainfall projections from GCMs.

The resolution of global models is, however, too coarse to provide information at the local and regional scales needed for vulnerability assessments and the development of local adaptation strategies (Aldrian et al., 2004; Xianfu, 2006). This is particularly true for the Caribbean as most of the small islands are not represented in the GCMs. Regionalization or downscaling techniques are therefore necessary for extracting finer scale information from GCM output, which may prove useful for the impacts and adaptation communities. Downscaling techniques can be classified into three categories: (1) high resolution and variable resolution 'time-slice' Atmosphere GCM experiments; (2) nested limited area (or regional) climate models (RCMs) and (3) empirical/statistical and statistical/dynamical methods (Mearns et al., 2003). Each category has its suitability depending on varying criteria including the scale of climate information that is required (see discussions by Wilby and Wigley, 1997; Mearns et al., 2003; Dobler and Ahrens, 2008).

This paper has its foundation in type (2) downscaling, and is an examination of climate change projections for the Caribbean region from the Hadley Centre HadRM3P model (Jones et al., 2004), which is the RCM within the Providing Regional Climates for Impacts Studies (PRECIS) model. For this study, the RCM is driven with boundary conditions from the HadAM3P GCM. Very few downscaling studies for the Caribbean are to be found in peer review literature (e.g. the sensitivity studies of Castro et al., 2006, using the International Centre for Theoretical Physics (ICTP) RegCM3 for the simulation of summer precipitation, temperature and local wind field). The authors are unaware of any studies detailing climate change scenarios for the Caribbean from RCMs. This study not only complements previous modelling work for the Caribbean, but, importantly, also documents

for the first time RCM-derived future climates for the region.

The PRECIS regional model has been widely used to develop regional climate change scenarios worldwide and to study extremes (Moberg and Jones, 2004; Tadross et al., 2005; Kumar et al., 2006; Zhang et al., 2006; Bloom et al., 2008; Kotroni et al., 2008; Islam et al., 2009; Marengo et al., 2009). Its choice for use in the Caribbean results from a deliberate collaborative effort to develop regional scenarios, which was initiated in 2003. The collaboration included institutions in four Caribbean countries (Belize, Jamaica, Cuba and Barbados) and was driven by the Caribbean Community Climate Change Centre. Details of the PRECIS-Caribbean project are given in Taylor et al. (2007). The overall aim is to use multiple RCMs and driving models to generate climate scenarios for the region, as is done in other parts of the world. The use of PRECIS represents an attempt not only to generate initial downscaled projections of climate change for the region, but also to build modelling capacity. The effort also allows for an evaluation of the PRECIS model's ability to simulate the climate of the Caribbean region. This is also reported in this study.

The remainder of the paper is sectioned as follows. Section 2 describes the PRECIS RCM and the subset of model experiments performed. The section also details the datasets used for the validation of the model. Section 3 presents an evaluation of the model skill in simulating present-day Caribbean climate using selected fields. Section 4 examines the model projections and Section 5 presents the summary and discussion of the results.

2. Data and methodology

2.1. Model description

The study uses version 1.3 of the Hadley Centre's regional climate modelling system – PRECIS. The PRE-CIS RCM is a dynamical downscaling atmospheric and

land surface model, which generates regional-scale climate scenarios at a minimum and maximum horizontal resolution of 25 and 50 km, respectively. The model, which is locatable over any part of the globe and is computationally inexpensive, can be used to diagnose a full range of meteorological variables at up to 19 levels of the atmosphere and surface variables on varying timescales. A description of the model's physics is found in Jones *et al.* (2003, 2004).

In this study, lateral boundary conditions for the PRECIS RCM are from the global atmospheric GCM, HadAM3P, which has a horizontal resolution of 1.25° latitude \times 1.875° longitude. The model formulation of the HadAM3P is the same as for the PRECIS RCM, thereby promoting consistency between high resolution and global model climate change projections. The PRE-CIS results reported in this paper derive from (1) a model simulated baseline spanning 1961-1990, which is considered representative of pre-industrialised climate, (2) a full range of different but equally plausible future climate scenarios for the 2071-2100 as gleaned from one realization consistent with each of the Special Report on Emissions (SRES) A2 and B2 emission scenarios, and (3) an actualised climate generated from the model driven by a reanalysis of the European Centre for Medium-Range Weather Forecast (ECMWF) dataset (ERA-15 hereafter) from 1979 to 1993.

The SRES scenarios are plausible representations of future emissions of greenhouse gases based on a coherent and internally consistent set of assumptions about driving forces such as demographics, socio–economic development and technological changes (Nakicenovic *et al.*, 2000). The reanalysis simulation is used in the validation of the model. For all the simulations, the sea-surface boundary conditions are derived from recent past observations and from future SSTs formed from the addition of mean changes and trends calculated from the global coupled ocean–atmosphere GCM HadCM3 (Jones *et al.*, 2004; Rowell, 2005).

2.2. Domain, data and methodology

Because of the region's location, large-scale influences, which modulate the underlying climatology, come from both the tropical Atlantic and Pacific oceans. These include the north Atlantic subtropical High, the northeast trade wind regime, sea-surface temperatures and their gradients over the tropical Pacific and Atlantic, the Caribbean low-level jet, vertical shear and divergence within the basin, and the effects of transient tropical and extra-tropical systems (detailed reviews of Caribbean climate dynamics are found in the study of Jury, 2009; Gamble and Curtis 2008; Ashby et al., 2005). The model's domain was chosen such that it represents an area large enough to allow the development of regionalscale circulations due to the above influences but not large enough to facilitate the RCM deviating from the GCM in the centre of the domain (Kumar et al., 2006). The PRECIS experiments were run at the 50 km resolution

over $0^{\circ}-36^{\circ}N$ and $55^{\circ}-120^{\circ}W$ (Figure 1). The domain includes the Caribbean, Central America, Florida and the northern territories of South America.

In assessing the model's ability to simulate regional seasonal variability, the baseline and ERA-15 driven model results are first compared with precipitation maps for the Caribbean extracted from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) datasets (Xie and Arkin, 1997) and surface temperature maps obtained from the National Centers for Environmental Prediction-National Centers for Atmospheric Research (NCEP-NCAR) reanalysis-1 dataset (Kalnay et al., 1996). The CMAP dataset is based on gauge observations, satellite estimates and model output constructed on a 2.5° longitude-latitude grid from 1979 to the present. The horizontal resolution for the reanalysis dataset is $2.5^{\circ} \times 2.5^{\circ}$. Because the Caribbean basin is largely ocean, the climatologies of individual islands are to a large extent determined by their location in the background spatial patterns. Consequently, these initial comparisons evaluate the model's ability to capture seasonal variability in the large-scale patterns over the Caribbean basin (a must for any model used over the region), even though it is recognized that the resolutions of the validating datasets are too coarse to enable comparison of the finer details produced by the PRECIS model (Castro et al., 2006).

Validation at the scale of the model is however important as further sub-regional climatological variations across the islands are induced by (among other things) the impact of orography and the orientation of the islands (see Hastenrath, 1976; Chen *et al.*, 1997; Giannini *et al.*, 2000; Chen and Taylor, 2002; Taylor *et al.*, 2002 for more on Caribbean climatology). Ideally validation at the RCM scale is done by comparison to station observations, but Caribbean station data are notoriously sparse. Consequently, evaluation of the model biases for seasonal precipitation and temperature fields were done using difference maps between a $0.5^{\circ} \times 0.5^{\circ}$ observational dataset from the Climatic Research Unit (CRU) (New *et al.*, 2001) and both the ERA-15 and baseline simulations.

Simulated and observed monthly, seasonal and annual time series were also computed for present-day and future periods by averaging over the whole domain (temperature) or over $10^{\circ}-20^{\circ}$ N and $65^{\circ}-83^{\circ}$ W (rainfall). The latter domain coincides with the Caribbean rainfall index of Taylor *et al.* (2002) (Figure 1). The seasons used were February–April (FMA), May–July (MJJ), August–October (ASO) and November–January (NDJ) to be consistent with the seasonality of the region as identified by Chen and Taylor (2002).

In determining climate change scenarios for the region, the absolute change in temperature and percentage change in precipitation for the period 2071–2100 relative to the simulated baseline under the A2 and B2 SRES scenarios were also computed. The changes are depicted using plots of monthly, seasonal and annual change values for the

Та	bl	e l	[.]	List	of	extreme	indices	s and	their	associated	l meanings.
----	----	-----	------	------	----	---------	---------	-------	-------	------------	-------------

Variable name	Definition
Consecutive dry days (CDD)	Maximum number of consecutive days with $RR < 1$ mm
Number of heavy precipitation days (R10)	Annual count of days when $PRCP > = 10 \text{ mm}$
Maximum 5-day precipitation amount (Rx5 day)	Monthly maximum consecutive 5-day precipitation
Very wet days (R95p)	Annual total PRCP when RR >95th percentile
Cool nights (TN10p)	Percentage of days when TN < 10 the the three the three terms of the terms of te
Cool days (TX10p)	Percentage of days when $TX < 10$ th percentile
Warm nights (TN90p)	Percentage of days when TN >90th percentile
Warm days (TX90p)	Percentage of days when TX >90th percentile

Station	Country	Metadata	Dat	ta
			Length (years)	Missing (%)
Le Raizet	Guadeloupe	16.27N 61.60W	25	38.7
Freeport	Bahamas	26.55N 78.70W	23	25.7
Worthy Park	Jamaica	18.50N 77.92W	40	30.4
Catie	Costa Rica	9.90N 63.75W	43	15.7
Casa Blanca	Cuba	23.17N 82.35W	43	0
Santa Rosa de Copan	Honduras	14.78N 88.78W	43	3.5
Picaro Iap	Trinidad & Tobago	10.37N 61.21W	43	7.2
Hewanorra	St. Lucia	13.75N 60.95W	35	7.1

Table II. Metadata for eight Caribbean stations.

Caribbean rainfall and temperature indices defined above and using seasonal and annual spatial maps.

Finally, an attempt was made to assess the model's ability to (1) simulate current trends in climate extremes and (2) project changes in the extremes. The validation was hampered by the sparse station data distribution in the region and in the end eight indices representative of short term climate events were calculated for eight stations, which had daily time series of reasonable lengths (20 or more years). The indices are listed in Table I and the stations are given in Table II. Future changes in the indices for the same stations were also calculated for the A2 and B2 scenarios. Because of the limited sample, caution is taken in interpreting the results.

3. Model validation

3.1. Precipitation

The PRECIS model demonstrates reasonable skill in reproducing the global-scale climatological patterns of precipitation across the Caribbean basin. The main feature of precipitation over the Caribbean is a well-defined annual cycle, which exhibits maximum precipitation from May through November and a dry period peaking in February–March. The wet season is also bimodal (Chen *et al.*, 1997) with peaks in May–June (early season) and August–October (late season). The latter peak coincides with peak hurricane activity.

Figure 2 shows the seasonal rainfall patterns from CMAP (row 1), PRECIS model simulated baseline (row 2) and for CRU minus model simulated baseline (row 3). All maps are for the period 1979–1990, which is the

common period of overlap for all the three datasets. The precipitation analyses are also restricted to a $5^{\circ}-28^{\circ}N$ and $57^{\circ}-90^{\circ}W$ domain because of our primary interest in the Caribbean. The large-scale seasonal variability in the Caribbean basin is well simulated by the model. There is a clear shift towards greater rainfall amounts with the onset of the rainfall season in MJJ (row 2) and the basin is driest in FMA.

The spatial patterns of each season are also equally well simulated. The zonal band of dryness which spans the Caribbean basin and the Caribbean coastline of Central America in FMA (between 10°N and 25°N) is evident in the model. In the wet seasons (MJJ and ASO), the precipitation centre off the Caribbean coastline of Panama associated with the Caribbean low-level jet (Whyte et al., 2008) is captured, as well as heavy rainfall in the equatorial Pacific (lower left corner of the domain). The dry belt over the southern Caribbean Netherland Antilles islands is also simulated for all seasons except NDJ, which is in keeping with the climatology of those islands (Martis et al., 2002). The model however extends the area of wetness associated with the southwestern Caribbean basin in NDJ further eastward, and places a larger rainfall maximum than seen in the CMAP dataset just east of Trinidad and Tobago. The benefit of the greater resolution in differentiating finer scale features, particularly over Caribbean landmasses, is also to be noted.

The difference maps depicting CRU observations minus model baseline (row 3) suggest that over most of



Figure 2. Diagram showing the spatial distribution of seasonal NDJ, FMA, MJJ and ASO precipitations, respectively, for CMAP (top row), PRECIS model simulated baseline (middle row) and CRU minus PRECIS model simulated baseline (bottom). All averages are for the period 1979–1990. Units are in cm. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

the domain shown, regardless of season, the model underestimates precipitation. The only place where the model overestimates precipitation is over portions of northern South America, i.e. over northern Columbia for all seasons and over north western Venezuela in NDJ and ASO. The patterns over northern South America are similar to those shown by Alves and Marengo (2009) in winter and summer validation maps for the continent using the PRE-CIS model. The model also produces more rainfall than observed over Panama and the Pacific coast of Guatemala in NDJ.

Over the Caribbean region, the model's dry bias is evident in all seasons over all island masses. PRECIS is consistent in simulating 1-2 mm/day less rainfall over Cuba, Hispaniola, Jamaica and Puerto Rico for all seasons. Alves and Marengo (2009) note that rainfall underestimations in PRECIS are likely related to poor representation of some components of the hydrological cycle (soil moisture, surface fluxes and vegetation types) or the convective parameterization. It is also noted that the maps in row 3 were essentially the same whether the differences were with respect to the simulated baseline or the model simulations using ERA reanalysis. For this reason the latter differences are not shown.

Finally, quantitative estimates of the model's precipitation biases and a more detailed analysis of its mean annual cycle are obtained from Figure 3. Figure 3(a) shows the simulated, observed (CRU) and CMAP reanalysis rainfall climatologies averaged over the Caribbean index region defined earlier (Figure 1). In the case of CRU only the land points in the domain are averaged. Key characteristics of the rainfall climatology, which are reproduced by the RCM include (1) lowest rainfall amounts at the start of the year; (2) distinct early (MJJ) and late wet seasons (ASO) and (3) a mid-summer rainfall minimum in July (Chen et al., 1997; Chen and Taylor, 2002). However, also evident is an overestimation of rainfall amounts in the late rainfall season months of October and November. The overestimation, though seemingly incongruous with the dry bias for the Caribbean noted earlier, is as a result of the rainfall maximum simulated over the waters south of Jamaica in NDJ (Figure 2), which falls within the Caribbean index domain. If only land points are averaged for the RCM, then the simulated late season values become comparable with the observed.

3.2. Temperature

The seasonal variability and general patterns associated with temperature are also well captured by the model. Figure 4 shows seasonal temperature patterns from NCEP (row 1) and PRECIS model simulated baseline (row 2).



Figure 3. (a) Caribbean rainfall climatological time series, averaged over the area $10 \text{ }^\circ\text{N}-20 \text{ }^\circ\text{N}$ and $65 \text{ }^\circ\text{W}-83 \text{ }^\circ\text{W}$, obtained from CMAP (dashed line with squares), CRU observations (dashed line with triangles) and PRECIS simulation (solid line with circles) for the period 1979–1990. Units are in cm. (b) Caribbean temperature climatological time series, averaged over the entire domain, obtained from NCEP–NCAR reanalysis (dashed line with squares), CRU observations (dashed line with triangles) and PRECIS simulation (solid line with circles) for the period 1979–1990. Units are in cm. (b) Caribbean temperature climatological time series, averaged over the entire domain, obtained from NCEP–NCAR reanalysis (dashed line with squares), CRU observations (dashed line with triangles) and PRECIS simulation (solid line with circles) for the period 1979–1990. Units are in °C.

For consistency with the precipitation maps shown previously, the averaging period is 1979-1990. The PRECIS model captures the peak in Caribbean temperatures in August-September, and the gradient pattern of a cool north but warmer south Caribbean in NDJ and FMA. Also captured are the appearance, eastward advancement and subsequent retreat of the Caribbean warm pool from May through December (Wang and Enfield, 2001). As seen in the model, the warm pool appears first in the western Caribbean Sea in MJJ and eventually engulfs the region by the late rainfall season (ASO). In general, seasonal temperatures across the Caribbean basin are overestimated by 1-2 °C (with respect to NCEP) with some underestimation evident over Central America and portions of South America. Topography influenced variability (particularly over the higher altitude regions of Central and South America) is also discernible due to the finer scale of the regional model.

Figure 4 also shows the model biases with respect to the CRU observations (row 3). Again, the CRU minus ERA driven model maps are not shown due to their similarity. The cold bias over Central America and northern South America and the warm bias over the Caribbean are better depicted. The model underestimates temperatures by 1-2 °C over much of Central America except for the Yucatan Peninsula where there is an overestimation (up to 3°C in FMA). Similarly, over northern South American, model simulated temperatures are up to 3 °C cooler, except for north Central Columbia, and coastal and northeastern Venezuela, where overestimation reaches up to 4°C. The cold bias of the PRECIS model over South America is also seen in the maps of Alves and Marengo (2009). Over the Caribbean land masses, model temperatures are warmer than observations by approximately 1-4 °C dependent on season. The warm bias is greatest in the FMA and least in NDJ.



Figure 4. Diagram showing the spatial distribution of seasonal NDJ, FMA, MJJ and ASO temperatures, respectively, for NCEP-NCAR reanalysis (top row), PRECIS model simulated baseline (middle row) and CRU minus PRECIS model simulated baseline (bottom). All averages are for the period 1979–1990. Units are in °C. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Figure 3(b) indicates that the PRECIS RCM averaged over the entire domain reproduces the mean annual variation in temperature with the lowest temperatures occurring during the boreal winter months (December–February) and maximum during the boreal summer (July–September). The effective annual temperature range is also captured approximately 2.6 °C (model) versus 2.4 °C (observed). The model however overestimates NCEP–NCAR mean monthly temperatures by between 1 and 1.7 °C. The difference is greatest for boreal winter months and least for boreal summer months.

3.3. Extremes

Of the eight extreme indices analysed, only the simulated temperature extremes (TN10p, TX10p, TN90p, TX90p) bear any similarity to extremes calculated using daily data from the eight stations listed in Table II (not shown). TN90p and TN10p (TX90p and TX10p) are respective measures of the occurrence of very hot and cold nights (days). Whereas, the magnitudes of the RCM-derived temperature extremes were not comparable, the time series of their annual variation for overlapping periods were significantly correlated for most stations (not shown). For TN90p, correlations were significant and high (>0.60) for seven of the eight stations. The

simulated temperature indices also showed increasing linear trends for the baseline period, though not all the linear trends were significant. An increasing linear trend is also noted by Peterson *et al.* (2002) for similar temperature indices calculated for the Caribbean basin as a whole.

There were, however, few similarities between the magnitudes and trends for the three rainfall indices and one dryness index when calculated using model and observed data. There are inherent difficulties in correctly simulating daily rainfall in any model, and the problem is compounded by the fact that the comparisons here are between grid box values and single data points. Table III shows the calculated magnitudes of R95, R10, Rx5 and CDD for the eight stations and for their corresponding model grid boxes. The first three indices are indicators of rainfall intensity and the last is a measure of dryness. A plus (minus) sign is placed beside each calculated value to indicate whether the general trend is increasing (decreasing) over the periods of analysis. None of the trends is, however, significant due to the strong interannual variability associated with the rainfall indices. A similar thing is noted by Peterson et al. (2002) for similar mean Caribbean rainfall indices that they calculated.

and base	line siı	nulatic	ons respe	ective	ely. Th	te plus	,+	and mir	-, snt	-' signs	repre	sent a po	sitive	or nega	tive lir	near trei	ld, res	pectively	, over	the peri	od of	observa	tion o	· simula	ttion.	
Stations			Obs	ervec	d (197()-198	(6					ER.	A15 (1979–19	92)					Base	eline (1970-1	(686			
	CDD	Trend	l Rx5	Tre	and R	95 I	rend	R10	Trend	CDD	Trend	x5	Trene	d R95	Tren	d R10	Tren	d CDD	Trend	Rx5	Trene	1 R95	Tren	d R10	Tren	р
Bahamas	23.30	I	168.14		- 355	5.54	+	40.65	+	21.43	+	146.54	I	277.24	1	41.29	I	18.60	+	142.55	I	295.23	1	53.5(і О	
Costa Rica	14.68	I	250.60	+	- 727	7.39	+	77.11	+	11.43	+	86.21	I	245.79	+	37.00	+	25.50	+	52.05	I	139.77		8.1(і О	
Cuba	30.60	U	172.76	+	- 318	8.83	+	33.85	+	40.50	+	74.68	I	141.55	1	10.00	I	31.60	+	77.04	I	151.33	1	12.4	I	
Guadeloupe	NaN		NaN		Ž	aN		NaN		14.50	I	81.21	I	212.19	1	21.50	I	11.25	+	82.92	I	211.30	і О	37.00	і О	
Honduras	29.60	+	159.05	+	- 387	7.23	+	47.05	+	23.07	+	84.63	I	208.59	1	24.93	I	18.80	+	76.00	I	211.80	і О	24.5(+	
Jamaica	NaN		NaN		Ž	aN		NaN		46.36	I	67.68	+	94.31	+	3.43	I	32.00	+	72.70	I	117.92	۱ ۵	4.8(ו	
St. Lucia	21.50	+	199.34	۱ ب	- 495	5.36	+	59.93	+	16.50	+	55.10	I	202.50	1	38.50	I	13.05	+	49.26	I	199.95	I	43.5	I	
Trinidad and	16.73	+	149.57	+	- 458	8.62	+	36.73	+	28.71	+	73.74	I	115.75	I	8.07	+	17.65	+	66.59	+	126.35	+	12.0	+	
Tobago																										

Table III. Table showing calculated magnitudes of rainfall extreme indices: R95, R10, Rx5 and CDD for eight Caribbean stations and for their corresponding grid boxes from ERA15

The signs of the modelled rainfall extremes suggest a tendency towards decreasing heavy rainfall and increasing dry days over the baseline period. It is the opposite tendencies, which are however reported by Peterson *et al.* (2002) and which are seemingly suggested by the station data. The model does not seemingly capture the rainfall extreme trends. We reiterate, however, that care must be taken when interpreting the results as only eight stations are analysed and the trends are not significant. A more detailed analysis of the model's ability to simulate extremes will be the subject of a future paper.

4. Projections

Annual and seasonal projections under the A2 (medium high) and B2 (medium low) SRES emission scenarios for the period 2071–2100 relative to the model baseline (1961–1990) are examined. The A2 SRES scenario represents a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower in comparison to other scenarios. The B2 scenario represents an emphasis on local solutions to economic, social and environmental sustainability with continuously increasing population (lower than A2) and intermediate economic development (Nakićenović, 2000). Assuming stationarity in model biases, changes seen are primarily due to climate change.

Annual (panel a) and seasonal spatial patterns (panels b through e) of change are presented in Figures 5 and 6 for rainfall and temperature, respectively, for the A2 scenario. In general the change patterns are similar for the B2 scenario but with smaller magnitudes (not shown). Changes in the monthly, seasonal and annual values of the Caribbean index are also presented in panel F. As an indication of the robustness of the change, the standard deviation is also plotted in panel F for both rainfall and temperature. The standard deviation is calculated using the CMAP and NCEP datasets for the 1979–1990 period and is plotted as a measure of typical change due to natural variability.

4.1. Rainfall

4.1.1. Annual

With the exception of the far northern latitudes (i.e. southern Florida, the Bahamas and northern Cuba), projections show a decrease in annual rainfall under both A2 (Figure 5(a)) and B2 scenarios (not shown) for much of the Caribbean. The decrease ranges from 25-50% and is largest over the Lesser Antilles and the Central Caribbean basin, under the A2 scenario, including Jamaica and Puerto Rico (i.e. $\sim 10-20^{\circ}$ N). The pattern of drying is similar under the B2 scenario, but the largest change ($\sim 50\%$) is now located in the Netherland Antilles. Under both scenarios, the northern edge of the Caribbean is becoming wetter: $\sim 25\%$ for A2 and between 0-25% for the B2 projections.



Figure 5. Rainfall projections for the period 2071–2100 relative to the period 1961–1990 baseline under the A2 scenario. Percentage change is presented. Panels (a), (b), (c), (d) and (e) represent annual, NDJ, FMA, MJJ and ASO, respectively. Panel (f) shows monthly, seasonal and annual changes calculated by averaging over the domain shown in (a)–(e). The solid line represents one standard deviation as calculated from the CMAP dataset. This figure is available in colour online at

This spatial pattern of the changes is consistent with that obtained by Christensen *et al.* (2007) using 21 global models under the A1B SRES scenario. Of the 21 models, 15 models projected decreased annual rainfall over the Caribbean, excepting parts of the far north basin, from 2080–2099 relative to 1980–1999. Approximately ten models projected an increase over southern Florida. The results are also consistent with the annual precipitation decline projected by Nurse and Sem (2001). The annual rainfall total derived from the Caribbean index also shows a decrease of approximately 20% for the A2 Scenario

wileyonlinelibrary.com/journal/joc



4.1.2. Seasonal

Projections of seasonal rainfall changes for the Caribbean for the period 2071-2100 under the A2 scenario are shown in Figure 5(b-e). The gradient pattern of a wetter



north-drier south Caribbean is a strong feature during the dry seasons NDJ and FMA. The projections indicate up to a 75% increase over the northern Caribbean (above 25° N) under the A2 scenario, even as the central Caribbean exhibits a strong decrease (~50%) in rainfall. The wetter north-drier south pattern is absent in MJJ when uniform drying (~50%) across the plotted domain is the trend, but begins to re-emerge in the late wet season (ASO). In ASO, the expanse of wetness is, however, greatly reduced in comparison to NDJ and FMA. The significance of the projected wetter north-drier south pattern during the dry season is discussed in the following section.

A drier Caribbean during MJJ and ASO (Figure 5(d-e)) is also noteworthy. Angeles *et al.* (2006) similarly show decreased summer rainfall over Cuba by mid-century using a fully coupled GCM. Christensen *et al.* (2007) show a robust drier Caribbean by the 2090s for a June–August season. A mechanism for the projected summer drying has been proposed by Neelin *et al.* (2003). We also discuss the summer drying further in the following section.

Simulated changes in the seasonal and monthly indices [Figure 5(f)] indicate that the general tendency is for drying over the Caribbean and adjacent regions in three of the four defined seasons by the 2071-2100 period. The change exceeds that due to natural variability for both MJJ (~28 vs 15%) and ASO (~35 vs 17%). The monthly indices further suggest that the tendency towards drying is robust for the entire period June–October when all the monthly changes projected are clearly outside the range of natural variability.

4.2. Temperature

4.2.1. Annual

Temperatures are projected to increase over the Caribbean (including Central and South America) under both the A2 [Figure 6(a)] and B2 scenarios (not shown). Projections are for 2-5 °C (2-4 °C) rise over the Caribbean region under the A2 (B2) scenario. The larger Caribbean islands, i.e. Cuba, Jamaica and Hispaniola, exhibit the greatest warming. The annual temperature change scenarios are comparable with IPCC projections of 1.5-4.5 °C increase in average global temperature (above preindustrial levels) under the A1B by the end of the century (Solomon et al. 2007). The results also agree with increased temperatures projected using the Statistical DownScaling Model (Wilby et al., 2002) for stations in Trinidad (2.2 °C/1.6 °C), Barbados (2.3 °C/0.7 °C) and Jamaica (2.0-3.0 °C/1.5-2.3 °C) for the A2/B2 scenario (Chen et al., 2006).

The annual index shown in Figure 6(f) suggests an increase of approximately 2.9 °C over the domain. The change is well outside the range of natural variability as indicated by the one standard deviation value.

4.2.2. Seasonal

The seasonal temperature projections [Figure 6(b-e)] show increased temperatures across the Caribbean region

including Central America and northern South America. The warming is strongest over land, particularly over Cuba, Jamaica, Hispaniola, Central America and northern South America, where the increase is approximately 2-5 °C (2-4 °C) under the A2 (B2) scenario across all seasons. The seasonal indices [Figure 6(f)] show that FMA and NDJ exhibit the strongest temperature response, i.e. approximately 3.1 and 2.9 °C, respectively, though across seasons the projections are within 0.5 °C of each other. As for the annual index, the temperature change in all months and in all seasons (irrespective of scenario) far exceeds that due to natural variability.

4.2.3. Extremes

Figure 7(a) shows the map of the Caribbean on which bar plots of R95 (very wet days) and Rx5 (maximum 5-day precipitation) for seven of the eight stations are superimposed. The plots show the magnitude of the index averaged over the baseline and future periods. Figure 7(b) is identical but for R10 (number of heavy precipitation days) and CDD (consecutive dry days). The general pattern is such that the far northern Caribbean stations (Bahamas and Cuba) and the Honduras station show increases in rainfall intensity in the future. This is true for R95 and Rx5 for all three stations, and for R10 (except for Cuba, which shows marginal decline). The northern Caribbean stations also show a decline in consecutive dry days by the 2071-2100 period [Figure 7(b)]. The opposite pattern is true for the remaining Caribbean stations. All show a decrease in the rainfall intensity indices and an increase in the dryness index. The patterns indicated by the seven stations are consistent with the mean projections for the basin (Section 4.1). It seems that the wetter north-drier south pattern of the 2071-2100 period is characterized by more (less) intense rainfall and less (more) dry days in the northern (southern) Caribbean basin. We consider, what this may mean in the following section.

5. Summary and discussion

The aim of this paper was twofold: to evaluate the performance of the PRECIS model in simulating observed climate variability over the Caribbean and to use it to produce climate change scenarios for the region for the 2071-2100 period. The PRECIS RCM shows reasonable skill in simulating 'present-day' rainfall and temperature variability over the Caribbean and adjacent regions. The simulated temperature climatology reproduces the summer maximum–winter minimum temperatures but with a bias ranging from +1 to +1.7 °C. The seasonal spatial patterns of temperature are also well simulated including the north–south temperature gradient in boreal winter months and the eastward expansion of the Caribbean warm pool from spring onwards.

Similarly, the simulated rainfall climatology of the central Caribbean basin (as represented by area averaged rainfall over the Caribbean index domain shown



Figure 7. Observed and simulated (baseline and A2) magnitudes for extreme rainfall events indices: (a) maximum 5-day precipitation, Rx5, and very wet days, R95, (solid bar), (b) number of days precipitation was greater than or equal to 10 mm, R10 (striped bar) and the number of days precipitation was below 1 mm, CDD (solid bar), for seven Caribbean territories.

in Figure 1) captures the bimodal characteristics of Caribbean rainfall though overestimating the late season peak rainfall and displacing the rainfall maximum to November. Both the overestimation and the displaced peak are seemingly due to the model's eastward extension of a rainfall maximum found in the far southwest corner of the basin (off the coast of Panama) at this time, such that it now falls within the Caribbean index domain. This is seen in the seasonal maps of simulated rainfall (Figure 3). If, however, only land points are averaged, the overestimation disappears and the peak now occurs in October (not shown). Otherwise, the expected

seasonal spatial patterns of rainfall for the Caribbean domain are well captured, not withstanding a dry bias over the Caribbean island masses.

The placement of the NDJ rainfall maximum south of Jamaica in NDJ is interesting and suggests that the model may be over or underestimating the strength of the Caribbean low-level jet (CLLJ). The CLLJ is similarly located and influences rainfall totals in its Caribbean entrance and exit regions and along the Caribbean coast of Central America, as well as moisture flux to the southeastern United States (Wang, 2007; Munoz *et al.*, 2008; Whyte *et al.*, 2008). Calculations of the magnitude of the CLLJ index defined by Whyte *et al.* (2008) (not shown) reveal a slight overestimation of the winter strength by the PRECIS model, which could in part explain the NDJ pattern. It may also suggest a particular sensitivity of PRECIS simulated rainfall in the Caribbean to modelled trade wind speeds, which should be borne in mind when interpreting the future climates simulated by the model.

The annual and seasonal projections under the A2 and B2 scenarios reveal three other key features worth highlighting. Firstly, for 2071-2100, the annual rainfall is projected to increase north of 22 °N and decrease $(\sim 25-50\%)$ south of this demarcation. The pattern is even more pronounced during the dry seasons NDJ and FMA. This gradient pattern, already the dominant mode of NDJ and FMA rainfall variability (Giannini et al., 2000; Spence et al., 2004; Stephenson et al., 2007), is linked to the Hadley overturning of the north tropical Atlantic. It is also the pattern manifested during the Caribbean dry season for warm phases of El Niño Southern Oscillation (ENSO) events (Stephenson et al., 2007). The implication is that under a climate changed world marked by global warming, there may be a favouring of or possible strengthening of 'present-day' circulation patterns over the region - at least for the boreal winter months.

Secondly, by the 2071–2100 period, there is a projected drying (up to 35% under the A2 scenario) during MJJ and ASO, which is a basin-wide feature. The monthly indices indicate that the drying tendency is robust for June–October and in excess of the range of variability currently observed. This observation is in line with the consensus from previous GCM work that the drying signal during the summer months is a significant feature over the Caribbean and is very likely (following IPCC notation) to manifest in the future. This has strong implications for the use of water resources, especially when coupled with the previous idea of a probable drier dry season.

Given the previous observations about the likely link between trade wind speeds and rainfall in the Caribbean domain in the PRECIS model, it is noteworthy that the simulated CLLJ index shows an increase in the phenomenon's strength between June and August by the end of the century (not shown). Strengthening of the summer manifestation of the CLLJ is associated with a drier Caribbean basin (Whyte et al., 2008) partially due to the increased vertical wind shear. Angeles et al. (2006) also noted moderate increases in wind shear during the Caribbean wet season by the end of the century. Again this is something worthy of further investigation (as is currently being done), especially as trade wind strength and the CLLJ are key components of a wider dynamical regime that is known to control the Caribbean wet season (Gamble and Curtis, 2008), which might seemingly be strengthened in the future.

Finally, it is noteworthy that Caribbean temperatures are projected to increase $(1-4 \degree C)$ following global trends. The increased temperatures are projected for all locations in the domain and are irrespective of scenario. The changes over land are larger than over open water, and the magnitude of the increase exceeds by far due to natural variability.

It is clear from the analysis that the projected changes, should they materialize, are indicative of altered dynamical circulation patterns in both the dry and wet seasons. These would in turn lead to changes in the intensity and frequency of rainfall events as indicated by the projected changes in the extreme indices. The changes in the atmospheric dynamics that govern Caribbean climate under a much warmer world scenario need to be further investigated. It must also be borne in mind that the changes depicted in this paper, though consistent with GCM projections for the region, derive from simulations from only one regional model. Future work must involve the use of additional RCMs to engender greater confidence in the projections.

The analysis, however, does highlight the additional detail obtainable from the use of an RCM, e.g. differential rainfall and heating over land versus ocean points or variable patterns over land due to orography. Such detail is not available from GCMs. Scope exists, therefore, for using the projections from PRECIS to deliver more refined climates for climate impact studies, in turn enabling more tailored adaptation options to the threat of climate change within the Caribbean region.

Acknowledgements

This work was conducted as part of a collaborative effort between Cuba (Instituto de Meterologia de la Republica), Barbados (the Department of Computer Science, Mathematics and Physics, the University of the West Indies) and Jamaica (The Climate Studies Group Mona, The University of the West Indies). The project was funded by the Caribbean Community Climate Change Centre (Belize). Special thanks to the Hadley Centre (UK) for the PRECIS model support.

References

- Aldrian E, Dümenil-Gate L, Jacob D, Podzun R, Gunawan D. 2004. Long-term simulation of Indonesian rainfall with the MPI regional model. *Climate Dynamics* 22: 794–814, DOI: 10.1007/s00382-004-0418-9.
- Alves LM, Marengo JA. 2009. Assessment of Regional Seasonal predictability using the PRECIS regional climate modeling system over South America. *Theoretical and Applied Climatology* **100**: 337–350, DOI: 10.1007/s00704-009-0165-2.
- Angeles ME, Gonzalez JE, Erickson DJ III, Hernández JL. 2006. Predictions of future climate change in the Caribbean region using global general circulation models. *International Journal of Climatology* 27(5): 555–569, DOI: 10.1002/joc.1416.
- Ashby SA, Taylor MA, Chen AA. 2005. Statistical models for predicting rainfall in the Caribbean. *Theoretical and Applied Climatology* 82: 65–80, DOI: 10.1007/s00704-004-0118-8.
- Bloom A, Kotroni V, Lagouvardos K. 2008. Climate change impact of wind energy availability in the Eastern Mediterranean using the regional climate model PRECIS. *Natural Hazards and Earth System Sciences (NHESS)* 8: 1249–1257.
- Castro DM, da Rocha RP, Benzanilla-Morlot A, Alvarez-Escudero L, Reyes-Fernández JP, Silva-Vidal Y, Arritt RW. 2006. Sensitivity studies of the RegCM3 simulation of summer precipitation, temperature and local wind field in the Caribbean region. *Theoretical*

and Applied Climatology 86: 5-22, DOI: 10. 1007/s00704-005-0201-9.

- Chen AA, Rhoden CL, Taylor MA. 2006. Climate change science and future climate change scenarios. In *Climate Change Impact on Dengue: The Caribbean Experience*, Chen AA, Chadee DD, and Rawlins S (eds). Climate Studies Group Mona, University of the West Indies: Mona, Jamaica; 66–77.
- Chen AA, Roy A, McTavish J, Taylor MA, Marx L. 1997. Using SST Anomalies to Predict Flood and Drought Conditions for the Caribbean. COLA Report 49.
- Chen AA, Taylor MA. 2002. Investigating the link between early season Caribbean rainfall and the El Niño +1 year. *International Journal of Climatology* **22**: 87–106, DOI: 10.1002/joc.711.
- Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P. 2007. Regional climate projections. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA; 847–940.
- Dobler A, Ahrens B. 2008. Precipitation by a regional climate model and bias correction in Europe and Asia. *Meteorologische Zeitschrift* 17(4): 499–509.
- Gamble DW, Curtis S. 2008. Caribbean precipitation: review, model and prospect. *Progress in Physical Geography* **32**(3): 265–276.
- Giannini A, Kushnir Y, Cane MA. 2000. Inter-annual variability of Caribbean rainfall, ENSO, and the Atlantic Ocean. *Journal of Climate* 13: 297–311.
- Hastenrath S. 1976. Variations in low-latitude, circulation and extreme climatic events in the tropical Americas. *Journal of Atmospheric Sciences* 33: 202–215.
- Islam S, Rehman N, Sheikh MM. 2009. Future change in the frequency of warm and cold spells durations over Pakistan simulated by the PRECIS regional climate model. *Climate Change* 94: 35–45, DOI 10.1007/s10584-009-9557-7.
- Jones RG, Hassell D, Hudson D, Wilson S, Jenkins G, Mitchell J. 2003. Workbook on Generating High Resolution Climate Change Scenarios Using PRECIS. UNDP: New York.
- Jones RG, Noguer M, Hassell D, Hudson D, Wilson S, Jenkins G, Mitchell J. 2004. Generating High Resolution Climate Change Scenarios Using PRECIS. Met Office Hadley Centre: Exeter, UK.
- Jury MR. 2009. A quasi-decadal cycle in Caribbean climate. Journal of Geophysical Research 114: D13102, DOI:10.1029/2009JD011741.
- Kalnay É, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society 77(3): 437–471.
- Kotroni V, Lykoudis S, Lagouvardos K, Lalas D. 2008. A fine resolution regional climate change experiment for the Eastern Mediterranean: Analysis of the present climate simulations. *Global* and Planetary Change 64(1–2): 93–104.
- Kumar KR, Sahai AK, Kumar KK, Patwardhan SK, Mishra PK, Revadekar JV, Kamala K, Pant GB. 2006. High-resolution climate change scenarios for India for the 21st century Indian Institute of Tropical Meteorology. *Current Science* **90**(3): 334–345.
- Marengo JA, Jones R, Alves LM, Valverde MC. 2009. Future change of temperature and precipitation extremes in South America as derived from the PRECIS regional climate modeling system. *International Journal of Climatology*, DOI: 10.1002/joc.1863.
- Martis A, van Oldenborgh GJ, Burgers G. 2002. Predicting rainfall in the Dutch Caribbean – more than El Niño?. *International Journal of Climatology* 22: 1219–1234.
- Mearns LO, Giorgi F, Whetton P, Pabon D, Hulme M, Lal M. 2003. Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments. DDC IPCC TGCIA.
- Moberg A, Jones PD. 2004. Regional climate models simulations of daily maximum and minimum near-surface temperatures across Europe compared with observed station data for 1961–1990. *Climate Dynamics* 23: 695–715.
- Munoz E, Busalacchi AJ, Nigam S, Ruiz-Barradas A. 2008. Winter and summer structure of the Caribbean Low-Level Jet. *Journal of Climate* 21: 1260–1276.
- Nakicenovic N, Swart R (eds).2000. Special Report on Emissions Scenarios. A Special Report of Working Group III of the

Copyright © 2010 Royal Meteorological Society

Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA; 599.

- Neelin JD, Chou C, Su H. 2003. Tropical drought regions in global warming and El Niño teleconnections. *Geophysical Research Letters* 30(24): 2275, DOI: 10.1029/2003GL018625.
- New M, Todd M, Hulme M, Jones P. 2001. Precipitation measurements and trends in the twentieth century. *International Journal of Climatology* 21: 1899–1922.
- Nurse LA, Sem G. 2001. Small island states. In Climate change 2001 – the scientific basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Houghton. JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Xiaosu D (eds). Cambridge University Press:Cambridge; 843–875.
- Peterson TC, Taylor MA, Demeritte R, Duncombe DL, Burton S, Thompson F, Porter A, Mercedes M, Villegas E, Fils RS, Klein Tank A, Martis A, Warner R, Joyette A, Mills W, Alexander L, Gleason B. 2002. Recent changes in climate extremes in the Caribbean region. *Journal of Geophysical Research* **107**(D21): 4601, DOI: 10.1029/2002JD002251.
- Rowell DP. 2005. A scenario of European climate change for the late 21st century seasonal means and inter-annual variability. *Climate Dynamics* **25**: 837–849.
- Singh B. 1997a. Climate-related global changes in the southern Caribbean: Trinidad and Tobago. *Global and Planetary Change* **15**: 93–111.
- Singh B. 1997b. Climate changes in the greater and southern Caribbean. *International Journal of Climatology* **17**: 10936–1114.
- Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL. 2007. Summary for Policymakers. Cambridge University Press: Cambridge.
- Spence JM, Taylor MA, Chen AA. 2004. The effect of concurrent sea surface temperature anomalies in the tropical Pacific and Atlantic on Caribbean Rainfall. *International Journal of Climatology* 24: 1531–1541, DOI: 10.1002/joc.1068.
- Stephenson TS, Chen AA, Taylor MA. 2007. Toward the development of prediction models for the primary Caribbean dry season, accepted. *Theoretical and Applied Climatology* **92**: 87–101, DOI: 10.1007/s00704-007-0308-2.
- Tadross M, Jack C, Hewitson B. 2005. On RCM-based projections of change in southern African summer climate. *Geophysical Research Letters* 32: L23713, DOI:10.1029/2005GL024460.
- Taylor MA, Centella A, Charlery J, Borrajero I, Bezanilla A, Campbell J, Rivero R, Stephenson TS, Whyte F, Watson R. 2007. In *Glimpses of the Future: A Briefing from the PRECIS Caribbean Climate Change Project*. Caribbean Community Climate Change Centre: Belmopan, Belize.
- Taylor MA, Enfield DB, Chen AA. 2002. Influence of the tropical Atlantic versus the tropical Pacific on Caribbean rainfall. *Journal of Geophysical Research* **107**(C9): 3127, DOI: 10,1029/2001JC001097.
- Wang C. 2007. Variability of the Caribbean low-level jet and its relations to climate. *Climate Dynamics* **29**: 411–422.
- Wang C, Enfield DB. 2001. The tropical Western Hemisphere warm pool. *Geophysical Research Letters* 28(8): 1635–1638.
- Whyte FS, Taylor MA, Stephenson TS, Campbell JD. 2008. Features of the Caribbean low level jet. *International Journal of Climatology* 28: 119–128.
- Wilby RL, Dawson CW, Barrow EM. 2002. SDSM A decision support tool for the assessment of regional climate change impacts. *Environmental Modelling and Software* 17: 147–159.
- Wilby RL, Wigley TML. 1997. Downscaling general circulation model output: A review of methods and limitations. *Progress in Physical Geography* 21(4): 530–548.
- Xianfu L. 2006. Guidance on the development of regional climate scenarios for vulnerability and adaptation assessments within the Framework of National Communications from Parties not Included in Annex I to the United Nations Framework Convention on Climate Change, National Communications Support Programme, UNDP-UNEP-GEF New York, USA, 1–41.
- Xie P, Arkin PA. 1997. Global Precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the American Meteorological Society* **78**(11): 2539–2558.
- Zhang Y, Yinlong X, Wenjie D, Lijuan C, Sparrow M. 2006. A future climate scenario of regional changes in extreme climate events over China using the PRECIS climate model. *Geophysical Research Letters* 33: L24702, DOI:10.1029/2006GL027229.