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Climate influence on dengue epidemics in Puerto Rico

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The variability of the insect-borne disease dengue in Puerto Rico was studied in relation to climatic variables in the period 1979–2005. Annual and monthly reported dengue cases were compared with precipitation and temperature data. Results show that the incidence of dengue in Puerto Rico was relatively constant over time despite global warming, possibly due to the offsetting effects of declining rainfall, improving health care and little change in population. Seasonal fluctuations of dengue were driven by rainfall increases from May to November. Year-to-year variability in dengue cases was positively related to temperature, but only weakly associated with local rainfall and an index of El Niño Southern Oscillation (ENSO). Climatic conditions were mapped with respect to dengue cases and patterns in high and low years were compared. During epidemics, a low pressure system east of Florida draws warm humid air over the northwestern Caribbean. Long-term trends in past observed and future projected rainfall and temperatures were studied. Rainfall has declined slowly, but temperatures in the Caribbean are rising with the influence of global warming. Thus, dengue may increase in the future, and it will be necessary to anticipate dengue epidemics using climate forecasts, to reduce adverse health impacts.

Keywords: dengue; climate influence; Caribbean; epidemics

Introduction

Dengue fever is a significant vector-born viral infection affecting more than 2.5 billion people (World Health Organization [WHO] 1997). In the Caribbean, the mosquito *Aedes aegypti* spreads the disease mainly during periods of high humidity and temperature that make incubation more efficient (Wilson 2001). The disease is caused by four viruses (Valdes et al. 2000) and propagation depends on susceptible populations living in urban environments where sanitation is poor and where rainfall run-off water collects. Symptoms of the disease appear within a week of being bitten by an infected mosquito, and include fever and aches and in some cases bleeding with a regional infection rate of 0.1% and a fatality rate of $\sim$0.05% of total population per annum (Heslop-Thomas et al. 2006).

Historical records of epidemics suggest that dengue has been present in the Caribbean over 200 years and probably much longer. Epidemics have been reported in recent times with clinical evidence: 1953 in Trinidad; 1963 and 1968 in various Caribbean islands; and 1977 in Jamaica where 105,000 cases were estimated (Ehrenkranz et al. 1971). From there,

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dengue spread across the Caribbean and northern South America, followed by further epidemics in 1981 and 1994.

Although malaria was eliminated in the Caribbean, thousands of cases of mosquito-borne dengue have been reported (The Caribbean Epidemiology Centre [CAREC] 2002). Studies in other sub-tropical regions have associated vector-borne epidemic outbreaks and transmission to climatic factors (Koopman et al. 1991; Focks et al. 1995; Hales et al. 1996; Martens et al. 1997; Jonathan et al. 1998; Poveda et al. 2000; Gagnon et al. 2001). Pools of stagnant water following rainy spells enhance mosquito breeding and dengue transmission rates. Like other regions of the world there is a warming trend in the Caribbean (Chen and Taylor 2002; Peterson et al. 2002; Jury and Winter, in press), and there are responses to El Niño events whereby rainfall increases in the early summer of the following year. There is concern that global warming will enhance vector-borne diseases such as dengue since the development, geographical distribution and transmission of the vectors and viruses are influenced by climate (Martens et al. 1997). The mosquito is appearing at higher elevations and more northerly latitudes than previously found (Suarez and Nelson 1981; Koopman et al. 1991; Hales et al. 2002). Thus, dengue outbreaks in the Caribbean are expected to be related to precipitation, temperature and other indicators of climate variability.

Rigau-Perez et al. (2001) report dengue epidemics in Puerto Rico in 1963, 1969 and the early 1990s. Depradine and Lovell (2004) studied relationships between weekly dengue cases and climate in Barbados. Positive cross correlations were found with water vapor pressure at a lag of 6 weeks, rainfall at 7 weeks, minimum temperature at 12 weeks and maximum temperature at 16 weeks. There was a negative correlation with wind speed at a lag of 3 weeks. A multi-variate predictive model was developed for dengue in Barbados that explained 35% of variance.

In this paper, the influence of climate on dengue outbreaks in Puerto Rico is studied using methods similar to Jury and Kanemba (2007), Chadee et al. (2006) and Amarakoon et al. (2007), first considering seasonality then interannual variability. Although the focus is on climate factors leading to epidemics, defined as years when $>10{,}000$ cases are reported; there are confounding factors such as changes in the endemic nature of dengue, mosquito control and public education; which are outside the scope of this study. The paper is divided into Data and methods, Results and Discussion sections.

Data and methods

Data on reported cases of dengue were provided by the Puerto Rico Department of Health, and were derived from reports submitted from various hospitals throughout the island. The annual number of cases was available in the period 1979–2005 ($n = 27$), whilst monthly data were available over the period 1990–2005 ($n = 16 \times 12$). An upward trend was expected, but it was found that dengue cases in Puerto Rico are relatively constant in time, with infrequent epidemics related to climatic conditions.

As the health data are available in two distinct formats (monthly and annual), the data analysis is handled separately. Annual data that represent total dengue cases each calendar year are converted to standardized departures (e.g. the mean is subtracted and the value is then divided by the standard deviation) to facilitate comparison with climatic data. For monthly data, the mean and standard deviation each month is calculated and used to produce standardized departures in the same manner. For monthly data, a 5-point centered running mean was applied prior to inter-comparison. The annual data are left unsmoothed.

Climatic data were obtained from the US National Climate Data Center, in the form of station data across the island of Puerto Rico (>60 for rainfall, >20 for temperature). These were averaged into an all-island value over the same period: monthly from 1979–2005 inclusive. In addition satellite-station merged rainfall (CMAP) estimates, Climatic Research Unit (CRU) area-averaged station rainfall and temperature, and National Center for Environmental Prediction (NCEP) reanalysis model temperature and wind speed data were extracted for the Puerto Rico grid-box and compared with the all-island station data. Correlations were found to exceed 90% for smoothed consecutive monthly series. Puerto Rico rainfall and temperature indices were formed by averaging the available station data, following removal of data of poor quality. The (relatively small) annual cycle was filtered to produce standardized departures, and smoothed with the 5-month running mean. Thus, the climatic data were reduced so as to 'match' the health data.

An analysis was carried out to make the most appropriate choice of 'influencing season', by comparing the time of optimal correlation of annual dengue cases with different seasons of standardized departures of rainfall and temperature. With a degrees of freedom of 26, 90% confidence is reached at $r > 31\%$. The July to December period was found to be most highly correlated with annual dengue cases, and thus most influential.

In order to assess how inter-annual and spatial climatic patterns influence dengue variability, high and low dengue seasons were identified using a method similar to that employed by Jury and Kanemba (2007) for malaria in Africa. High dengue seasons include 1990, 1994, and 1998; whilst low seasons are 1979, 1984, 1985. The relationship with Caribbean hurricane frequency was tested and found to be random: some greater (1998) and some lesser (1984). Then, composite maps of surface temperature, surface-specific humidity, sea surface temperature, surface air pressure, satellite outgoing longwave radiation (OLR, an estimate of cloud depth), mid-level atmospheric vertical motion, and surface winds were analyzed using the NOAA Climate Diagnostic Center website: www.cdc.noaa.gov/Composites. Composite environmental fields for low dengue seasons were calculated and subtracted from high dengue seasons and notable features were plotted and interpreted. The composite maps may be thought of as weather maps (based on year-to-year differences) favoring enhanced dengue transmission.

To understand the seasonal cycle of dengue, a hovmoller (time–longitude) analysis of climatological mean precipitable water (vertically integrated specific humidity) and meridional (north–south) wind was prepared using NOAA climate data and websites, extending from 40–80E across the Caribbean latitudes 10S–20N.

To analyze the long-term trends of temperature and rainfall, monthly data since 1900 for the area around Puerto Rico (15–20° N, 60–75° W) were extracted from the CRU gridded surface weather data base via the IRI climate library website. Temperature and rainfall anomalies were computed, smoothed with a 5-year running mean and then linear trends were analyzed. To assess future projected trends for these variables, identical monthly anomaly data were extracted from the Geophysical Fluid Dynamics Lab (GFDL) C2.1 coupled model, run for the Intergovernmental Panel on Climate Change 4th assessment (IPCC AR4) with the SRES A1B (moderate CO2 increase) scenario (Meehl et al. 2007). The GFDL C2.1 model is described by Delworth et al. (2006), Gnanadesikan et al. (2006), Wittenberg et al. (2006) and Griffies et al. (2006). The period from 2001–2100 is considered and the monthly data are smoothed and trend analyzed as for the historical data. In the following section, results are presented and interpreted.

Results

Figure 1 illustrates the close match between the annual cycle of dengue and rainfall departures, calculated by averaging monthly standardized departures over 16 years. There was no lag, whereas some delay was anticipated between rainfall, *Aedes* mosquitoes, and reported dengue cases. In African malaria, there is a 2- to 3-month lag following an increase of rainfall (Jury and Kanemba 2007) due to the longer parasite incubation period and different characteristics of the *Anopheles* mosquito. Here it is seen that an increase in rainfall from May to November drives a seasonal increase in dengue without delay.

Figure 2 illustrates the consecutive monthly variability of dengue cases together with an index comprised of Puerto Rican air temperature and rainfall standardized departures added together in equal parts. Two epidemics occurred in 1994 (almost 19,000 cases, Rigau-Perez et al. 2001) and 1998 (over 16,000), with lesser peaks in 1992 and 1993. There were no epidemics from 1998–2005, as rainfall decreased. Other factors contributing to a decrease in dengue cases include public awareness and adequate medical facilities (Rigau-Perez et al. 2001), but further consideration of non-climatic factors is outside the scope of this study. The (T + R) climate index appeared to exhibit some annual cycle variability, but closer inspection revealed that the cycles were variable and marched back and forth across the calendar year, and generally peaked in the second half.

In Figure 3 annual data on dengue cases and July to December mean temperature departures are plotted. A visual inspection reveals that some epidemics coincide with higher temperatures, most notably 1998. However, a number of warm years do not induce higher dengue cases: 1987 and 1995. The correlation between the two series was 37% achieving significance at the 95% confidence limit with 26 degrees of freedom. Adding rainfall and surface wind speed in a multi-variate regression provided no additional value;

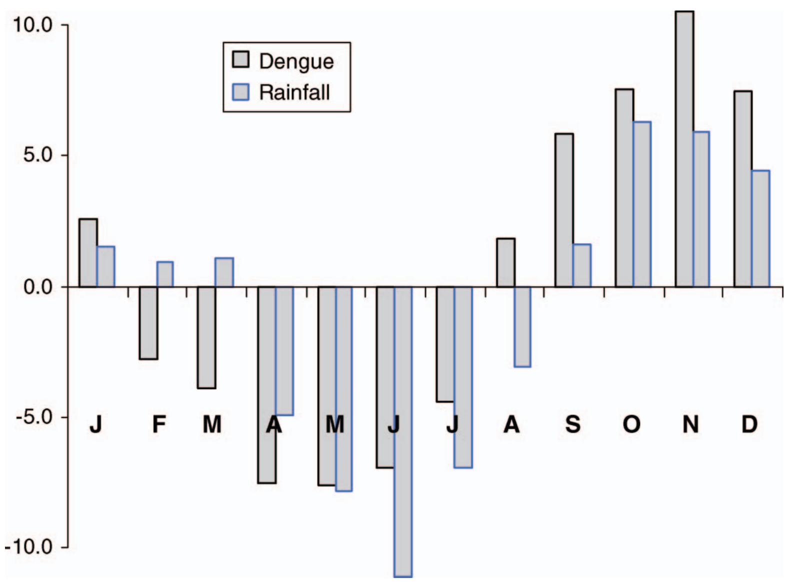

Figure 1. Mean annual cycle of rainfall and dengue cases (bars with bold surround), expressed as standardized departures × 10, based on monthly averages over 16 years (1990–2005).

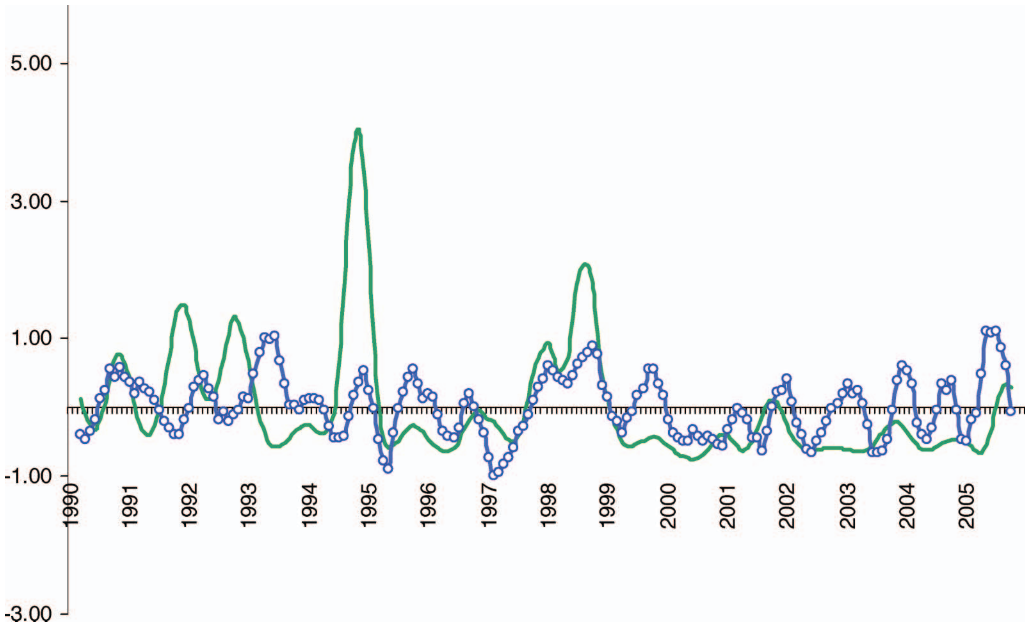

Figure 2. Monthly variability of dengue cases (solid) compared with an index of rainfall and temperature (line with open dots), as standardized departures smoothed with a 5-month running mean.

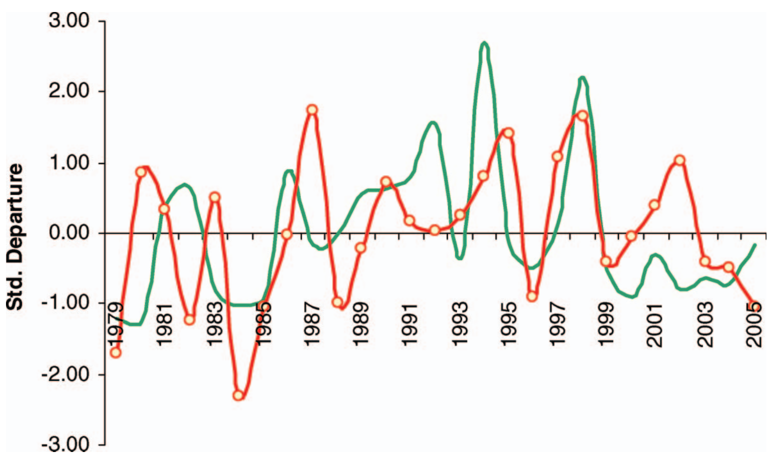

Figure 3. Annual dengue cases (solid) versus July–December mean temperature (line w/dots), as standardized departures.

the result was the same correlation. The reason for this is apparent in Figure 4, where dengue cases were individually plotted against rainfall and temperature departures fitted with a second order polynomial trend. The trend line for temperature was positively sloped and nearly linear (14% of variance), but for rainfall the trend line peaked near normal and dropped rapidly at higher values. This reflects the process of floods washing away

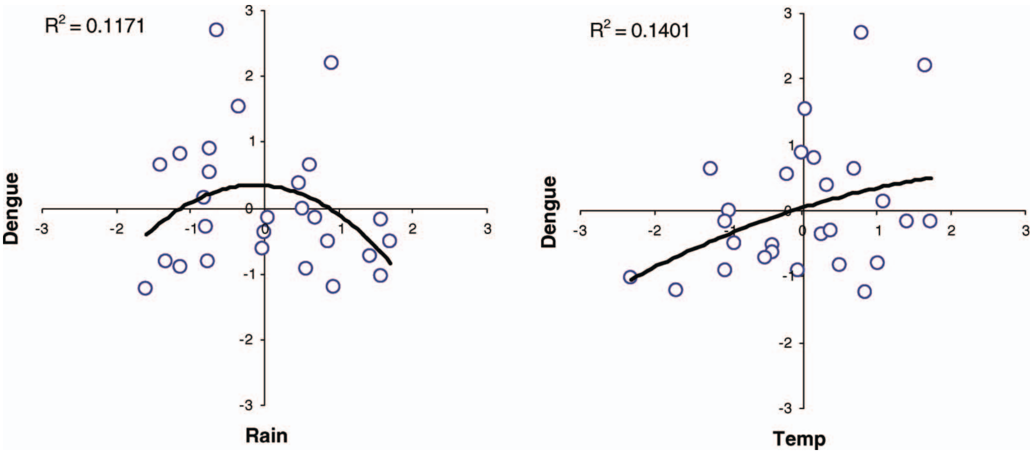

Figure 4. Scatterplots of annual dengue cases (y-axis) and July to December rainfall (left) and temperature (right) fitted with a second order polynomial trend (bold). All values are standardized departures.

mosquito larvae, inhibiting dengue transmission. The influence of rainfall was thus limited (11% of variance), in agreement with Amarakoon et al. (2007). For wind speed (not shown) the trend line was similar to rainfall, and only 8% of variance was explained. Higher wind speeds corresponded with lower dengue cases, but average to lower wind speeds had little effect. In general, correlations of local climate indices against dengue were marginally significant; temperature emerged as the most important predictor.

Testing the El Niño Southern Oscillation (ENSO) influence using the central Pacific (Nino3) sea surface temperature (SST) index, a cross-correlation of 23% was found that does not achieve statistical significance. Neither does the ENSO index help in a multivariate prediction of Puerto Rican dengue, unlike that found in Trinidad, Tobago and Barbados where an ENSO-driven wet spell precedes a warm spell, followed by a dengue epidemic affecting a higher percentage of the (growing) population (Amarakoon et al. 2007).

In Figure 5 composite maps for high minus low dengue seasons are illustrated for: (a) surface air temperature, (b) specific humidity, and (c) air pressure. These 'dengue weather maps' confirm that temperatures were above normal over a wide area, extending from Florida across the Caribbean, in agreement with Watts et al. (1987). The temperature signal was strongest over the southeastern USA, where differences were up to 1°C. This suggests that cold air masses, originating from the NW, were deflected away from the Caribbean during autumn. The satellite OLR field (not shown) revealed higher values indicating reduced cloudiness to the east of Puerto Rico, indicating sunny weather associated with higher levels of solar radiation. In Figure 5b and 5c, composite maps of high minus low dengue seasons are provided for surface specific humidity and sea level air pressure. Humidity values were above normal in the northern tier along 25N latitude. The reasons for this enhanced moisture are apparent in the pressure map, where lower pressure was found off the coast of Florida. This pressure pattern brought about a reduction of easterly trade winds over the Caribbean. With lighter winds, the fragile bodies of mosquitoes were less likely to experience damage from turbulence. The low pressure also brought about southerly air flow over the Bahamas, helping to 'shield' the Caribbean from

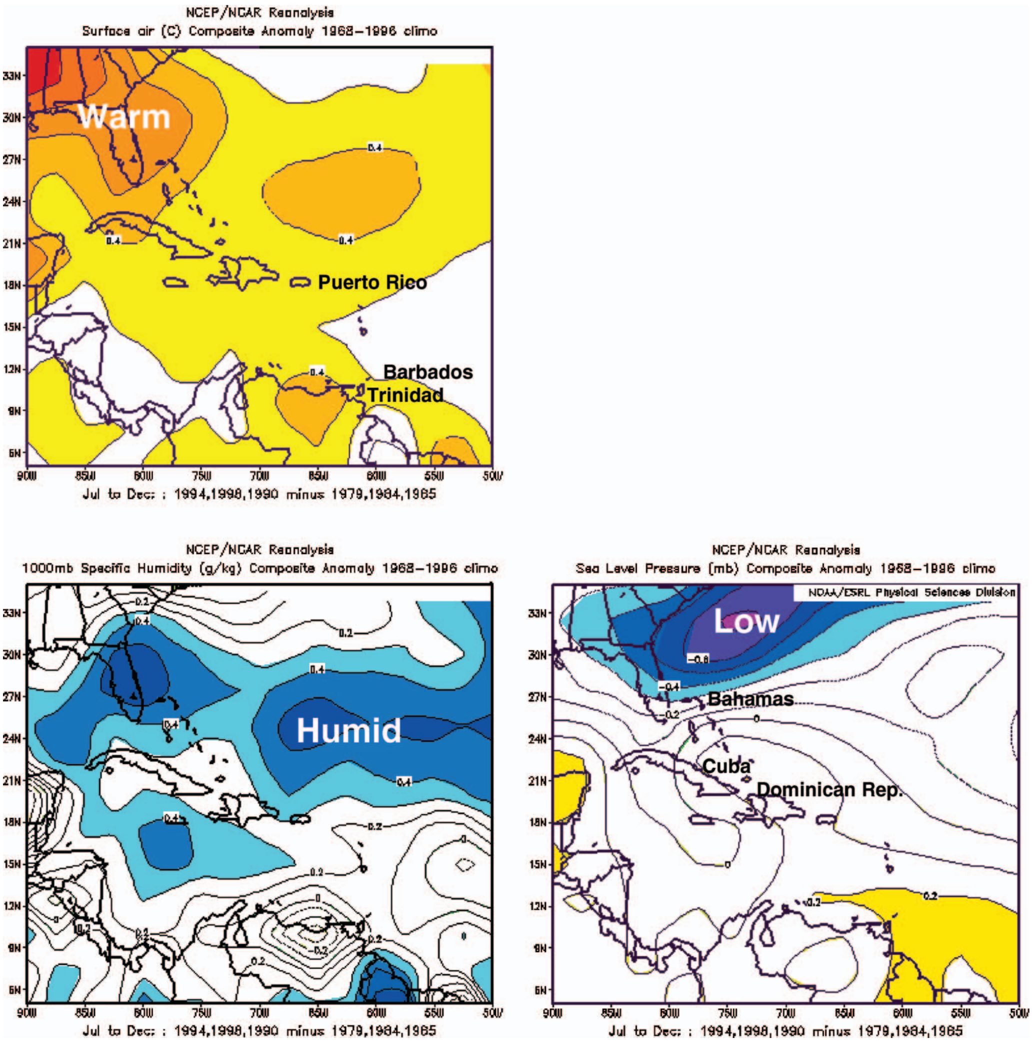

Figure 5. Composite climatic maps for dengue high seasons minus low seasons: (a) surface air temperature, (b) surface specific humidity and (c) sea level air pressure differences (right). Shaded regions highlight areas of large differences. Contour intervals for temperature 0.2°C, specific humidity 0.1 g/kg, and sea level pressure 0.1 hPa. Place names are given.

cool dry air masses moving off the continental US. The more southerly air flow infuses the relatively dry sub-tropics with an air mass that is more hot, humid and equatorial in character.

Discussion

An analysis of the association of dengue cases in Puerto Rico with temperature, rainfall and wind speed was presented. The number of dengue cases exhibited no significant overall trend despite an increase in temperature. This is thought to be due to a gradual decline in rainfall in the period after 1998, and to better public awareness of the problem coupled with adequate healthcare (Morens et al. 1978; Rigau-Perez et al. 2001). In addition, the population of Puerto Rico is nearly constant due to emigration to the USA. However, in the earlier period a number of epidemics occurred, most notably in 1994 and 1998 when temperatures were >1 standard deviation above normal. These epidemics coincided with wet conditions and positive rainfall departures from May to November.

Figure 6 illustrates why the second half of the year is more conducive to dengue epidemics across the Caribbean. The inter-tropical convergence zone (ITCZ), represented by precipitable water (vertically summed humidity) and meridional (north–south) winds, advanced furthest north from September to November. This corresponds to a northward shift in convergence associated with the equatorial Hadley circulation and 'thermal equator'. Wind flow from the south (+V) increased and spread northward from June to November each year, bringing conditions conducive to tropical diseases to Puerto Rico and other Caribbean islands (Amarakoon et al. 2007).

To place the relatively short health records into broader context, climatic data over a longer time were analyzed. The Caribbean is fortunate to have more than a century of

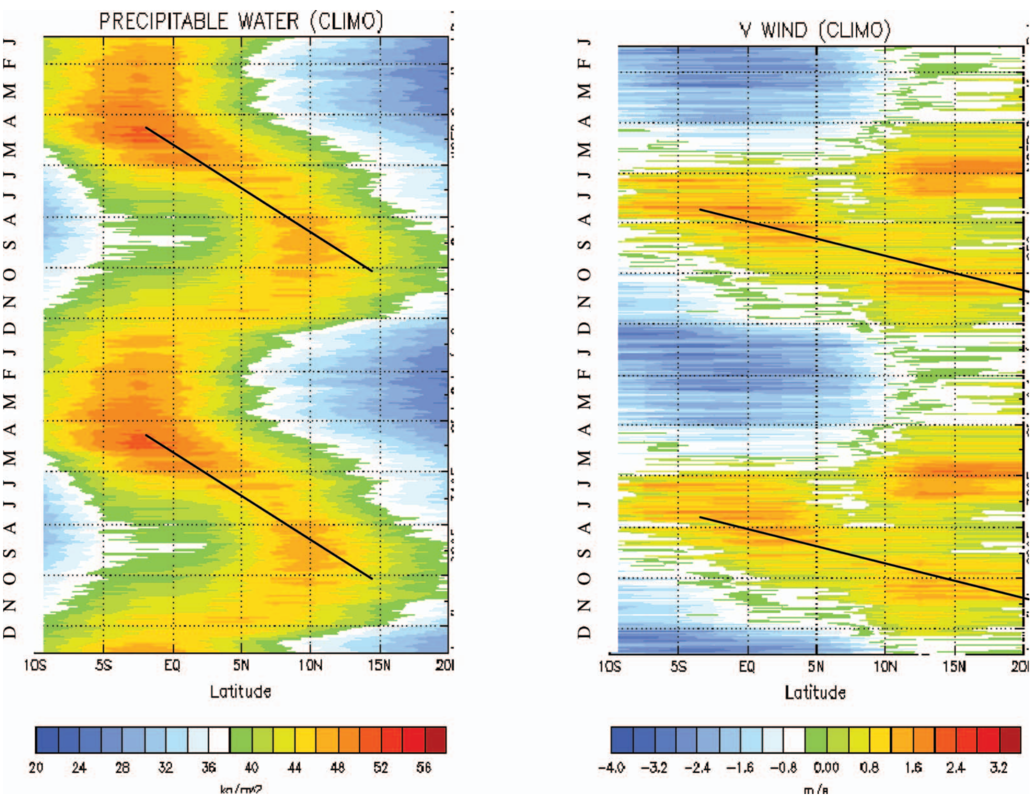

Figure 6. Climatology of precipitable water (left) and meridional V wind, from NCEP data, analyzed over the Caribbean and Venezuela 40–80W, 10S–20N, as a hovmoller plot over two annual cycles (time goes down on y-axis with month labels), based on NCEP data averaged from 1979–1998. Lines represent the northward spread of humid air (left) with a southerly wind (right) to the latitude of Puerto Rico (18N).

accurate temperature and rainfall observations. Future projected trends of climatic variables were compared with past observed trends using the IPCC AR4 model output (Meehl et al. 2007). Here the GFDL C2.1 general circulation model forced with the A1B scenario was considered (see Delworth et al. 2006; Gnanadesikan et al. 2006; Griffies et al. 2006; Wittenberg et al. 2006 for details) and data were extracted for the Caribbean over the period 2000–2100 from the IRI climate library website. The historical trend of rainfall was -0.18 mm/yr and the projected decline is at a similar rate (-0.13 mm/yr) over the next 100 years (Figure 7a). The r^2 linear trend fit was relatively small (0.28 observed, 0.14

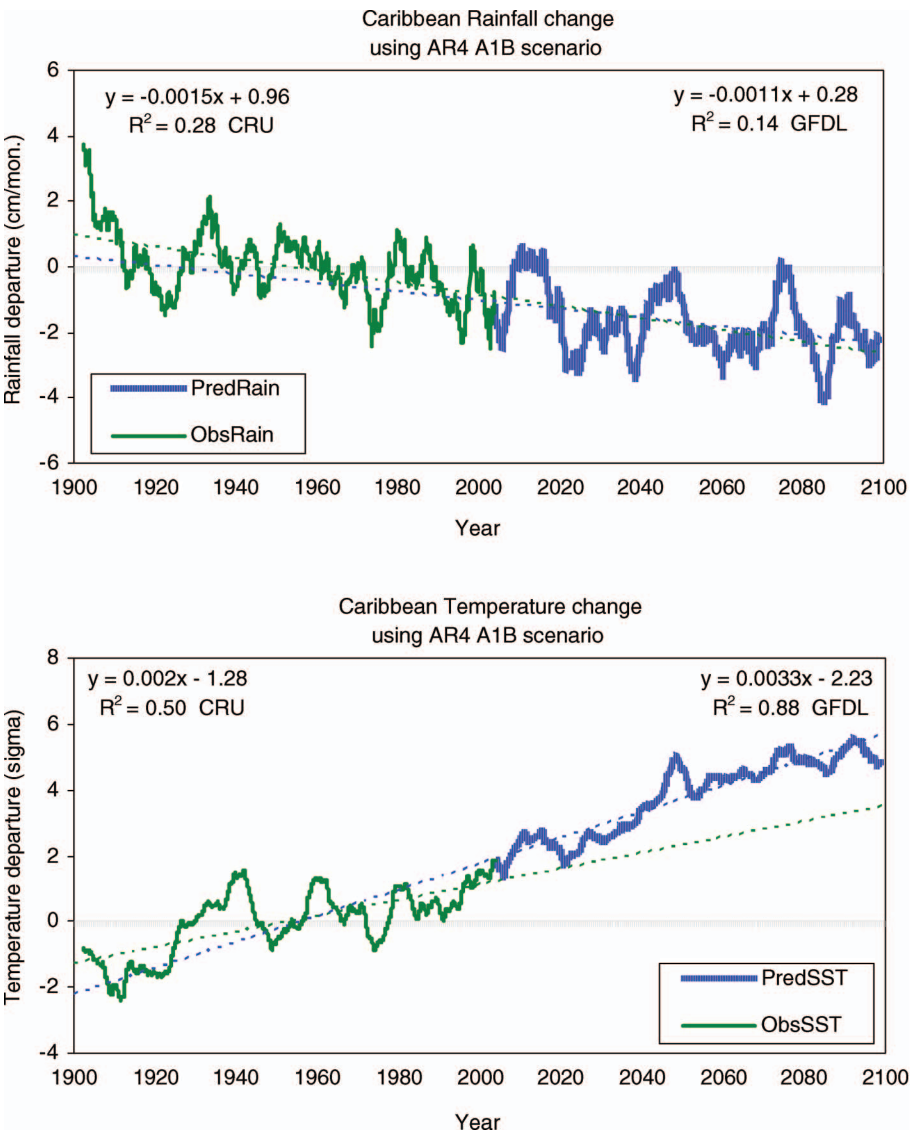

Figure 7. Observed (thin line) and projected trends in rainfall (top) and surface temperature averaged over the Caribbean. Weak downward trends in rainfall are consistent, but the rate of warming is accelerating in the GFDL C2.1 A1B forecast.

projected) because of a significant 6–12 year rainfall cycle, according to wavelet spectral analysis (not shown). Lower rainfall may influence dengue, but temperatures are clearly rising. The historical trend was +0.005°C/yr in the Caribbean region (Figure 7b) whilst the projected temperature trend is +0.008°C/yr, almost doubling. The r^2 linear trend fit increased from 0.50 in the past to 0.88 in future, suggesting that local temperature variability may be overwhelmed by global warming. Given that the relationship between dengue and temperature is stronger than rainfall, and the decline of rainfall is smaller (~1%) than the rise of temperature (~2%), a long-term increase in dengue seems likely. Indeed, at the time of writing this paper (2007), a new dengue epidemic has spread across Puerto Rico, affecting all strata of society.

Year-to-year (inter-annual) fluctuations in climate that control dengue in Puerto Rico were found to be different than in Trinidad, Tobago, and Barbados where epidemics affected a larger percentage of the (growing) population and were associated with warmer temperatures, *lower* rainfall and El Niño conditions (Amarakoon et al. 2007). For Puerto Rico, the El Niño connection was much weaker, likely due to its stronger control over early summer (March to May) rainfall (Jury et al. 2007) that, in turn, had less influence on dengue. The climate change projected for the Caribbean anticipates higher dengue levels.

Conclusion

In conclusion, the variability of insect-borne dengue in Puerto Rico was studied in relation to climatic elements in the period 1979–2005. Annual and monthly variability of reported cases were compared with precipitation, temperature and other climatic data. Results show that the incidence of dengue in Puerto Rico was relatively stationary. Annual fluctuations were driven by rainfall increases from May to November, whilst year-to-year variability in dengue cases was positively related to temperature. Seasons with higher (and lower) dengue cases were mapped, and it was found that lower pressures around Florida cause humidity to rise during epidemics, whilst maintaining high temperatures over the Greater Antilles. This study can be used to better understand the environmental causes of dengue epidemics in the Caribbean, but further research is needed to establish a predictive potential.

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