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CLIMATE CHANGE AND THE CARIBBEAN: REVIEW AND RESPONSE

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Abstract

Caribbean economies, lifestyles, activities, practices and operational cycles are intricately linked to climate, making them vulnerable to its variations and/or changes. As examples, climate extremes impact agriculture, fisheries, health, tourism, water availability, recreation, and energy usage, among other things. There is however limited incorporation of climate information in the long term developmental plans and policies of the region. This is in part due to a knowledge deficit about climate change, it's likely manifestation in the region and the possible impact on Caribbean societies. In this paper, a review of the growing bank of knowledge about Caribbean climate science; variability and change is undertaken. Insight is offered into the basic science of climate change, past trends and future projections for Caribbean climate, and the possible implications for the region. In the end a case is made for a greater response to the threats posed by climate change on the basis of the sufficiency of our current knowledge of Caribbean climate science. A general profile of what the response may look like is also offered.

Keywords: climate change, Caribbean, global warming, adaptation, mitigation, variability

Resumen

Las economías de los países caribeños, los estilos de vida, las actividades, y las prácticas y ciclos operativos están íntimamente ligados al clima, por lo que estas sociedades son vulnerables a los cambios y/o las variaciones del mismo. Los extremos climáticos afectan la agricultura, pesca, salud, turismo, disponibilidad de agua, recreación, uso de energía, para sólo mencionar algunos ejemplos. Sin embargo, no se incorpora mucha información acerca del clima en los planes de desarrollo a largo plazo ni en el desarrollo de políticas públicas de la región. Esto se debe en parte a un desconocimiento acerca del cambio climático, su manifestación probable en la región y su posible impacto en las sociedades caribeñas. Este artículo presenta una revisión del creciente banco de conocimiento sobre la ciencia climática caribeña;

sus cambios y variabilidad. Se ofrece una breve descripción de los fundamentos de la ciencia que estudia el cambio climático, las tendencias pasadas y las proyecciones futuras para el clima en el Caribe, así como los posibles impactos para la región. Al final se aboga por que haya una mayor respuesta a las amenazas que representan los cambios climáticos entendiendo que la ciencia climática caribeña cuenta con suficiente información actualizada. Además, se presenta un perfil general de cómo podría ser tal respuesta.

Palabras claves: cambio climático, Caribe, calentamiento global, adaptación, mitigación, variabilidad

Résumé

Les économies des pays caribéens, les modes de vie, les activités, les pratiques et les cycles opérationnels sont intimement liés au climat, à cause de la vulnérabilité de ces sociétés face aux changements climatiques et/ou aux variations de ces deniers. Les extrêmes climatiques affectent l'agriculture, la pêche, la santé, le tourisme, l'approvisionnement en eau, la consommation d'énergie, pour ne citer que quelques exemples. Cependant, peu d'importance est accordé au climat dans les plans de développement à long terme, ni dans le développement des politiques publiques de la région. Ceci est dû en partie à un manque de connaissance sur le changement climatique, sa probable manifestation dans la région et son possible impact dans les sociétés caribéennes. Cet article présente une vue d'ensemble de la croissante banque de connaissances sur la science du climat caribéen ; ses changements et ses variabilités. On propose une brève description des éléments fondamentaux de la science qui étudie le changement climatique, les tendances passées et les projections futures pour le climat dans la Caraïbe, ainsi que les menaces que représentent les changements climatiques, tout en considérant que tenant compte la science climatique caribéenne dispose suffisamment de données récentes. En outre, on présente un aperçu général de la façon dont le problème climatique pourrait être abordé.

Mots-clés : changement climatique, Caraïbe, réchauffement global, adaptation, mitigation, variabilité

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> 'Climate change is an issue of our times—one that the Caribbean cannot avoid contending with, preferably through voluntary action, now as opposed to later, and with a paradigm shift in thought and action equivalent to the shift necessitating it.' – Climate Studies Group at Mona 2011

Introduction – The Reality: Climate Change a Caribbean Developmental Issue

Human induced changes to the climate system and their impacts have emerged as a leading global concern in the last few decades. The changes, including increasing temperatures, more frequent extreme weather conditions and rising sea levels, disproportionately impact regions across the globe (IPCC 2007) and the Caribbean region has been identified as being amongst the most vulnerable (Lal, Harasawa and Takahashi 2002; Mimura *et al*. 2007).

The region's vulnerability arises from an inherent *climate sensitivity* which, on the one hand, is attributable to its geographic location which gives rise to a distinct climatology. The location of the Caribbean region makes it subject to the influences of synoptic features of both the tropical Atlantic (in which it is located) and tropical Pacific basins including the migration of the north Atlantic subtropical high and the Inter Tropical Convergence Zone, steady easterly trade winds, the expansion of the western hemisphere warm pool, the intrusion of cold fronts, and the passage of tropical depressions, storms and hurricanes (see Ashby, Taylor and Chen (2005) for a review of Caribbean climatology). Together these features define dry (December-April) and wet (May-November) seasons (Taylor, Enfield and Chen 2002; Gianinni *et al*. 2000; Chen *et al*. 1997) and along with a summer temperature maximum provide the backdrop against which Caribbean life has evolved and still revolves; lifestyles, disease cycles, recreational activities, and practices and operational cycles including planting and reaping (CARSEA 2007; Mimura *et al*. 2007; Pulwarty, Nurse and Trotz 2010).

The region's *climate sensitivity* is further enhanced by its geographic characteristics. With the exception of Guyana, Suriname and Belize, the Caribbean is composed of small islands and cays which are either low lying (e.g., Bahamas, most of the Grenadines, Barbuda), volcanic with mountainous interiors and very short coastlines (e.g., St. Kitts and Nevis, St. Lucia, St. Vincent, Dominica, Grenada, Montserrat), or with topographies combining both hilly interiors and limited coastal plains (e.g., Antigua, Barbados, Haiti, Jamaica and Trinidad and Tobago). For most of the islands the combination of size and topography restricts the availability of land and drives the use of narrow coastal areas and/or steep hillsides for the location of key infrastructure and population settlements (Pulwarty, Nurse and Trotz 2010; Simpson *et al*. 2010; Lewsey, Cid and Kruse 2004). In either instance there is inherent sensitivity to climate variations.

The region's *climate sensitivity* is also rooted in its dependence on economic activities such as agriculture and tourism and a reliance on seasonal rainfall for water. Both tourism and agriculture are critical to Caribbean population livelihoods and well-being. Both represent majority employers—approximately 30 percent and 13 percent respectively of the regional labour force (Pulwarty, Nurse and Trotz 2010; World Travel & Tourism Council 2008); and separately or in tandem are significant contributors to the GDPs of most Caribbean countries—agriculture contributing anywhere from 10 percent to 35 percent (STATIN 2000) and tourism and travel accounting for 13 percent (World Travel & Tourism Council 2008). The direct and indirect linkages between these sectors and climate (temperature, rainfall, extreme events) are increasingly being better documented (e.g., Ebi, Lewis and Corvalan 2006; Donner, Knutson and Oppenheimer 2007; Simpson *et al*. 2010) and include the fact that they are primary users of regional water stock which is strongly climate driven (Cashman, Nurse and Charlery 2010).

The (almost) intractability of the contributing factors ensures that *climate sensitivity* is both interwoven into and entrenched in all levels of Caribbean existence (at least for the present time). This in turn makes *vulnerability* to climate variations similarly a reality of Caribbean existence. That is, the region is highly susceptible to short (climate variability) or long timescale (climate change) changes in climate with the impacts being felt throughout Caribbean existence. The evidence is most easily seen in the annual impact of hurricanes, floods or droughts on the economies of the region, as captured in Table 1 for some recent extreme events.

It is the region's sensitivity and attendant vulnerability to climate variations that make climate change a developmental issue for the Caribbean. The region is inevitably vulnerable to the longer term changes in climate which may manifest as both increased variability (e.g., more frequent weather extremes) and incremental change (e.g., sea level rise). Present challenges are the quantification of these longer timescale changes and their associated impacts and the mainstreaming of appropriate response strategies into national and regional developmental plans.

In the ensuing sections of this paper we offer a review of climate change science for the Caribbean region, assessing what is currently known about how climate has already changed and how climate is projected to change. With reference to the likely implications for key sectors, we further assess whether the present knowledge is sufficient to

Table 1. Examples of estimated costs of damages caused by extreme events in the Caribbean.

Year	Country	Event	Estimated Damage Cost (US$)	Reference
1987	St. Vincent and the Grenadines	Drought affected 1000 people	5 million	EM-DAT (WHO Emergency Event Database) (2011)
1990	Belize	Cold wave	2.25 million	CARICOM (2003)
1993	Trinidad	Flooding caused 5 deaths	70,000	CARICOM (2003)
1998	St. Kitts and Nevis	Hurricane Georges affected 10,000 people	74 million	UNFCCC (2001); CARICOM (2003)
1999	St. Vincent and the Grenadines	Hurricane Lenny damaged roads, coastline, and houses	143,000	UNFCCC (2000)
2004	Dominican Republic	Hurricane Jeanne caused major damages to agricultural and production sectors	270 million	ECLACb (2005)
2004	Grenada	Hurricane Ivan killed 28 people and devastated agriculture, particularly nutmeg	889 million	ECLACa (2005)
2005	Cuba	Hurricane Dennis resulted in 16 deaths and damage to 120,000 homes	1.4 billion	NOAA (2005)
2010	St. Lucia	Hurricane Tomas killed 14 people and damaged major infrastructure	37 million	Jamaica Observer (2010)
2010	Jamaica	Tropical Storm Nicole caused flooding in 107 communities, landslides in 17, and storm surges in 16	125 million	ODPEM (2010)

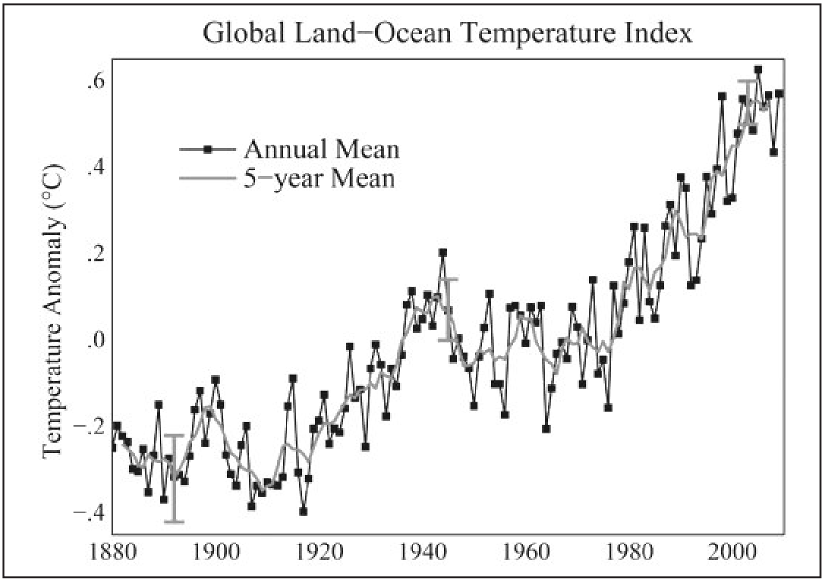
premise action as a region and what the profile of response to climate change may look like.

Review Part 1 - Climate Has Changed

What is Climate Change?

Climate change can be characterised as distinct shifts in measures of climate lasting for a long period of time. The changes are most readily seen in the rise in mean global temperature over the past century (Figure 1). The warmer temperatures in turn cause other changes in the

Figure 1. Change in global surface temperature relative to 1951-1980 average temperatures (bars represent measurement uncertainty). From NASA, 2010.

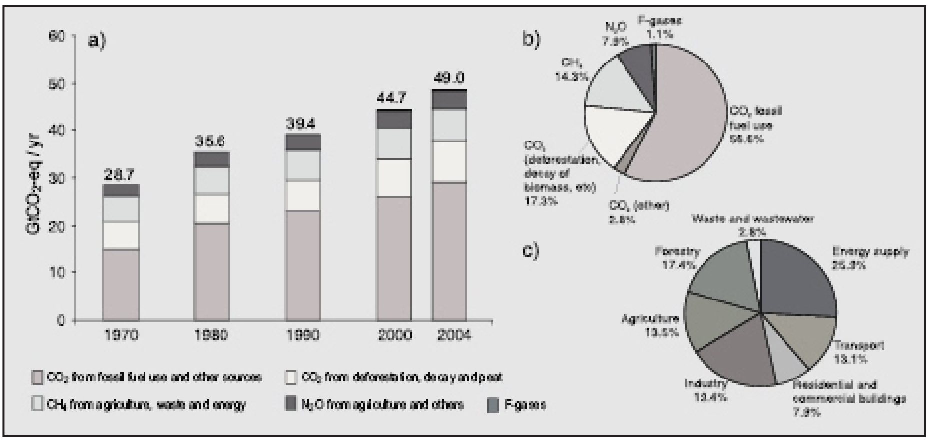


earth-atmosphere-ocean system, e.g., sea level rise, or decreasing snow cover. Global warming can be due to natural variations, volcanic eruptions and human activity. Natural variations occur as a normal phase in the life of the Earth and can arise due to changes in the earth's orbit or changes in solar intensity. It is natural variations that yielded the Ice Age which occurred in the pre-industrialized era (Mann, Bradley and Hughes 1998; Crowley 2000). Volcanic eruptions can also influence global climate by blocking sunlight, by altering the aerosols in the atmosphere and by altering carbon dioxide (CO_2) concentrations. However, these effects are not long term.

Human activity is arguably the most debated of climate influences. Land-use practices alter land cover resulting in changes in the reflective properties of the Earth. Since the 1750s, the post-industrial revolution has led to a rise in the burning of fossil fuels and biomass, which along with the removal of forest cover, has significantly altered the composition of the atmosphere primarily through the addition of greenhouse gases (GHGs) such as carbon dioxide (CO_2), water vapour (H_2O) and methane (CH_4). Human activities have been the primary source of a 36% increase in CO_2 and a 148% rise in methane (CH_4) concentrations since the pre-industrialized era (IPCC 2007). GHGs naturally act as a partial blanket for long wave radiation coming from the earth's surface and help to maintain the earth at a habitable temperature—a phenomenon known as the natural greenhouse effect. The increased concentrations of GHGs have enhanced the greenhouse effect resulting in a steady warming of the earth over the last century.

The principal human activities contributing to increased GHGs are given in Figure 2. The IPCC (2007) states that it is 'unlikely that the drastic changes in temperature experienced within the latter half of the last century are due solely to natural variability.' Climate reconstruction studies also show that the historical increases in global mean temperature can only be achieved if anthropogenic (human induced) impacts are accounted for (IPCC 2007).

Figure 2. (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004. (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of carbon dioxide equivalents (CO_2-eq). (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq. (Forestry includes deforestation). From IPCC, 2007.



Global and regional Climate Change

The National Oceanic and Atmospheric Administration (NOAA) suggests that as the world warms there should be seven increasing indicators—sea surface temperatures, temperatures over the sea, temperatures over the land, oceanic heat content, atmospheric humidity, sea levels and upper atmospheric temperatures—and three decreasing indicators—sea ice, snow cover and glaciers (Arndt, Baringer and Johnson 2010). There is ample evidence to support these kinds of changes globally (IPCC 2007). We discuss below some of the historical climate trends from both a global and Caribbean perspective.

Warmer temperatures

Global temperatures have increased by about 0.74°C (0.56°C to 0.92°C) since the 19th century (IPCC 2007). The warming trend is seen in both daily maximum (day time) and minimum (night time) temperatures, with minimum temperatures showing a steeper increasing trend than maximum temperatures. Land areas have tended to warm faster than ocean areas and 'winter' months have warmed faster than summer months (IPCC 2007).

Similar warming trends have been noted for the Caribbean. Analyses by country indicate an average warming of approximately 0.6°C since the 1960s or ~0.12-0.14 degrees Celsius per decade (McSweeney, New and Lizcano 2008). Peterson *et al*. (2002) show changes in temperature extremes calculated over the period 1958-1999. The frequency of very hot days and very hot nights exhibits an increasing trend, with nights warming at a faster rate than days. This implies a decrease in the diurnal temperature range i.e. the difference between the day time and night time temperatures. Peterson *et al*. (2002) also find that the frequency of very cool days and very cool nights exhibits a decreasing trend over the fifty year period and that the difference between the highest and lowest temperature for the year (the annual temperature range) is decreasing, though the trend is not significant at the 10% level. Alexander *et al*. (2006) show that these changes in the Caribbean are consistent with the rest of the globe, while a similar study for nearby Central America and northern South America (including their Caribbean coasts) corroborates the Caribbean trends (Aguilar *et al*. 2005).

Variable rainfall

Global rainfall trends vary widely by region and over time and show considerable variability on interannual and longer timescales. Though there have generally been significant changes in amount, intensity, frequency and type of precipitation for various parts of the world, there has been no statistically significant overall trend for global precipitation over the past century (IPCC 2007). Some specific global trends of relevance from the IPCC (2007) suggest that precipitation has generally increased over land north of 30°N from 1900-2005, but has mostly declined over the tropics since the 1970s. There has been an increase in the number of heavy precipitation events over many areas during the past century, as well as an increase since the 1970s in the prevalence of droughts —especially in the tropics and subtropics. Eastern North and South America, northern Europe and northern and central Asia have been found to be wetter, while there has been drying in the Sahel, southern

Africa, the Mediterranean and southern Asia.

Trends in Caribbean precipitation are not as marked as for temperature and, much like the global signal, are characterised by significant variability (Singh 1997a; Singh 1997b; Peterson *et al*. 2002). Annually the Caribbean is characterised by a dry winter-wet summer pattern (Taylor and Alfaro 2005; Ashby, Taylor and Chen 2005), with a 'midsummer drought' that progresses from June-July (Chen and Taylor 2002; Gamble, Parnell and Curtis 2008). The amount of rainfall received in each period is strongly modulated by changes in the tropical Atlantic and tropical Pacific including by the El Niño Southern Oscillation (ENSO) phenomenon (Chen *et al*. 1997; Giannini, Kushinir and Cane 2000; Chen and Taylor 2002; Taylor, Enfield and Chen 2002; Spence, Taylor and Chen 2004; Ashby, Taylor and Chen 2005; Gamble, Parnell and Curtis 2008). For example, the late rainfall season (August-November) tends to be drier in El Niño years and wetter in La Niña years (Giannini, Kushinir and Cane 2000; Martis, van Oldenborgh and Burgers 2002; Taylor, Enfield and Chen 2002; Ashby, Taylor and Chen 2005). El Niño events have increased in frequency, severity, and duration since the 1970s (Stahle *et al*. 1998; Mann, Bradley and Hughes 2000), implying that there have been more extremes in weather in the region since the 1970s. Anecdotally, recent climatic events seem to support this. Gamble *et al*. (2010) note that "Farmer perceptions of increasing drought might reflect relative changes in the early (April-June) and principal (August-November) growing seasons. Specifically, many farmers commented in interviews that drought is becoming more prevalent". There has, however, been little or no region-wide analysis undertaken to confirm these kinds of changes in weather extremes.

The analysis of Caribbean rainfall trends has generally been constrained by a paucity of daily station data. Notwithstanding, Neelin *et al*. (2006) use multiple sources to show a modest but statistically significant drying trend for the Caribbean's summer period in recent decades. Other analyses suggest that the maximum number of consecutive dry days is decreasing (1% significant level) and the number of heavy rainfall events in the Caribbean is increasing (10% significance level) (Peterson *et al*. 2002). The latter results may not take into account differences in the precipitation regime between the north and south Caribbean. There has also been an apparent increase in rainfall variability in the region which, in addition to large-scale oscillations between drier and wetter periods in the Eastern Caribbean, adds to uncertainty in overall trend evaluation across the region (Gamble 2009). The Caribbean changes are nonetheless not dissimilar to those reported from global analysis for the tropical regions (Trenberth *et al*. 2007).

Tropical storms and hurricanes

There was greater hurricane activity in the Atlantic from the 1930s to the 1960s, in comparison with the 1970s and 1980s and the first half of the 1990s. However, beginning in 1995, analysis of observed tropical cyclones shows a dramatic increase in frequency. The number of named tropical storms (hurricanes) in the Atlantic averaged 14.5 (7.6) per year from 1995 to 2009, compared with 11.6 (6.1) per year between 1980 and 1994 (Pulwarty, Nurse and Trotz 2010). This was in spite of three years (1997, 2002, and 2007) of low hurricane incidence coinciding with El Niño occurrences. An El Niño suppresses hurricane activity whereas a La Niña tends to enhance it.

The prevailing science suggests that increases seen in the last 15 years are more attributable to the region being in the positive (warm) phase of a multidecadal fluctuation (the Atlantic Multidecadal Oscillation) and not necessarily due to global warming (Goldenberg *et al*. 2001; Landsea *et al*. 2010). Attempts to link warmer sea surface temperatures with the increased number of hurricanes have proven to be inconclusive (Pielke *et al*. 2005; Webster *et al*. 2005). Nonetheless, both frequency and duration of hurricanes display recent increasing trends significant at the 99% confidence level. Webster *et al*. (2005) also note an almost doubling of the category 4 and 5 hurricanes. While the number of intense hurricanes has been rising, the maximum intensity of hurricanes has, however, remained fairly constant over the 35 year period.

Sea levels

One consequence of rising temperatures has been sea-level rise due to the expansion of ocean water caused by warmer ocean temperatures, melting of mountain glaciers and small ice caps, and to a lesser extent the melting of the Greenland and Antarctic Ice Sheets. The rate of observed sea level rise increased from the mid-19th to the mid-20th century. During the 20th century, sea level rose at an average rate of 4.8 to 8.8 inches per century (1.2-2.2 mm/year) (IPCC 2007). The IPCC (2007) notes that most of the Pacific and Atlantic basins are experiencing average to above-average sea level rise. Observed estimates over the period 1950 to 2000 also suggest that the rise in the Caribbean appears to be near the global mean (Church *et al*. 2004), although there is likely nonuniformity across the region due to differential tectonic displacement within the basin (Hendry 1993; Gamble 2009). More recent examinations of satellite measurements, however, estimate that global sea level has been rising at an even more alarming rate of 9 to 15 inches per century (2.4-3.8 mm/yr) since 1993 (Bindoff *et al*. 2007).

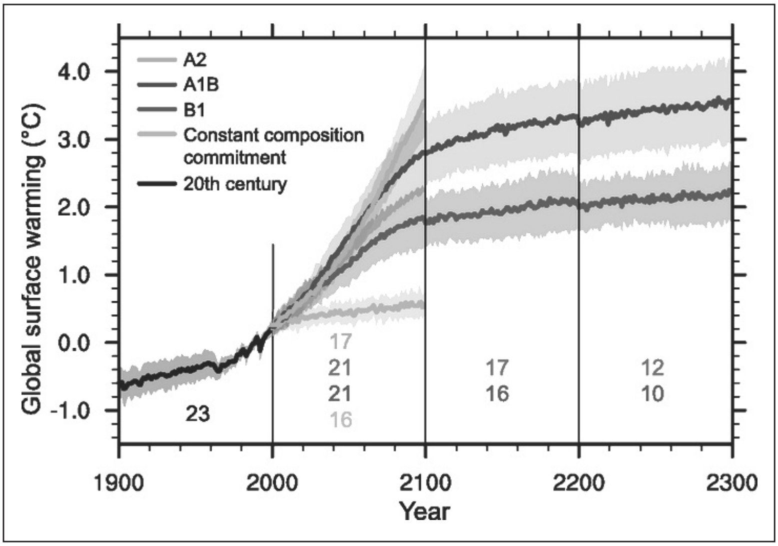
Review Part 2 - Climate Will Change

Climate models

There is no way to accurately predict future climate change which will be driven by the concentrations of GHGs in the atmosphere (see again Section 2.1). Future concentrations of GHGs will depend on multiple factors including changes in population, economic growth, energy use and technology. To address this challenge the IPCC constructed the Special Report on Emissions Scenarios (SRES) which represent possible pathways for future GHG emissions (see Nakićenović *et al*. 2000). There are 40 different scenarios or storylines divided into four families. None assume any future policies that explicitly address climate change although they necessarily encompass policies of other types to account for future global development paths.

The SRES scenarios are used to drive Global Climate Models (GCMs) to produce representations of future climate (see Figure 3). GCMs are comprehensive mathematical descriptions of key processes in the atmosphere, ocean and land surface (e.g., clouds, rainfall, winds). They simulate climate across the globe on coarse scales of a few hundred kilometres and represent for regions like the Caribbean, a first (albeit coarse) guess of its future climate. The models are run from present

Figure 3. Mean trends of surface warming projected for the 21st century relative to the period 1980–1999 under the scenarios A2, A1B and B1. Stabilization scenarios (A1B and B1) have been extended beyond 2100. From IPCC, 2007.



through the end of the current century from which future climate statistics are obtained.

To obtain information on a regional scale the outputs from the GCM are fed into high resolution regional climate models (RCMs) or into statistical downscaling models. RCMs are also comprehensive physical models of atmospheric, oceanic and land processes but with higher resolutions (e.g., up to 50 km). Statistical downscaling, on the other hand, uses observations at a particular location (e.g., rainfall measured at a station) to obtain relationships with large-scale climate variables (e.g., surface pressure, temperature). The relationships are applied to GCM outputs to determine future changes in the local variable. The technique assumes that the relationships obtained from current observations will remain unchanged in the future.

All climate models, whether GCMs or RCMs, have varying degrees of uncertainty. Uncertainties can however be reduced by running a number of models under varying initial conditions and varying emissions scenario.

The PRECIS experiments

The PRECIS-Caribbean Initiative represented a significant milestone in Caribbean climate science. Under the initiative, a coordinated effort was initiated in 2003 to provide future climate change scenarios for the region using the PRECIS (Providing Regional Climates for Impact Studies) RCM. The initiative involved collaboration between regional scientists and institutions located in Barbados, Jamaica, Cuba and Belize and was premised on a shared workload to quickly produce the needed future scenarios as well as build regional capacity to do so. Details of the PRECIS-Caribbean Project are given in Taylor *et al*. (2007).

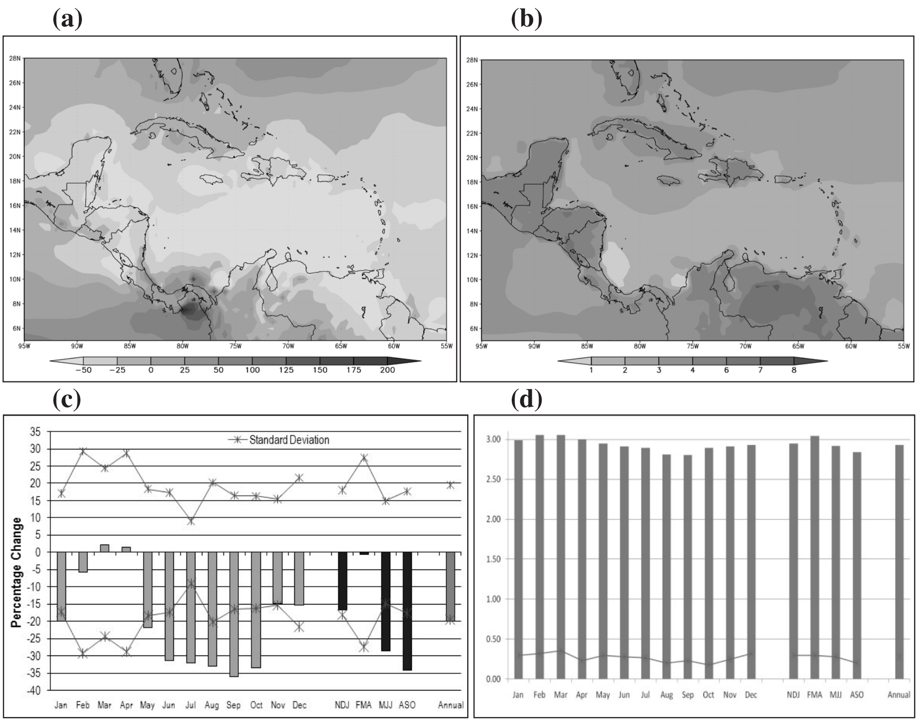
PRECIS experiments were run at the 50 km resolution over 0 - 36°N and 55 - 120°W. The domain covered the Caribbean, Central America, Florida and the northern territories of South America as well as portions of the Atlantic and Pacific oceans. The domain allowed for the inclusion of the large-scale influences from the Atlantic and Pacific that modulate the regions climate (see again Section 1). The PRECIS was run over present day (1961-1990) and future (2071-2100) periods forced with output from either the HadCM3 GCM (Jones *et al*. 2004) or the ECHAM GCM (Jones *et al*. 2003). The GCMs used either a relatively high SRES emissions scenario (A2) or a relatively low SRES emissions scenario (B2) (Nakićenović *et al*. 2000) to provide a range for the projections. The validation of the PRECIS model for present-day climate is described in Campbell *et al*. (2010). The PRECIS results form the basis for the rainfall and temperature projections presented below.

Caribbean Climate Projections

Warmer temperatures

Irrespective of scenario or technique employed, the Caribbean is expected to warm through the end of the century (Figure 4). The PRECIS RCM shows an increase in annual surface temperature of between 1 and 5°C by the end of the century over present day (1961-90) values. These results are consistent with increased temperature projections obtained using a Statistical DownScaling Model (Wilby, Dawson and Barrow 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, Chadee and Rawlins 2006), and with results extracted from GCM

Figure 4. Projections of changes in Caribbean climate up to the end of the century (2071-2100) as simulated by the PRECIS RCM under the A2 scenario. (a) Percentage change in rainfall, (b) Absolute change in temperature (°C), (c) Percentage mean monthly, seasonal and annual rainfall change averaged over a Caribbean domain, (d) Mean monthly, seasonal and annual temperature change averaged over a Caribbean domain. All changes are with respect to 1961-1990. Adapted from Campbell *et al*. 2010.



realizations (Singh 1997a; 1997b; Ángeles *et al*. 2007; Christensen *et al*. 2007; McSweeney, New and Lizcano 2008). Warming is greater under the A2 (high) versus B2 (low) emission scenario and is across all seasons and for all countries. See for example, projections by country in Table 2. The region-wide warming is consistent with projections for other parts of the globe, and far exceeds historical variability (Campbell *et al*. 2010).

Other studies also suggest for the Caribbean:

- Substantial increases in the frequency of days and nights that are considered 'hot' in current climate. For many Caribbean countries 'hot' days and nights occur up to 95% of all days by the 2090s (McSweeney, New and Lizcano 2008).
- Decreases in the frequency of days and nights that are considered 'cold' in current climate. For many Caribbean countries these events are expected to become exceedingly rare by the end of the century (McSweeney, New and Lizcano 2008).
- Land areas warming more than ocean areas (Campbell *et al*. 2010).
- Increases in sea surface temperatures in the Caribbean by similar amounts to air temperatures and similar to those for minimum air temperatures over coastal regions and islands (Simpson *et al*. 2010).

Less rainfall

The range of uncertainties in rainfall projections for the Caribbean, like other regions, is substantial, with some models suggesting increases

Table 2. Examples of future projections of average absolute temperature change (degrees °C) for the period 2071-2099 using the PRECIS (Hadley) model. Each column contains a range of values across the A2 and B2 scenarios.

Country	Absolute temperature change (°C)
Cayman Islands	2.1 - 2.7
Anguilla	2.3 - 3.2
Barbados	2.0 - 2.6
St. Vincent and the Grenadines	2.1 - 2.7
Guadeloupe	2.1 - 2.8
Antigua and Barbuda	1.9 - 2.4
Turks and Caicos	2.1 - 2.7
St. Kitts and Nevis	1.7 - 2.2

and others decreases. Therefore more confidence exists in the temperature patterns than in those for rainfall. Notwithstanding, annual rainfall projections from PRECIS show a drying tendency for the main Caribbean basin of between 25% and 30% (A2 scenario) in relation to present day values by the end of the century (Figure 4). This is consistent with the GCM studies of Christensen *et al*. (2007) (–39 to +11%, with a median of –12%) and Rauscher *et al*. (2008). The future rainfall patterns vary with seasons (Figure 4) with PRECIS showing that between June and October, i.e., the mean Caribbean wet season, the drying signal is robust and exceeds historical variability (Campbell *et al*. 2010). The summer drying is seen in other GCM studies (Christensen *et al*. 2007; Angeles *et al*. 2007; Rauscher *et al*. 2008). A significantly reduced wet season has serious implications for the Caribbean region, particularly in the context of an already deepening mid-summer drought (Gamble 2009).

Other studies note for the region:

- During November-January the northern Caribbean (north of 22°N) is projected to be wetter and the southern Caribbean drier by the end of the century (Campbell *et al*. 2010).
- Statistically downscaled results for stations in Jamaica show a summer rainfall decrease through the 2080s but an increase for the analyzed stations in Trinidad and Barbados (Chen, Chadee and Rawlins 2006).
- The proportion of total rainfall that falls in heavy events for the Caribbean islands decreases in most GCM model projections (McSweeney, New and Lizcano 2008).

Rising sea levels

By the end of the century under an A1B scenario (emissions are somewhere between A2 and B2 values), global sea levels are expected to rise by 0.21 to 0.48 meters (IPCC 2007). The IPCC models, however, exclude future rapid dynamical changes in ice flow, which if accounted for may lead to a doubling or more of the IPCC estimates (e.g., Vermeer and Rahmstorf 2009; Grinsted, Moore and Jefrejeva 2009; Jevrejeva, Moore and Grinsted 2010). It is anticipated that sea level rise will not be geographically uniform in the future which is consistent with the non-uniform patterns currently seen. Recent studies also suggest that sea level rise in the Caribbean may be more pronounced than in other regions because of its proximity to the equator (Bamber *et al*. 2009; Hu *et al*. 2009). Simpson *et al*. (2010) examine the consequences of 1 and 2 m sea level rise in the Caribbean, which they consider to not be unreasonable estimates by the end of the century. They note that even if GHGs emissions were stabilized now SLR would continue to rise beyond the end of the century, and suggest that '*the question is not* *if the Caribbean will face SLR of 1m or 2m under either a 2.0°C or 2.5°C global warming scenario, but rather when*'.

More intense hurricanes

Whereas the frequency of hurricanes increasing or decreasing under global warming is uncertain it is likely that with increased sea surface temperatures 'future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation' (IPCC 2007). The consistency between high resolution global models, regional hurricane models and scientific theories (e.g., Maximum Potential Intensity theories) support the idea of increased tropical cyclone intensity.

There is, however, less consensus about frequency. Whereas the modelling studies of Oouchi *et al*. (2006) project more intense hurricanes in the Atlantic, those of Knutson *et al*. (2008) found that overall the frequency of hurricanes decreased when compared to the model's present day values. Notwithstanding, while the overall frequency decreased, the number of more intense hurricanes with wind speeds over 35 km per hour increased. Bender *et al*. (2010) similarly suggest that the number of category 4 and 5 hurricanes will increase by a factor of 2 to 1, though the trend will not be clearly detectable until toward the end of the 21st century. Category 4 and 5 hurricanes in the North Atlantic have increased from 16 or 1.1 per year in the period of 1975-89 to 25 or 1.6 per year in the period of 1990-2004 (Webster *et al*. 2005). Under the scenario of a 2 to 1 increase, that number will be approximately 3 per year by the end of the century. Much more research needs to be done to arrive at a consensus on hurricane trends.

The Response - Climate Demands Change

Justification for action

The previous sections show that in the last decade a great deal of knowledge has been gained about the science of Caribbean climate—its variability and historical and future trends. Against this backdrop, Caribbean countries have cause to be concerned about the threat posed to their development by climate impacts. Even a limited listing of historical and future impact gleaned from recent studies (Table 3) shows impacts cutting across all key sectors and spheres of Caribbean life because of the inherent climate sensitivity alluded to earlier.

Whereas it would be imprudent to claim adequacy of knowledge, a reasonable claim can be made for sufficiency of regional climate change information to warrant and/or spur action (even if limited) in response

Table 3. Examples of recent and likely future impacts of climate variability or change within sectors and possible adaptation examples.

Threat-ened System	Recent Impacts	Likely Impacts	Adaptation Examples
Infra-structure	An assessment of the impact of Hurricane Ivan (2004) on Grenada suggests 90% of housing stock damaged, telecommunication lossess equivalent to 13% GDP, damage to schools and education infrastructure equivalent to 20% GDP, from (OECS 2004).	Under 1, sea level rise: Loss or damage of 21 (28%) Caribbean airports; lands surrounding 35 ports inundated (out of 44); loss of 567 km of roads (e.g., 14% of road network in The Bahamas, 12% Guyana, 14% in Dominica) from (Simpson *et al*. 2010).	Revised Caribbean Building Codes incorporating climate vulnerability at the national levels. National land use planning policies to restrict development in vulnerable areas. Building of sea wall de-fenses to protect critical coastal infrastructure. Risk Insurance.
Tourism	Hurricane Ivan destroys or dam-ages 90% of guest rooms in Grenada's tourism sector equivalent to 13% of GDP (OECS 2004).	Under a scenario of 1m sea level rise and 50m coastal erosion, 46% of CARICOM tourist resorts are at risk (Simpson *et al*. 2010) In the worst-case scenar-ios arrivals to the Carib-bean could fall by about 1% per year due to the effects of climate change, costing the region about US$118 million-US$146 million in lost revenue per annum (Moore 2010).	Redesign and retrofit tourism facilities to withstand stronger storms. Build sea walls, raise land levels, replant mangroves to protect against sea level rise. Retool workers who will be displaced due to less demand.
Health	Reported cases of dengue are cor-related with both temperature and rainfall, with warm-ing of early months of the year bringing earlier onset of reported dengue cases and epidem-ics e.g. Trinidad and Tobago 1997-1998 (Amarakoon *et al*. 2006).	A 2°C increase of temperature by 2099 is expected to increase the transmission of dengue fever three-fold (Chen, Chadee and Rawlins 2006). Extreme weather events could lead to increases in heat stress, respiratory complications, and diar-rhoeal distress (Taylor, Chen and Bailey 2009; Ebi, Lewis and Corvalan 2006).	The development and implementation of early warning systems for some diseases e.g. dengue. Improving the capabilities of national and regional disaster units to warn of, and (react) respond to disasters. Ensuring efficient water monitoring and management.

Table 3 continued.

Threatened System	Recent Impacts	Likely Impacts	Adaptation Examples
Agriculture	Agricultural sector of Grenada suffered a loss equivalent to 10% GDP due to Hurricane Ivan in 2004—caused an estimated delay of 10 years in the availability of cocoa and nutmeg, two of the island's main crops, for economic benefit (Mimura *et al*. 2007).	New forms of susceptible pests and diseases may arise due to changes in climatic variables (Cashman, Nurse and Charlery 2010). Over 3% of agricultural land lost under 2 meters sea level rise, with implications for food supply, security and rural livelihoods (12% in The Bahamas, 8% in St. Kitts and Nevis, 5% in Haiti) (Simpson *et al*. 2010). For CARICOM countries the biological effects of 2050 climate relative to 2000 climate are yield declines ranging from 3% to over 8% for rice, maize, and cowpea (Simpson *et al*. 2009).	Investments in crop research to provide farmers with new heat, salt and/or drought tolerant varieties. New agro-management techniques and methodologies e.g. greenhouse technology, pest and disease management methodologies. Improved water harvesting, management techniques. Income diversification and insurance schemes.
Biodiversity	Decrease in Jamaican dry season rainfall has been found to reduce food availability and hence physical condition of migratory birds over wintering on the island, as well as their spring departure times (Studds and Marra 2007). Devastating coral bleaching event of 2005 caused by anomalously high sea surface temperatures in the Eastern Caribbean and North Atlantic; e.g., 90% of corals affected in British Virgin Islands (Donner, Knutson and Oppenheimer 2007).	Loss of one third of sea turtle nesting beaches under 0.5m sea level rise (Mimura *et al*. 2007). Coral calcification will be hindered by increased oceanic temperatures and acidification (Hoegh-Guldberg *et al*. 2007).	The creation of protected areas as an important component of national environmental management plans. Strengthen regulations to protect ecological buffers. Increase community involvement in ecosystem management through sustainable use and protection.

Table 3 continued.

Threat-ened System	Recent Impacts	Likely Impacts	Adaptation Examples
Water resources	Potworks Reservoir, an important surface water source for the island of Antigua, was left dry after a 2003 drought (Farrell, Moseley and Nurse 2007). During the 2004–2005 Cuban droughts 2.6 million people were forced to rely solely on truck-borne water (Pulwarty, Nurse and Trotz 2010).	Most small Caribbean islands will experience extreme water stress regardless of SRES scenario (Cashman, Nurse and Charlery 2010). Sea-level rise will increase the risk of saltwater intrusion into coastal aquifers, particularly those that are already at risk from over abstraction (Simpson *et al.* 2009).	Improved management of watersheds and catchment areas to optimise groundwater recharge. Improved water resource monitoring for conservation and improved water distribution to reduce loss. Increase water storage capacity to mitigate the effects of drought. Desalination for periods of water shortages.

to the threat of climate change. The claim to sufficiency is based on the nature of the regional science generated to date including (i) its relevance (about the Caribbean as opposed to, for example, global mean projections) (ii) its 'small island' scale (e.g., regional model generated projections at 50 km versus global climate model projections at 125 km or greater), and (iii) its ability to generate second generation research questions (e.g., there is a discernible shift in Caribbean climate research to answer questions about the impacts of the projected changes on Caribbean life and existence). With a basis for action, the ensuing question must then be 'what must the action in response to the climate change threat look like?'

The profile of response to climate change for the Caribbean region will have many determinants including the scale of the proposed response (individual, community, national, regional), the underlying purpose of the response (e.g., coping versus surrender or retreat), the ability to resource the response, and the 'driver' of the response (top down government led models or bottom up community driven). See Tompkins *et al.* (2005) for a useful guidebook for small island states. Table 4 shows some action plans generated in recent years for the Caribbean region with respect to climate change. The listing is itself evidence of an increasing recognition of the threat posed and the need to factor climate change into the future development of the region. An examination of the action plans reveals useful elements for any regional response plan. We suggest that the regional response profile to climate change must include the following: Coordinated Research and Data Gathering, and Mitigation and Adaptation Strategies.

Table 4. Examples of action plans generated in recent years for the Caribbean region with respect to climate change (Source: CCCCC (5C's) found at <http://caribbeanclimate.bz/projects/projects.html>.

Action Plan	Timeline	Objective
Caribbean Planning for Adaptation to Climate Change Project (CPACC)	1997-2001	Capacity building in the region for climate change vulnerability assessments and adaptation planning.
Adaptation to Climate Change in the Caribbean Project (ACCC)	2001-2004	Increase technical capacity of regional climate research groups, formulate adaptation strategies for health, food and water risks, include climate change in physical planning and increase public awareness.
Mainstreaming and Adaptation to Climate Change (MACC)	2004-2007	Cost effective identification and reduction of climate risks and vulnerability and increase in public awareness.
Special Program on Adaptation to Climate Change (SPACC)	2007-2011	Support the implementation of pilot adaptation projects in St. Lucia, Dominica and St. Vincent and the Grenadines in response to the impacts of climate change on natural coastal resources.
Pilot Project for Climate Resilience (PPCR)	2010-	To provide incentives for scaled-up action and transformational change in integrating consideration of climate resilience in national development planning consistent with poverty reduction and sustainable development goals. Regional pilots: Dominica, Grenada, Haiti, Jamaica, Saint Lucia, Saint Vincent and the Grenadines as well as regional track.

Coordinated research and data gathering

Notwithstanding the data sufficiency to justify response, there is need for more Caribbean climate and climate change related data and research to hone the response. On the one hand, there is dire need for historical atmospheric data (e.g., temperatures, rainfall, etc.) on daily timescales, at station-level and of sufficient temporal length to complete the picture of historical trends, particularly in vulnerable locations within individual Caribbean territories. Knowledge of the direction and magnitude of present day trends is (among other things) useful for model validation and evaluating the credibility of model projected change. Data mining is yet to be seriously undertaken in the region, particularly of ship logs, old meteorological reports, and plantation records. This should be complemented with coordinated attempts to capture and store current data over sufficient spatial scales to facilitate examination of sub-regional trends, and for monitoring changes as they occur over the coming decades. Examples of organizations involved in data mining and storage efforts include the International Environmental Data Rescue Organization (see <http://www.iedro.org/>) and the Caribbean Institute of Meteorology and Hydrology (CIMH).

To facilitate the investigation of climate change impacts on critical sectors, there will also be need to both expand the range of atmospheric data captured and to include other non-atmospheric climate data. This would include (but is not limited to) the need to capture surface, upper air and atmospheric composition data, oceanic surface and sub-surface data, and terrestrial data particularly those that serve as biodiversity indicators and which capture the water budget. Data collection and compilation in the socio-economic and natural resources realms will also become increasingly necessary given the need to assess and address the issues of climate change impact adequately and at all levels (UNEP 2009).

Similarly, an expanded research agenda must form part of the regional response. It is so far largely the basic climate change science that has been undertaken for the region (e.g., regional modeling to produce end-of-century estimates of mean change). There is much more to be attempted to answer the questions thrown up by the science already done. An expanded science research agenda must attempt to further refine the projections (including defining how extreme conditions like droughts, floods and hurricanes are likely to be altered) and also analyze historical and projected changes in regional atmospheric and oceanic dynamics due to climate change. Equally important is the need for research that links historical and projected climatic change to the life and livelihoods of Caribbean nationals through an exploration of sectoral vulnerabilities and impact assessments. We reiterate that a decade of Caribbean climate science has advanced the region to the point where this kind of research is now possible and is in fact being demanded (i.e., 'evidenced-based action').

Unfortunately, whereas the science has largely benefitted from established methodologies, there is a plethora of vulnerability and impact assessment approaches being proposed and/or currently being employed in the region. For this reason, both data gathering and research lend themselves to coordinated regional approaches given the uneven distribution and general limitations of resources (human, technical and financial) of each Caribbean territory. There is a clear role for regional agencies and entities, e.g., those listed in Table 5, to take the lead in this aspect of the regional response profile by defining and coordinating the execution of both data gathering exercises and further climate change research.

Table 5. Examples of Caribbean institutions that are currently undertaking climate data gathering and research.

Institution	Acronym	Country (Base)
Caribbean Community Climate Change Centre	CCCCC (5C's)	Belize
The CARIBSAVE Partnership	CARIBSAVE	Barbados
Caribbean Disaster Emergency Management Agency	CDEMA (formerly CDERA)	Barbados
Caribbean Institute of Meteorology and Hydrology	CIMH	Barbados
Caribbean Meteorological Organisation	CMO	Trinidad and Tobago
Climate Studies Group, Mona (The University of the West Indies)	CSGM	Jamaica
Instituto de Meteorología de la República de Cuba (Cuban Meteorology Institute)	INSMET	Cuba
Office of Disaster Preparedness and Disaster Management	ODPEM	Jamaica

Mitigation

The severity of the climate change threat is dependent on the levels of GHG concentration in the atmosphere (see again section 2.1). The Alliance of Small Island States (AOSIS) of which many Caribbean countries are a part, has called for limits of 350 ppm of carbon dioxide so that temperature increases can be no more than 1.5^{o}C (AOSIS 2009). The European Union and other developed countries have called for a ceiling of 450 ppm in order to limit temperature increases to 2^{o}C (UNDP 2007). These limits are advocated because they are seen as 'tipping points' beyond which small changes in temperatures will cause irreversible consequences. To achieve these limits, mitigation, i.e., actions taken to reduce greenhouse gas emissions, must also be a part of the response profile of the Caribbean.

Though there is some merit in the argument that reductions in GHGs is primarily the responsibility of the big emitters of the past, e.g., the USA, EU, and now, China and India, it seems incongruous that the Caribbean should absolve itself of the shared global responsibility to cut GHG emissions when it is amongst the most vulnerable to the consequences if they are not. Justice and equity models governing emission reductions allow a differentiation between developed and developing countries' mitigation targets. The models recognize that the developed world has achieved its status at the expense of increasing GHGs over the last century. Consequently, under these models it is the developed world that cuts back first while allowing the developing countries to continue emitting for a time to reach sustainable development (see for example the UNDP (2007) scheme). Notwithstanding, eventually, all countries must cut back.

It is prudent, then, that small islands like the Caribbean which are in development mode should also consider inevitable emissions reductions in their response plan to climate change. This would ensure that regional development is also premised on morally sustainable grounds. The primary target of regional cutbacks in GHGs should be in all areas of energy usage: electricity generation, road, shipping and aviation transportation, industry and building. This makes this aspect of the response strategy well suited to be led by national governments and regional policy-setting and economic groupings (e.g., CARICOM, OECS, etc.). Reductions could come from a combination of more efficient use of fossil fuels, oil, LNG and/or clean coal as well as the introduction of renewable energy technologies, i.e., a transitioning to a low carbon economy. The spin off effect would be reduced economic costs, increased productivity and improved quality of life.

Adaptation

Even if global emission-reduction targets were to be met, the present concentrations of GHGs commit the globe to climate change through the end of the century. Adaptation to new climatic regimes must be a part of the regional response profile to climate change. Whereas credible arguments can be proffered to delay mitigation actions, the region's inherent climate sensitivity and attendant vulnerability to climate change make adaptation a priority and a necessity. There are multiple models for adaptation (see for example Tompkins *et al*. 2005), and within the English-speaking Caribbean a number of programmes aimed at mainstreaming of climate change adaptation into national policy and development plans have already been undertaken with varying degrees of success (see again Table 4). Irrespective of the methodology, there are some features that must characterize the regional adaptation strategy.

Firstly, if climate sensitivity is as pervasive as previously argued, then regional adaptation strategies must target all spheres of Caribbean life and existence. This justifies a sectoral approach to adaptation (e.g., agriculture, tourism, water, etc.) which has largely been the strategy employed so far within the region. The sectoral approach holds some advantages, including the prioritization of response in the face of resource constraints. Nonetheless, the integrated nature of Caribbean existence requires a simultaneous coordinated approach across sectors as much as within sectors, as actions undertaken in any one sector necessarily impact lives and livelihoods in another.

If sectoral adaptation is to be effective it must be hinged on more specific knowledge of the threat within each sector, more so than what is currently available. This again makes the case for coordinated data gathering and research, particularly research which refines the climate-sectoral linkages. A research agenda must be a feature of the adaptation response. Table 3 shows that some of this work is already underway, and there is a growing body of knowledge attempting to document the likely impact on various Caribbean sectors of future climate change in the face of a warmer and drier region, higher sea levels and more intense hurricanes by the century's end. It is from focused research studies that targeted adaptation options arise, e.g., those listed in Table 3 per sector. The study of Chen, Chadee and Rawlins (2006) is a useful model of crafting an adaptation strategy once a specific sectoral threat is identified, in this case increased dengue fever due to warmer temperatures. The study includes data gathering and analysis to make the climate sectoral linkage, assessment of vulnerability and likely impact of the projected change, and the use of the latter information to craft a raft of possible adaptation strategies ranging from public education alone to scientific, technical and behavioural solutions dependent on the availability of resources. The study also makes the important point that the responsibility for adaptation lies at all levels—individual, community and national levels.

Finally, since adaptation inevitably demands change in behavior and/or thought, adaptation strategies must of necessity include public education and awareness. The premise is that awareness engenders change and it is a change in approach that is being sought, i.e., the climate has and will continue to change therefore so too must the approach to dealing with it. Since adaptation can be tackled at multiple levels, public education and awareness must similarly be targeted at all levels (governmental, community and individual), to all ages, and must utilize traditional (e.g., newspapers, radio, television, workshops) and newer communication methodologies (cell phones, web groups, etc.) and techniques.

Summary

Inasmuch as climate change is a global issue, it is one that cannot be ignored in the Caribbean region. In this paper we have argued that climate change is a developmental issue for the region because of an inherent climate sensitivity which pervades Caribbean existence and which therefore gives rise to an inevitable vulnerability to changes in climate whether short or longer term. Caribbean climate science points to a climate regime that has changed and is currently in the throes of change, and that will continue to change through the end of the century. The prospects are for a much warmer and drier region under increased threat from rising sea levels and more extreme weather. The vulnerability is further exacerbated by limited resources and an over reliance on natural resources and environmental degradation.

We however argue that, in the face of growing Caribbean climate science, there is a sufficiency of knowledge on which to premise action in response to the climate change threat, where action is a must and not an option. The profile of any regional response to climate change must encompass (among other things) a combination of all three of the following: coordinated and expanded data gathering and research, mitigation and adaptation. We single out adaptation as an 'if nothing else' option given the commitment the globe has already made to climate change. Even if targeted reductions in GHGs were to be achieved in the very near future, adaptation would still represent a 'no regrets' option, as a cursory glance at sectoral-focused adaptation strategies (as given in Table 3) suggest them as very similar to those which the region should be pursuing nonetheless to achieve sustainable development. Notwithstanding, there is a recognition that some actions will require sizeable and sustained investment in resources beyond that which the region is currently able to provide on its own.

In tandem, then, a response profile to the climate change threat must be premised on coordinated and expanded data gathering and research, as well as mitigation and adaptation strategies. This would indicate a recognition of the problem, a claim of responsibility in part for its creation, and a readiness to respond to the challenge. A response premised on all three planks will put the Caribbean on the road to building more climate resilient societies. There can be no doubt that *climate change is an issue of our times—one that the Caribbean cannot avoid contending with, preferably through voluntary action, now as opposed to later, and with a paradigm shift in thought and action equivalent to the shift necessitating it.*

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