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Caribbean precipitation: review, model and prospect

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Abstract: The study of Caribbean climate pre-1990 focused almost exclusively on attempts to link spatial patterns in climatic variables to physical processes. Much of this research assumed a 'simple' regional climate, warm year round with a wet season dominated by tropical cyclones, but researchers soon found that a precipitation regionalization of the Caribbean was not as straightforward and simple. Consequently, a satisfactory understanding of the regional precipitation climate has eluded researchers for much of the second half of the twentieth century. Recently, with the increased availability and quality of satellite and precipitation data, researchers have begun to use gridded data sets to identify the spatial boundaries of the bimodal precipitation region and the atmospheric processes associated with the two maxima and minimum in precipitation. The findings of these most recent studies can be combined to construct a five part (North Atlantic high pressure, low level Caribbean jet, subsidence caused by Central America convection, basin wide increased wind shear, and divergence around Jamaica) conceptual Caribbean precipitation model that begins to address spatial variability in the bimodal structure of annual rainfall and the development of the midsummer minimum in precipitation. Such a regional precipitation climate model provides hypotheses to be tested and investigated in future research. Further, researchers must work towards a more effective and clear communication of the bimodal nature of Caribbean precipitation and the associated summer decrease in precipitation, integrate upper air analysis into the current working hypotheses, and further examine the interannual to interdecadal variability of the Caribbean midsummer drought for prediction purposes.

Key words: bimodality, Caribbean precipitation, climate change, midsummer dry spell, midsummer drought.

I Introduction

The study of Caribbean climate pre-1990 focused almost exclusively on attempts to link spatial patterns in climatic variables to physical processes for the development of a conceptual model of the regional climate. Much of this research assumed a 'simple' regional climate, warm year round

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with a wet season dominated by tropical cyclones, but researchers soon found that a climatic regionalization of the Caribbean was not so straightforward. Granger (1985) characterized the climate of the Caribbean as diverse with as many climate types as islands. Given this complexity and diversity of Caribbean climate, a wide variety of climate classifications were produced over the years that offered either too much or too little information, creating unparsimonious climate regionalization schemes. Adding to the difficulty of developing a broadly accepted climate regionalization for the Caribbean, a paucity of long-term, quality meteorological data inhibited the study of the physical processes associated with spatial patterns of climatic phenomena (Granger, 1985). Consequently, a satisfactory understanding of regional climate has eluded researchers for much of the second half of the twentieth century.

One example of a 'hyper-regionalization' of Caribbean climate is provided by Portig's (1973) regionalization of precipitation that identifies 22 rainfall regimes for the Greater Antilles and Bahamas and 19 rainfall regimes for the Lesser Antilles. Clearly, 41 total rainfall regimes for the Caribbean, rigorous as it is in its detail, is not conducive to the development of an elegant conceptual model describing the interaction of regional climate processes. On the other end of the regionalization spectrum is the reliance upon global climate classification schemes to classify the Caribbean. The frequently used Köeppen climate classification system provides three climate types for the Caribbean: Tropical Monsoon (Am), Tropical Wet and Dry (Aw) and Semiarid (BS) (Griffiths and Driscoll, 1982). Such climate types are useful for understanding global climate systems but are far from adequate for understanding regional scale processes. Trewartha (1981) labelled the Köeppen classification of the Caribbean 'problematic' due to its inability to incorporate a second annual maximum in rainfall that consistently occurs in May or June across the region. This maximum is followed by a decrease in July precipitation before the beginning of the longer and greater (in terms of monthly precipitation totals) wet season.

Several exceptions to the focus upon climate regionalization during this period do exist. Gutnick (1958) provided pioneering work on the climatology of the Caribbean trade wind inversion. Hastenrath (1967; 1976; 1978; 1984) offered climatologic research of rainfall along the Caribbean coast of Central America, and the relationship between low-latitude circulation and Caribbean climate extremes and anomalies. Granger (1982; 1983; 1985) provided examples of how Caribbean climatic variability can affect development of water resources, and also offered the most extensive review of Caribbean climate literature during the period. Such research was key to development of a fundamental understanding of Caribbean regional climate processes, as opposed to identifying spatial patterns and climate classifications for the region.

Despite the difficulties faced in researching the Caribbean's regional climate, by the late twentieth century significant progress was made towards understanding the thermal component of the regional climate (Granger, 1985). In contrast, a thorough understanding of the region's precipitation processes, particularly rainfall not associated with tropical cyclones, has yet to be achieved (Chen and Taylor, 2002). Specifically, the bimodal nature of the annual rainfall regime in the Caribbean region is poorly understood. The bimodal structure is displayed with two maxima (May–June and September–October) separated by what has been termed a midsummer drought (MSD) (July–August) (Magaña *et al.*, 1999; Curtis, 2002) (Figure 1). In southern Mexico and Central America this midsummer drought is called the *canicula* or *veranillo*, depending on the region where it is experienced (Magaña *et al.*, 1999). The decrease in precipitation can be significant with as much as a 40%

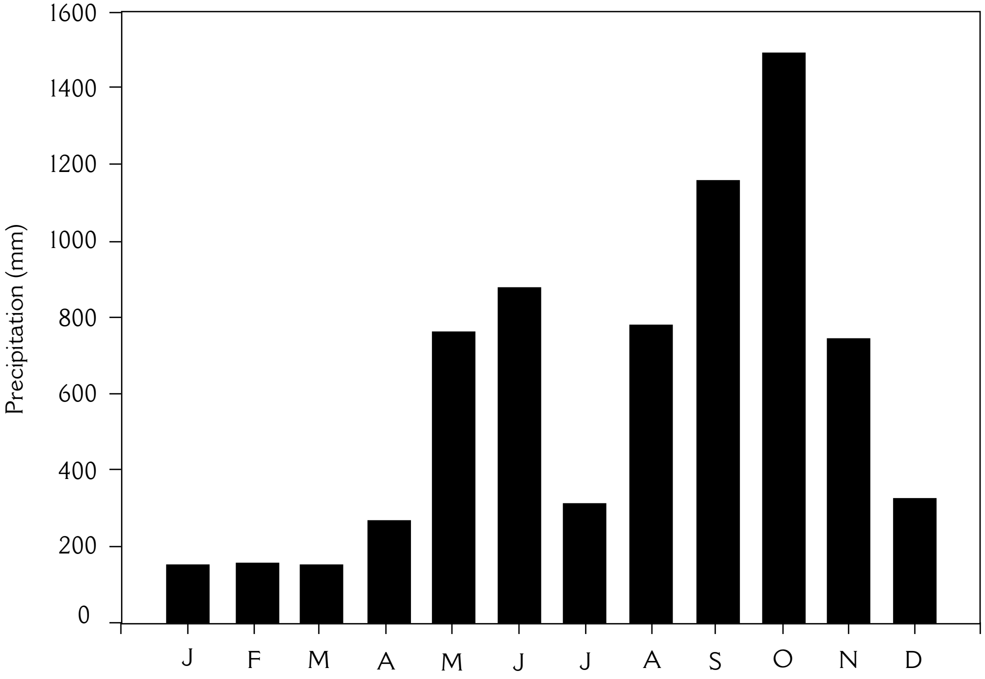

Figure 1 Example of the annual bimodal distribution of Caribbean precipitation: monthly mean precipitation for Kingston, Jamaica (1850–2000)

decrease in late July and early August compared to June and September (Hastenrath, 1976). Such variability offers a challenge to rain-fed agriculture and water supply across the region, particularly on small carbonate islands (Gamble, 2004; Beckford and Barker, 2007).

II Current knowledge of the Caribbean precipitation bimodality and the MSD

Recently, with the increased availability and quality of satellite and climate data – ie, GPCP (Xie *et al.*, 2003) and the NCEP/NCAR Reanalysis Data (Kalnay *et al.*, 1996) – researchers have begun to use gridded data sets to identify the spatial boundaries of the bimodal precipitation region and the atmospheric processes associated with the two maxima and minimum in precipitation (Magaña *et al.*, 1999; Giannini *et al.*, 2000; Chen and Taylor, 2002; Curtis, 2002; 2004; Taylor *et al.*, 2002; Angeles *et al.*, 2007; Curtis and Gamble, 2007; Small *et al.*, 2007). Curtis (2002), through a novel application of harmonic analysis, analysed the bimodal distribution of May to October rainfall across the globe and found the most extreme pattern over Pan America (Guatemala and El Salvador) and adjacent oceans. This analysis also indicated that the bimodal structure, though not as significant over Central America, explains a large portion of variability in annual Caribbean rainfall.

The most widely accepted theory as to the cause of the Caribbean MSD is the intensification and expansion of the North Atlantic Subtropical High Pressure Cell (NAHP) into the region in July (Hastenrath, 1967; 1976; 1978; 1984; Granger, 1985; Giannini *et al.*, 2000; Mapes *et al.*, 2005). According to this theory, the intensification and expansion of the NAHP translates into stronger trade winds, lower sea surface temperatures (SST), increased subsidence, and diminished

Caribbean rainfall. Hastenrath (1976) also notes that the winter preceding a particularly dry summer in the Caribbean is characterized by an early southward displacement of the NAHP, stronger trade winds, and equatorward shift of the East Pacific Inter Tropical Convergence Zone (ITCZ).

Despite general acceptance of this theory, it has been noted in several studies that the influence of the NAHP on the Caribbean MSD may not be consistent across the region (Granger, 1985; Curtis and Gamble, 2007; Gamble *et al*., 2008). For example, Giannini *et al*. (2000) found that the bimodal pattern of annual rainfall centred around an MSD accounts for 66% of the total variance of the annual cycle of Caribbean rainfall and is most pronounced in the western Caribbean. Curtis and Gamble (2007) and Gamble *et al*. (2008) found the MSD to begin May–June in the eastern Caribbean and June–July in the northwest Caribbean, with the greatest decrease in summer precipitation over Jamaica and the western Caribbean. Thus, it is obvious that the NAHP is one of the dominant controls of the Caribbean MSD, but spatial and temporal variability exists in the occurrence of the MSD and the cause(s) of this variability is not completely understood.

Magaña *et al*. (1999) investigated the MSD in Mexico, Central America and the eastern Pacific (the area identified by Curtis with the most pronounced MSD) and found that the meridional extent of the MSD and its simultaneous occurrence in separate locations rule out the possibility of the MSD being caused by the double crossing of the ITCZ in the region. Hastenrath (2002), however, contends that the double-peaked annual cycle of the latitude position of the ITCZ is a major contributor to the double peak in the annual cycle of Central American rainfall. Magaña *et al*. (1999) suggest that the MSD is created through a combination of three local to regional mechanisms over the eastern Pacific. The first mechanism is a shadowing effect, as cloudiness and rainfall produced by convection in the early summer months block incoming solar radiation. This leads to a negative feedback as surface waters cool, inhibiting further convection. The decrease in solar radiation is then followed by divergent wind anomalies caused by an anticyclonic circulation of low level winds. The final mechanism is a strengthening of the trade winds that increase evaporation due to wind stirring. The end result is a decrease in rainfall in the middle of the summer, a period when rainfall, particularly convective rainfall, may be expected to increase. Magaña *et al*. (1999) note that the same suite of mechanisms that is responsible for the Mexico/Central America MSD may not be responsible for the Caribbean MSD. For example, Caribbean SSTs do not exhibit significant fluctuations during the summer months and non-local changes in convection may play a larger role (Small *et al*., 2007).

More specific to the Caribbean MSD is a series of articles by the Climate Research Group in the Department of Physics, University of West Indies (UWI), Mona, that investigates the annual cycle of rainfall over the Caribbean basin (10–20°N, 65–83°W) (Chen and Taylor, 2002; Taylor *et al*., 2002; Spence *et al*., 2004; Ashby *et al*., 2005; Stephenson *et al*., 2007; Whyte *et al*., 2008). Specifically, this research indicates that characterization of annual rainfall variability in the region is biased to the *latter* portion (September–October) of the rainy season since the majority of previous Caribbean precipitation studies focus upon its abundance of rainfall and coincidence with peak hurricane activity (Chen and Taylor, 2002). This late season bias may cause inaccurate conclusions since mechanisms controlling rainfall in the early rainfall season are not the same as mechanisms controlling rainfall in the late wet season. Specifically, early season rainfall variability is strongly influenced by anomalies in the SSTs of the tropical North Atlantic, while late season rainfall variability is influenced by SSTs in the equatorial Pacific and Atlantic (Taylor *et al*., 2002).

Furthermore, the connection with the El Niño Southern Oscillation (ENSO) appears to be different for the two wet seasons, with a wet early rainfall season existing in the year of ENSO decline (the El Niño + 1 year) and a dry late rainfall season in the year of an ENSO event (Chen and Taylor, 2002; Spence *et al*., 2004). Such results suggest that the bimodal distribution of annual rainfall may be controlled by different processes in the Caribbean compared to southern Mexico and Central America. Ashby *et al*. (2005) develop statistical models to predict rainfall in the Caribbean with Caribbean SST anomalies, tropical North Atlantic sea level pressure anomalies, vertical shear anomalies in the equatorial Atlantic and the size of the Atlantic portion of the Western Hemisphere Warm Pool, effective predictors of early season (May–July) Caribbean rainfall; and Caribbean SST anomalies and tropical North Atlantic sea level pressure anomalies, effective predictors for late season (August–October) Caribbean rainfall. The statistical models also indicate that on the inter-annual timescale equatorial Pacific SST anomalies are significant predictors for both early and late season precipitation, the NINO3 index is significant for early season rainfall only, and zonal gradients of SST between the equatorial Pacific and tropical Atlantic are retained as effective predictors for late season rainfall. Stephenson *et al*. (2007) found an ENSO signal during the primary Caribbean dry season (November–April) composed of oppositely signed precipitation anomalies over the north and south Caribbean with the southeastern Caribbean dry in response to a warm event.

Despite the identification of potentially different causal mechanisms in the early and late wet seasons of the Caribbean, one aspect of the bimodal nature of Caribbean rainfall which was not addressed by Chen and Taylor (2002), Taylor *et al*. (2002), Spence *et al*. (2004), Ashby *et al*. (2005) and Stephenson *et al*. (2007) is the specific cause of the decrease in midsummer rain. The research suggests that a lag between the two processes causing early and late wet season rainfall may cause the MSD, yet a clear causal mechanism for the MSD is not provided. Other researchers have offered specific MSD causal mechanisms. Angeles *et al*. (2007) contend that an increase in vertical wind shear in combination with enhanced Saharan dust plays an important role in the bimodal structure of rainfall. Curtis and Gamble (2007) suggest that an increase in July surface pressure and surface divergence, caused by the changing wind field, appears to contribute to a strong concurrent MSD over the waters bounded by Jamaica, Cuba and the Yucatan peninsula. Whyte *et al*. (2008) examine the Caribbean low level jet (CLLJ) and hypothesize that convergence at low to mid-levels near entrance and exit regions over the southern Caribbean contribute to subsidence and a dry summer. Further, Wang (2007) indicates that this dryness is enhanced by low level moisture advection away from the Caribbean to the southern United States by the CLLJ.

III A new conceptual model for Caribbean regional climate and the MSD

Through a combination of the different causal mechanisms offered in existing literature, a new five-part conceptual model of regional atmospheric processes causing the MSD and its associated spatial variability can be constructed (Figure 2). The regional conceptual model is multiscale in that local and regional scale processes are embedded within synoptic and global scale processes. The components are listed in declining scale, and one scale process should not be characterized or thought of as dominating another (ie, large scale dominating local scale); the degree to which different scale processes contribute to development of the MSD at a given location still needs to be determined. It is important also to note that this regional climate model does not contain five separate,

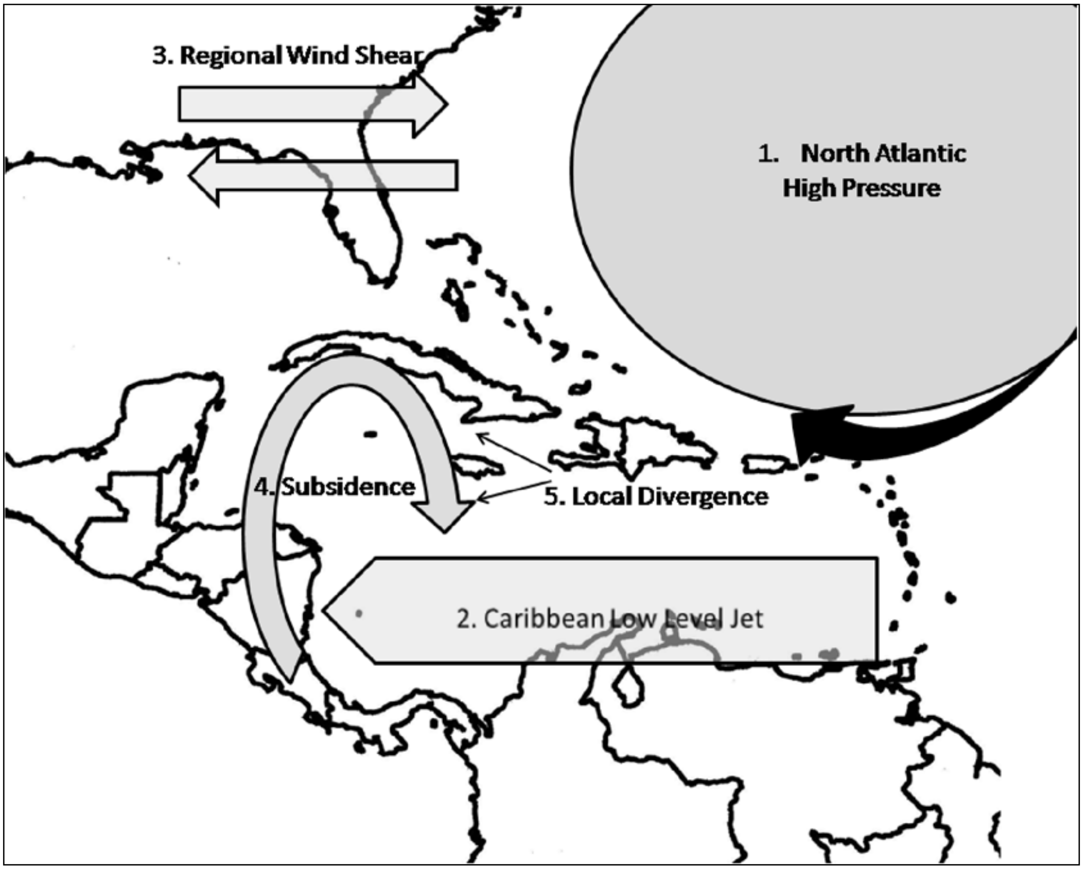

Figure 2 A new conceptual model of regional atmospheric processes causing the Caribbean midsummer drought and its associated spatial variability

individual components. To truly understand the formation of the MSD, the five components should be thought of holistically, interacting with each other to create the MSD at different times and strength across the Caribbean basin.

The first component of the model is the intensification and expansion of the NAHP into the region in July (Hastenrath 1976; 1978; 1984; Mapes *et al*., 2005). Based upon spatial patterns in the MSD exhibited in previous mapping analyses (Curtis and Gamble, 2007; Gamble *et al*., 2008), it is hypothesized that this expansion affects the entire region but is most pronounced in the northern Caribbean. As the NAHP expands into the region, the second component of the model, the CLLJ, intensifies between 12.5° and 17.5° latitude, creating convergence at low to mid-levels near entrance and exit regions over the southern Caribbean and surface divergence, while at the same time causing low level moisture advection away from the Caribbean by the CLLJ. Given the distinct spatial boundaries of this feature (see Whyte *et al*., 2008: Figure 1), it is most likely that the CLLJ has a direct impact on the north coast of South America, ultimately as cool coastal upwelling, and the Caribbean sea west of Jamaica. Beyond the core region of the CLLJ, Angeles *et al*. (2007) found a regionwide increase in vertical wind shear, the third component of the model, to contribute to the development of the MSD.

Concurrently with the intensification of the CLLJ, the fourth component, subsidence over the Caribbean, at approximately 70–75°W, is produced by intensification of direct circulation associated with tropical convection along the Central America Caribbean (see Magaña and Caetano, 2005: Figure 4). Such subsidence may add to the increased MSD documented in the region close to Jamaica (Curtis and Gamble, 2007). The fifth component of this model is an increase in surface pressure and surface divergence in July that is enhanced as the island of Jamaica blocks the flow of trade winds as they migrate northward. The impact of this phenomenon is localized, affecting areas downwind of Jamaica (Curtis and Gamble, 2007).

It should be noted that two other region-wide phenomena coincide with the timeframe of this conceptual model, creating an environment conducive to MSD development, but are not identified as specific processes in this conceptual model. The first phenomenon is a minimum in tropical cyclogenesis in the Caribbean basin in July (Inoue *et al*., 2002). This minimum pertains to the development of storms within the basin, not the passage of storms across the basin from other regions. Since fewer storms form in the Caribbean, less rain occurs within the region. The second phenomenon is a peak in Saharan Dust transported by easterly waves into the region (Angeles *et al*., 2007). The dust causes a large concentration of small cloud condensation nuclei resulting in small rain droplets which are associated with a decrease in convective precipitation (Rosenfeld *et al*., 2000).

IV Future research into the bimodal structure of Caribbean annual precipitation

The twenty-first century has seen a significant increase in the knowledge of the bimodal nature of annual Caribbean precipitation and the Caribbean MSD. The findings of various studies can be combined to construct a conceptual regional model that begins to address spatial variability in the bimodal structure of annual rainfall, particularly development of the midsummer minimum. However, as researchers continue to investigate these phenomena, several important issues need to be addressed. The first, which may seem trivial, is the term used to identify the summertime decrease in rainfall. Currently, 'midsummer drought' is the accepted label for the phenomenon. However, such a label can be misleading, particularly to government officials and the public outside the academic community. Many times government officials and the general public associate the term drought with the *complete* absence of water. Such is not the case with the Caribbean MSD. It is important to note that this 'drought' is not characterized by a complete absence of rainfall during this period. Rather the MSD is a decrease in rainfall over the summer months compared to the spring and late summer/autumn. Thus, in order to identify the MSD, consecutive months must be compared and a decrease in rainfall from month to month indicates 'drought conditions'.

True, drought in its broadest sense can be defined as a period with lower than expected precipitation (Nott, 2006). Using this definition, the Caribbean MSD can be called a drought because it occurs during the summer, a time when high SSTs and an increase in the elevation of the trade wind inversion supports development of convection and rainfall production in the region (Gutnick, 1958; Granger, 1985). However, as one moves beyond this conceptual moniker towards an operational definition for the Caribbean MSD that identifies the onset, severity and termination of drought in terms of moisture deficit, the term 'drought' becomes a misnomer. The reason for this incorrect label is that, upon review of climate data, the normal or expected conditions are low precipitation in summer or a dry season/arid period (Soulé, 1992). Consequently, a true midsummer drought event, in an operational climatology sense, would be *below normal* rainfall for the summer months. Thus a midsummer drought does not occur every year, rather a midsummer minimum in rainfall or a short dry season occurs every year. We recommend that the use of the term 'midsummer drought' should be avoided unless specifically referring to a precipitation deficit in the summer months. Based upon this discussion, the authors suggest the term 'midsummer dry spell' to replace 'midsummer drought'. This terminology allows for the continued use of the acronym 'MSD'.

The second key issue that needs to be incorporated into existing efforts regarding the Caribbean precipitation and the Caribbean MSD is the role of upper level dynamics in development of the MSD. As mentioned previously, recent research has begun to investigate the Caribbean low level jet and its role on regional precipitation patterns. However, dynamics created by atmospheric processes above the CLLJ, higher than 500 mb, have yet to be investigated. For example, the position and strength of the tropical upper-tropospheric trough (TUTT) may be related to the strength and timing of the MSD. Such research could add significantly to the understanding of the MSD, resulting in a more accurate conceptual regional climate model.

The final issue for future research into the Caribbean MSD and the associated annual bimodality in rainfall is documentation and investigation of interannual to interdecadal variability in the MSD, particularly in response to global processes such as El Niño and La Niña, Atlantic multidecadal oscillations (AMOs), tropical Atlantic climate variability (TAV) and the Madden-Julian Oscillation (MJO). To a limited degree this has been addressed in some of the existing literature (for example, see Whyte *et al.*'s 2008 discussion of the CLLJ's inter-annual variability associated with ENSO events). However, a thorough analysis that links variations in the atmospheric processes and spatial variations in the MSD has yet to be completed. Such analysis will lead to an understanding of how climatic change and global warming may affect the Caribbean bimodal structure and the MSD. Such an understanding is particularly important given the inability of some General Circulation Models to reproduce correctly the occurrence of the MSD (Kiehl *et al.*, 1998; Angeles *et al.*, 2007).

Some progress has been made in documenting historical trends in Caribbean climate. These recent assessments show that Caribbean rainfall is changing, with mean annual total rainfall declining by approximately 250 mm for Caribbean islands (Nurse and Sem, 2001). Gray (1993) found a weak indication that rainfall is decreasing across the Caribbean. Taylor *et al.* (2002) also found a decrease in precipitation for the Caribbean with a marked negative trend starting in the 1960s. In an analysis of climate extremes in the Caribbean 1958–99, Peterson *et al.* (2002) found that the number of heavy rain events is increasing and the number of consecutive dry days is decreasing. Site-specific studies indicate a wide variety of trends in Caribbean precipitation, making it difficult to make one broad statement about the region. However, multiple studies do indicate a decrease in precipitation for the central Caribbean and an increase in precipitation at peripheral locations such as Nassau and Maracaibo (Aparicio, 1993; Hanson and Maul, 1993; Granger, 1995; Singh, 1997; Walsh, 1998; Martin and Weech, 2001).

In terms of climate projections due to global warming for the Caribbean, the IPCC TAR (Houghton *et al.*, 2001) projected a slight decrease in annual precipitation (–5.2% ± 11.9% for 2050, –6.8% ± 15.8% for 2080) but this trend is not considered significant given the high natural variability of precipitation in the region and difference in model projections (Nurse and Sem, 2001). Seasonal projections include a slight increase for winter (December–February) and a decrease in summer (June–August) (Nurse and Sem, 2001). Due to the variability in model results, the greatest confidence is placed in the summer projection. Projections of extreme precipitation events indicate that there will be fewer annual rain days but an increase in the daily intensity of precipitation (Nurse and Sem, 2001). The more recent IPCC FAR (Solomon *et al*., 2007) precipitation projections also have a broad range for the Caribbean (ie, –14.2 to +13.7% by 2039) and further support the prediction of extreme precipitation events with a lower number of annual rain days but an increase in the daily intensity of precipitation.

Some seasonal rainfall projections for global warming do exist for the Caribbean. Singh (1997) created mean wet and dry seasonal rainfall projections for the Caribbean and found slight decreases (–1.0 to –1.5 mm day^{-1}) in the dry season (January–April) and a slight increase (0.1 to 2.0 mm day^{-1}) during the wet season (May–August). Further, analysis for the transitional season (September–December) indicates small changes in rainfall, with a tendency to a slight decrease in the northern Caribbean and a slight increase in the southern Caribbean.

Combining all of these projections with existing knowledge of spatial variability in the MSD as reported by Gamble *et al*. (2008), cursory hypotheses concerning the effects of climate change from global warming upon the Caribbean MSD can be constructed. For the northwestern Caribbean, the reduction in precipitation may cause the June to July decrease in precipitation to become greater. Also, since there is a marginal increase in precipitation from July to August, the drying trend may negate this change, with the end result being an increase in the magnitude and duration of the MSD in this region. For the southern coasts of Hispaniola and Puerto Rico, the increase in precipitation before and after the MSD is greater. Thus, the projected decrease in precipitation would most likely increase the magnitude of the MSD, but not affect the duration of the dry spell. For the northern Lesser Antilles, the projected decrease in precipitation may cause the initial June to July decrease in precipitation to increase in magnitude, and, given the marginal increase in precipitation from July to September, a projected decrease in precipitation may extend the length of the MSD. For Coro, Venezuela, there is potential for the magnitude of the MSD to be more severe since the MSD in these locations occurs from July to August. However, since the increase in precipitation is very small in Coro from May to June, the MSD may also begin earlier in the year. Barbados may potentially experience a minimal impact from climate change on the MSD since the MSD occurs from August to September, a month later than the seasonal forecast for a decrease in precipitation.

V Conclusion

A significant increase in the knowledge of the bimodal nature of annual Caribbean precipitation and the Caribbean MSD has resulted from climatologists' use of gridded data sets of atmospheric variables in the past decade. The findings of these most recent studies can be combined to construct a five-part conceptual Caribbean precipitation climatology model that begins to address spatial variability in the bimodal structure of annual rainfall and the development of the midsummer minima in precipitation. Such a regional climate model provides hypotheses to be tested and investigated in future research. One such opportunity may be the Intra Americas Study of Climate Processes (IASCLIP), which has been proposed to a subcommittee of the World Climate Research Program. If implemented, IASCLIP would coordinate an intense observation period of the Intra-Americas seas (including the Caribbean) in 2012. This field data would bolster current findings which are primarily based on model output and satellite estimates. Finally, researchers must work towards a more effective and clear communication of the bimodal nature of Caribbean precipitation and the associated summer decrease in precipitation, integrate upper air analysis into the current working hypotheses, and further examine the interannual to interdecadal variability of the Caribbean MSD for prediction purposes. Through such efforts, researchers can help officials and planners to prepare for the potential increase in magnitude and duration of the MSD due to global warming and mitigate drought impacts upon agriculture and water supply.

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