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ORIGINAL ARTICLE

Dengue epidemics in the Caribbean-temperature indices to gauge the potential for onset of dengue

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Abstract The seasonality, patterns and the climate associations of the reported cases of dengue in the Caribbean were studied by analyzing the annual and monthly variability of reported cases as well as those of climate parameters (temperature and precipitation). More attention was given to Trinidad and Tobago, Barbados, and Jamaica, as those countries contributed mostly to the reported cases. The data were for the period 1980–2003. Results showed that the incidence of dengue in the Caribbean were higher in the last decade (1990s) compared to that in the previous decade (1980s). The yearly patterns of dengue exhibited a well-defined seasonality. The epidemics appeared to occur in the later half of the year following onset of rainfall and increasing temperature. Analysis revealed that the association of the epidemics with temperature was stronger, especially in relation to the onset of dengue, and the probability of epidemics was high during El Niño periods. In years with early warmer periods epidemics appeared to occur early, which was a scenario more probable in the year after an El Niño (an El Niño + 1 year). Indices linked to temperatures that are useful for gauging the potential for onset of dengue were examined. An index based on a moving average temperature (MAT) appeared to be effective in gauging such potential and its average (AMAT) signals a threshold effect. MAT index has potential use in adaptation and mitigation strategies.

Keywords Caribbean dengue epidemics · Climate variability · Correlations · Disease onset · Heat build up · Lapse and lead time · Mosquito breeding environments · Moving average temperature · Statistical lag

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1 Introduction

Millions of people are under the threat of dengue fever (DF) in the tropics and subtropics. The factors that can influence DF outbreaks are numerous. They involve social, biological and environmental factors, the introduction of a new serotype, the immunity of the population, the free movement of people in a region, and climate factors. Although DF outbreaks are multifactorial, climate factors play a significant role. Studies done in different regions of the globe (Patz et al. 1998; Martens et al. 1997; Gagnon et al. 2001; Hales et al. 1996; Poveda et al. 2000; Focks et al. 1995; Koopman et al. 1991; Cazelles et al. 2005) have associated dengue outbreaks and the transmission of the disease with climate variability (evidenced by the occurrences of El Niño Southern Oscillation/ENSO events), through temperature increases and availability of stagnant and stored mosquito-accessible water during droughts as well as after rains. These conditions i.e., temperature increases and moisture availability, appear to enhance dengue transmission rates and mosquito breeding. The extrinsic incubation period (period of incubation of parasite inside the vector or EIP) shortens at higher temperatures (Focks et al. 1995) and a decrease in the incubation period can lead to higher transmission rates (Koopman et al. 1991) through more frequent vector–human contacts. Moisture is required for vector breeding and subsequent transformation of eggs to larvae, and then to pupae, and finally to the mosquitoes. An excess or lack of rain can contribute to an increase in breeding sites and vector abundance. Excess of rainfall results in pools of stagnant water on the ground, and also non-biodegradable containers such as discarded automotive tyres, metal and plastic containers can retain stagnant water, which are potential breeding sites. Lack of rainfall, on the other hand, encourages water storage. Water storing containers can become breeding places if they are not properly covered and left unattended.

Dengue fever has been reported in the Caribbean for over 200 years (Ehrekranz et al. 1971; Gubler 1997). Although the frequency of the epidemics had been low till about the 1970, over the 22 year period (1980–2001) in the last century, 43,000 cases of dengue (Caribbean Epidemiology Centre/CAREC 2002, communications) have been reported. The incidence has been very high in the last decade, reported cases totaling to about 41,000. An explanation for the rise in dengue cases in the last decade or two of the last century can be the warming of the Caribbean and the scenarios leading to mosquito breeding sites. Published studies (Ropelewski and Halpart 1996; Malmgren et al. 1998; Taylor 1999; Chen and Taylor 2002; Peterson et al. 2002), indicate that in the Caribbean, drier than normal conditions with warmer temperatures in the latter half of El Niño years, an increase in precipitation in the early part of the following year (El Niño + 1 year), and there is a warming trend. During the last two decades in the last century there were many El Niño episodes; 1982/1983, 1986/1987, 1990/1991 (weak), 1992/1993, 1994/1995(weak), and 1997/1998. Thus, climate conditions had been favourable for dengue outbreaks as temperature increases enhance dengue transmission rates, and lack or excess of rain enhances mosquito breeding and hence vector abundance. Water storage and proliferation of water retaining receptacles such as discarded tyres and other non-biodegradable containers are common in many parts of the Caribbean.

Another possible explanation for the upsurges in dengue is the immune status of the Caribbean (host) population to new serotypes. If the hosts have not been exposed to the serotypes entering into the region previously, they will be highly susceptible to the new serotype. This can cause severe epidemics at least in the first year of introduction. This appeared to have been the case when dengue serotype 1 was introduced in 1977 that caused a devastating pandemic in the Caribbean (PAHO 1994). Similarly dengue serotype 4 was introduced in 1981 (PAHO 1994) and resulted in a sporadic activity throughout the Caribbean. Dengue serotypes 2 and 3 had been introduced prior to 1970 (PAHO 1994), and during early and mid 1970s serotypes 2 and 3 had become endemic in the region. In the 1990s all four serotypes had been in circulation in the Caribbean (Rawlins 1999), with dengue serotype 3 becoming the primary serotype within the region, again, since 2001 (Salas and George 2002). Apart from the emergence of a new serotype, other possible scenario that can cause an increase in dengue incidence is the re-emergence of a serotype in a region after being absent from that region for a while. People who have missed the infection at the last epidemic, especially the younger ones, will be at high risk in a re-emergence. Perhaps, in this scenario, severity of the epidemic could be much less compared to that due to the introduction of a new serotype.

The reasons for emergence and re-emergence of serotypes are not very visible. One reason can be the free movement of people within and beyond the Caribbean region. However, considering the facts that only one new serotype was introduced during the last two decades (serotype 4 in 1981) and the conduciveness of the climate conditions existed in the last two decades to enhance the frequency of vector-human contact (disease transmission rate) and vector abundance, it is more likely that the climate factors have had significant influence on the epidemics observed, especially in the 1990s. In respect of climate associations of dengue in the Caribbean region, Wegbreit (1997) has reported a statistically significant relationship between lagged temperature and dengue incidence rates in Trinidad and Tobago. Campione-Piccardo et al. (2003) have indicated a temporal correlation with reported dengue incidence and rainfall data in Trinidad and Tobago. Most recently, Depradine and Lovell (2004) have shown correlations of reported dengue cases with lagged vapour pressure, minimum temperature, maximum temperature, and rainfall in the parish of St. Michael in Barbados. Further, the work of Joseph Keating (2001) on cyclical incidence of dengue fever in Puerto Rico has shown, through a second order model, a statistically significant correlation between monthly dengue cases reported and the temperature lagged 3 months.

The purpose of this study is to investigate further the nature and extent of the association between climate and the incidence of dengue across the Caribbean, and to examine temperature indices that may prove useful in gauging the potential for onset of dengue. Temperature is an easily measurable climate parameter and future temperatures can be projected with more certainty than rainfall. If temperature indices to gauge the onset of dengue can be derived, they will be of immense value in better planning and strengthening of mitigation and adaptation strategies.

2 Data and methodology

2.1 Dengue data

Data on reported cases of dengue were provided by the disease surveillance unit, CAREC (Caribbean Epidemiology Centre) in Trinidad, and were derived from reports submitted from the Ministries of Health in the various countries. The number of Caribbean countries considered was 21 (Table 1). The data mainly spanned the period 1980–2001. They were in the form of annual totals for all the countries over the period 1980–2001. They were also on the basis of epidemiological months for all the countries and calendar months for some

Table 1 (a) The 21 countries for which dengue incidence data were available. (b) Description of available monthly dengue data for Trinidad & Tobago, Barbados and Jamaica

(a) Countries with annual data from 1980 to 2001

Anguilla, Antigua, Aruba, Bahamas, Barbados, Belize, Bermuda, British Virgin Islands, Cayman Islands, Curacao, Dominica, Grenada, Guyana, Jamaica, Montserrat, St. Lucia, St. Vincent, St. Kitts-Nevis, Surinam, Trinidad & Tobago, Turks & Caicos

(b) Features of monthly data for Trinidad & Tobago, Barbados and Jamaica

Country	Data span	Resolution	Data missing years
Trinidad & Tobago	1992–2004	Epidemiological monthly	1993 and 1995
Barbados	1995–2001	Epidemiological & calendar monthly	
Jamaica	1995–2001	Epidemiological monthly	
	1995 & 1998	Calendar monthly	

countries over the period 1995–2001. An epidemiological month as used in this paper is a time period spanning over four consecutive weeks.

Attention was focused more on Trinidad and Tobago, Barbados, and Jamaica for a number of reasons. The data indicated that the prevalence of dengue in Trinidad and Tobago was about 50% of the reported cases, in Barbados about 20% of the reported cases, and in Jamaica about 8% of the reported cases. Also it was easy to access climate data for these countries. The datasets for Trinidad and Tobago, Barbados, and Jamaica are also described in Table 1. Note that epidemiological month datasets were used for Trinidad and Tobago while calendar month datasets were used for Barbados and Jamaica. The choice of epidemiological months or calendar months was based on the available formats of dengue and climate data. This should not be a problem however, as a calendar month is almost an epidemiological month (4 weeks). In the following sections then, the time interval ‘‘month’’ means an epidemiological month for Trinidad and Tobago and a calendar month for Barbados and Jamaica.

A cause for concern in studies of the type that is being presented here is the completeness of disease data. There may be under reporting in times of low occurrence, e.g., in between epidemics. Cases may be missed, or diagnosed wrongly. On the other hand, in epidemics, there may be over reporting. Diseases with similar symptoms may often be reported as dengue fever. Recent work on seroprevalence of dengue in Trinidad (Campbell et al. 2007) indicates that the reporting rate is 94.4%, which is satisfactory in respect of data completeness.

2.2 Climate data

The climate data (precipitation, mean temperature, maximum temperature, and minimum temperature) were obtained from the data repository of the Climate Studies Group Mona at the Department of Physics, the University of the West Indies, Mona Campus, Jamaica. The climate data were available on a daily or a calendar monthly basis. The data were converted to annual averages or monthly averages as required for use in the analysis. Trinidad and Tobago and Barbados had long-term series of climate data. Trinidad and Tobago climate data were from the meteorological station at Piarco International Airport and Barbados climate data were from the meteorological station at Husbands. The climate data for Jamaica caused a minor problem as a long-term series was not available because a fire at the meteorological data depository destroyed data for the early 1990s. Fortunately, relevant monthly data were available for the years 1995 and 1998 from Manley International Airport in Jamaica. Years 1995 and 1998 were strong epidemic years in Jamaica. However, to understand the past climate variability in Jamaica a country average gridded data set from the Tyndall Centre (Mitchell 2003) was used when necessary.

2.3 Methodology

Data analysis consisted of the analysis of the time series of the reported cases of dengue fever and their rates of change; analysis of the time series of mean temperature and mean precipitation; study of the climatology of temperature and precipitation; study of monthly variability of reported cases and seasonality; correlation analysis including lag; and examining indices based on temperature patterns that have the potential to gauge the onset of dengue including the deriving of an index referred to as the Moving Average Temperature (MAT). The rate of change mentioned here is equal to the reported cases in a given year minus that in the previous year, and is expected to provide additional features of the pattern of variation of the disease.

The MAT index referred to previously is defined by the Eq. 1, given below.

$$\text{Moving Average Temperature (MAT)} = \frac{1}{M}\sum_{N=1}^{M} \theta_N \tag{1}$$

In Eq. 1, θ_N is the average temperature during the Nth month and the index M varies from 1 to 13 in Trinidad and Tobago (13 epidemiology months), and 1 to 12 in Barbados and Jamaica. According to this definition the first value of MAT, that is for $M = 1$, is the average temperature for the first month. The second value (for $M = 2$) is the average temperature for the first 2 months, and so on in a given year.

Monthly dengue data from 1992 to 2001 (except 1993 and 1995) together with monthly temperature data from 1979 to 2001 were used to derive the properties of MAT for Trinidad and Tobago. Monthly data for 2002, 2003, and 2004 were used to test the effectiveness of MAT for Trinidad and Tobago. Similarly monthly dengue data from 1995 to 1999 together with monthly temperature data from 1979 to 1999 were used to derive the properties of MAT for Barbados. Monthly data for 2000, 2001, and 2002 were used to test the effectiveness of MAT for Barbados. Monthly dengue and temperature data for 1995 and 1998 were used to derive the properties of MAT for Jamaica.

The sorting of El Niño and La Niña episodes, for the study period were according to the NOAA-CDC MEI index classification. El Niño episodes were 1982/1983, 1986/1987, 1990/1991 (weak), 1992/1993, 1994/1995 (weak), 1997/1998, and 2002/2003. La Niña episodes were 1988/1989, latter part of 1998–2000.

3 Results

Results are summarized in Figs. 1–8 and Tables 2–8.

3.1 Dengue seasonality, patterns and associations with climate

Figure 1 illustrates the variability in the monthly reported cases in the Caribbean using data for the 21 countries listed in Table 1 and for the period 1996–2001. The pattern indicates

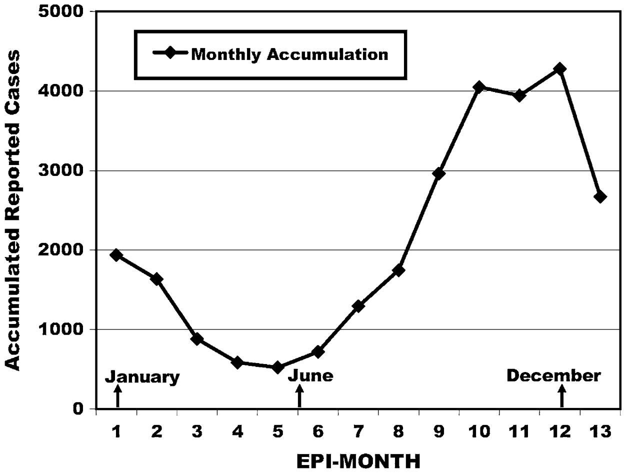


Fig. 1 Monthly variability of reported dengue cases in the Caribbean for the period 1996–2001

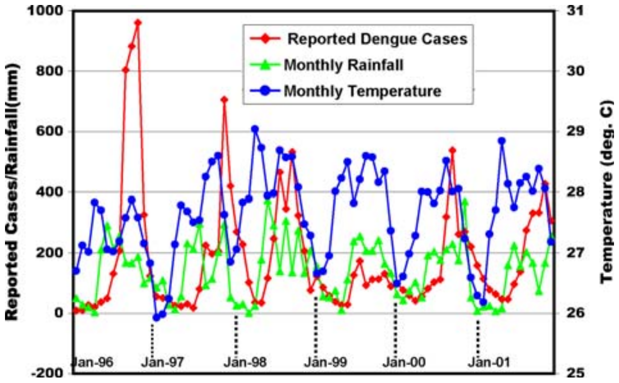


Fig. 2 Time series of monthly reported cases, rainfall and temperature in Trinidad and Tobago for the period 1996–2001

that in the Caribbean the epidemics (outbreaks) of dengue have a well-defined seasonality, occurring in the latter half of the year when the region is warm and wet. The term *epidemic* as used here refers to the status of rapid growth and spread of the disease, and can persist over a period of a month or two.

The seasonality of Fig. 1 is also present in the patterns of the disease for individual countries. Data from Trinidad and Tobago are used to illustrate this. Figure 2 shows the monthly variability of reported cases as well as temperature and rainfall for Trinidad and Tobago from 1996 to 2001. The dengue seasonality is evident in individual years as is the typical seasonality of the Caribbean temperature and rainfall. From the figure a simple pattern emerges re onset of the epidemic: some amount of warming occurs first as indicated by the early peak in temperature, then rainfall, and then the onset of dengue. This pattern is replicated in other countries.

Figure 3 illustrates the time series of annual reported cases and rate of change in the Caribbean. The arrows in Fig. 3 indicate El Niño, El Niño + 1, and La Niña or Neutral

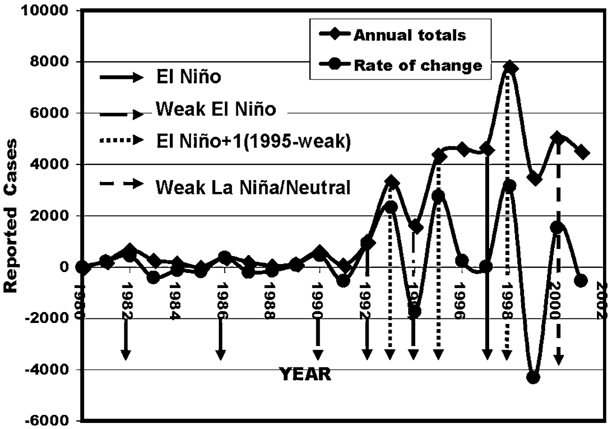


Fig. 3 Annual variability of reported dengue cases and rate of change in the Caribbean for the period 1980–2001

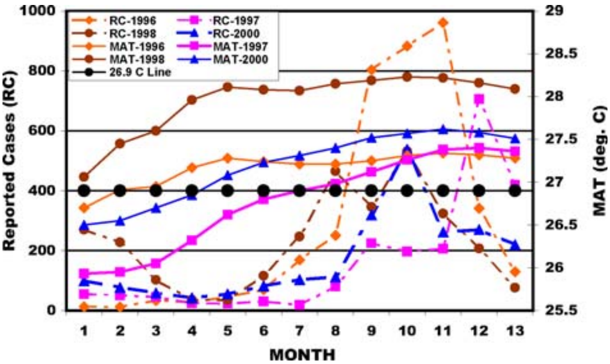


Fig. 4 Monthly variability of reported cases and moving average temperature (MAT) during 1996, 1997, 1998 and 2000 in Trinidad and Tobago

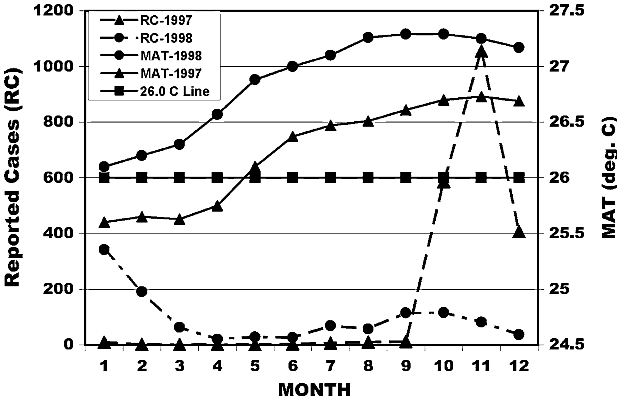


Fig. 5 Monthly variability of reported cases and moving average temperature (MAT) during 1997 and 1998 in Barbados

years. From Fig. 3 it is also evident that the probability of an epidemic during an El Niño period (El Niño and El Niño + 1 years) is higher. The results given in Table 2 support this inference. Thus, it appears that dengue outbreaks have a strong association with El Niño events, probably because for the Caribbean the latter part of the El Niño year is warmer and the early part of the El Niño + 1 year is wetter and warmer (Chen and Taylor 2002). These

Fig. 6 Monthly variability of reported cases, temperature and moving average temperature (MAT) during 1995 and 1998 in Jamaica

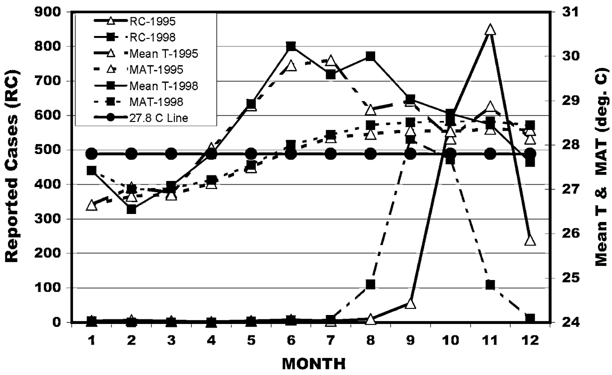


Fig. 7 Monthly variability of reported cases and moving average temperature (MAT) during 2002 and 2003 in Trinidad and Tobago

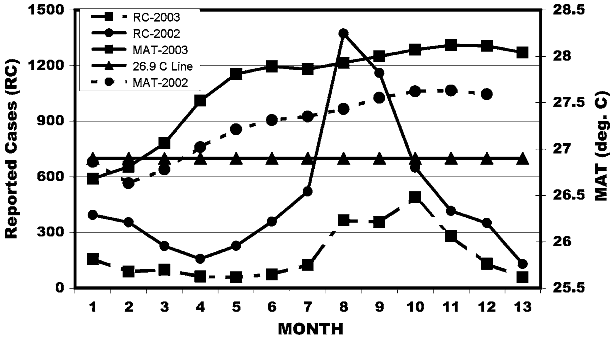
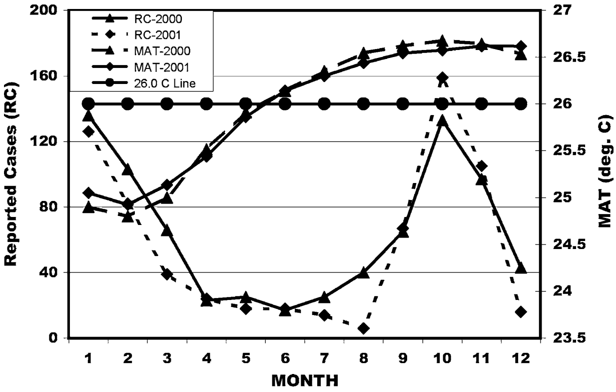


Fig. 8 Monthly variability of reported cases and moving average temperature (MAT) during 2000 and 2001 in Barbados



climate conditions are more favourable for sustaining the epidemics through increases in mosquito habitats, shortening of the EIP, and increases in disease transmission rates. The rate of change curve in Fig. 3 also shows that the epidemics have a periodicity that approximately agrees with the periodicity of El Niño events. This type of periodicity has been analysed and reported for dengue in Thailand by Cazelles et al. (2005).

Table 2 Distribution of dengue peaks among the ENSO phases during 1980–2001

Region	Total	El Niño and + 1	La Niña	Neutral
Caribbean	8[a]	7	–	1
Trinidad & Tobago	8	6	–	2
Barbados	6	5	–	1
Jamaica	5	4	–	1
Belize	4	3	1	–

[a] Number includes year 1992, which is on the rising side of the peak in 1993; El Niño: 1982/1983, 1986/1987, 1990/1991 (weak), 1992/1993, 1994/1995 (weak), 1997/1998; La Niña: 1988/1989, latter part of 1998–2000

Table 3 Results for correlation of annual dengue cases with mean annual temperature and rainfall in Trinidad and Tobago (Row 2) and Barbados (Row 3)

Country	Temperature $r{:}p$[a]	Rainfall $r{:}p$[a]
T & T[b] (1980–2003)	0.5174:0.01	Not significant
El Niño (1980–2003)[c]	0.5396:0.07	Not significant
Non-El Niño (1980–2003)	Not significant	Not significant
Barbados (1980–2002)	0.479:0.02	Not significant
El Niño (1980–2002)[c]	0.5854:0.06	Not significant
Non-El Niño (1980–2002)	Not significant	Not significant

[a] r = correlation coefficient and p = significance level

[b] T & T is Trinidad and Tobago

[c] In addition to the El Niño episodes mentioned under Table 2, episode in 2002/2003 was considered in the annual correlation

Table 4 Results for the early peak in temperature, temperature at dengue onset, rainfall at dengue onset, dengue onset time, statistically significant lag between dengue epidemics and temperature, for Trinidad and Tobago

Year	Tep[a] (°C)	Tdo[a] (°C)	Rfdo[a] (mm)	Dot[a] (month)	Ssl[a,b] (months)
1992	28.3	27.0	321.0	7th	6
1994	28.4	28.3	28.0	5th	5
1996	27.8	27.1	29.0	2nd	5
1997	27.8	27.5	213.0	7th	7
1998	29.0	28.7	178.0	5th	4, 6
1999	28.5	28.5	112.0	6th	3
2000	28.0	27.2	103.2	4th	4, 5
2001	28.8	28. 1	158.8	6th	5, 6

[a] Tep = early peak in temperature, Tdo = temperature at dengue onset, Rfdo = rainfall at dengue onset, Dot = dengue onset time, Ssl = statistically significant lag between dengue epidemics and temperature

[b] Lags in all years are statistically significant ($r > 0.72$ and $p < 0.05$), except 1998

Table 5 Results for the early peak in temperature, temperature at dengue onset, rainfall at dengue onset, dengue onset time, statistically significant lag between dengue epidemics and temperature, for Barbados, and Jamaica

Country	Year	Tep[a] (°C)	Tdo[a] (°C)	Rfdo[a] (mm)	Dot[a] (month)	Ssl[a,b] (months)
Barbados	1995	27.7	27.7	348.0	7th	5
	1996	27.0	27.0	103.9	6th	–
	1997	27.7	27.5	12.2	5th	5
	1998	28.1	27.4	44.7	4th	3
	1999	27.8	27.1	219.2	7th	5
Jamaica	1995	29.9	29.9	172.8	7th	4
	1998	30.2	30.2	26.2	6th	3

[a] Abbreviations are same as in Table 4

[b] Lags in all years are statistically significant ($r > 0.71$ and $p < 0.05$), except 1996

Table 6 Results for the estimated lapse time, lead time, moving average temperature at dengue onset, calendar quarter in which the epidemic persisted, and time of approach to country average MAT (AMAT) for Trinidad and Tobago

Year	Lst[a] (weeks)	Ldt[a] (months)	MATdo[a] (°C)	CQ[a] (quarter)	At[a] (month)
1992	8		26.9	Early 4th	6th
1994	<4		27.2	Later 3rd to early 4th	4th
1996		2	26.9	3rd to early 4th	2nd to 3rd
1997	8		26.9	4th	7th
1998	4		28.1	Later 2nd to 3rd	~1st
1999	<4		27.5	3rd	3rd to 4th
2000		1	26.9	Later 3rd to early 4th	4th
2001	4		27.4	Early 3rd to 4th	4th

[a] Lst = estimated lapse time, Ldt = estimated lead time, MATdo = moving average temperature at dengue onset, CQ = calendar quarter in which the epidemic persisted, At = time of approach to AMAT

Table 7 Results for the estimated lapse time, lead time, moving average temperature at dengue onset, calendar quarter in which the epidemic persisted, and time of approach to country average MAT (AMAT) for Barbados and Jamaica

Country	Year	Lst[a] (weeks)	Ldt[a] (months)	MATdo[a] (°C)	CQ[a] (quarter)	At[a] (month)
Barbados	1995	<4		26.6	Early 4th	5th
	1996	<4		26.2	Later 3rd to early 4th	5th
	1997		1	26.1	Early 4th	5th
	1998		1	26.6	Early 3rd to early 4th	~1st
	1999	4		26.4	Later 3rd to 4th	5
Jamaica	1995	<4		28.2	Later 3rd to later 4th	6th
	1998	<4		28.0	Later 3rd	5th to 6th

[a] Abbreviations same as in Table 6

Table 8 Results for the observed dengue onset time, time of approach to AMAT, calendar quarter observed and calendar quarter estimated for the test years in Trinidad and Tobago, and Barbados

Country	Year	Dot[a] (month)	At[a] (month)	CQo[a] (quarter)	CQe[a] (quarter)
T & T[b]	2002	4th	3.5th	Later 2nd to early 3rd	3rd
	2003	5	2.5th	Later 2nd to 3rd	3rd
	2004	4th to 5th	3rd	Later 2nd to early 3rd	3rd
BB[c]	2000	6th	5.5th	Early 3rd to early 4th	Early 4th
	2001	8th	5.5th	Later 3rd to early 4th	Early 4th
	2002	8th	4th	Mid 3rd to mid 4th	3rd

[a] Dot = dengue onset time, At = time of approach to AMAT, CQo = calendar quarter observed, CQe = calendar quarter estimated

[b] T&T is Trinidad & Tobago

[c] BB is Barbados

Further detailed analysis of the patterns of reported cases (annual and monthly) and climate parameters (temperature and rainfall) including lagged cross-correlation studies also revealed the following:

(i) The association of dengue with temperature is much stronger than that with rainfall. This is seen from the correlation of annual reported cases with temperature and rainfall. Table 3 shows results for Trinidad and Tobago and Barbados.

(ii) Statistically significant lag exists between temperature and dengue epidemics. If attention is focused on the peaks in both variables (see for example Fig. 2) then the observed lags between the early temperature peak and the dengue peak are of the order of a few months ($\sim$3–7 months). The results for Trinidad and Tobago and also for Barbados and Jamaica form similar plots and are summarized in Tables 4 and 5. Statistical analysis consistently produces high correlation coefficients (r values) ≥ 0.7 and significant levels (p values) ≤ 0.05 between the two variables, except for 1998 for Trinidad and Tobago and 1996 for Barbados.

For Trinidad and Tobago, the epidemic has a doublet nature in 1998 (Fig. 2) with the separation of the peaks being about 2 months. The doublet nature might account for the low statistical significance of lag. The strongest correlations for 1998 are seen at lags of 4 months (r = 0.42 and p = 0.26) and 6 months (r = 0.47 and p = 0.29), which are the time intervals between the early temperature peak and the first and the second epidemic peaks respectively. For Barbados, the epidemic was weak in 1996 and the peak was not well defined. This might account for the low statistical significance of lag. Others (Wegbreit 1997; Depradine and Lovell 2004) also have observed lags of the order of a few months between dengue cases and temperature. Wegbreit (1997) reported a statistically significant relationship between temperature and dengue incident rate given a six-month time lag.

(iii) Statistically significant lag exists between rainfall and the epidemic peaks. Lags observed were one to three months. The lag between temperature and an epidemic was generally greater than the lag between the rainfall and the epidemic.

(iv) During years in which warming or rising temperatures occur earlier, the onset (initial appearance of the clinical cases) of the disease and the transformation to an epidemic appears to occur earlier than usual and the onset together with the transformation closely follows the epidemic of the previous year. This feature is more pronounced if the previous year is a warmer one. An example of this was 1997/1998 in Trinidad and

Tobago (Fig. 2). In support of this, observed disease onset times are given in Table 4 for Trinidad and Tobago, and in Table 5 for Barbados and Jamaica. The calendar quarters (CQ) in which the epidemics persisted are given in Table 6 for Trinidad and Tobago, and in Table 7 for Barbados and Jamaica. The term calendar quarter refers to one-quarter of a year (three calendar months or 3.25 epidemiology months).

(v) Start or onset of the disease generally appears to occur during the summer period and follows the early temperature peak by a few weeks in many years. This lapse time (the time between the early temperature peak and the start or onset of the disease) as opposed to the lag between early temperature and dengue *peaks*, varied from 0 to about 8 weeks. The lapse time was smaller ($\leq$4 weeks) when the early part of the year was warmer than normal. There were a few years however, during which the onset of the disease occurred before the early temperature peak. Examples are 1996 and 2000 in Trinidad and Tobago, 1997 and 1998 in Barbados. These lead times are also of the order of a few weeks, 2 and 1 month, respectively for the two cases mentioned in Trinidad and Tobago, and 1 month for the cases in Barbados. The early peak in temperature (Tep), temperatures at onset of dengue, rainfall at onset of dengue are given Tables 4 and 5. Visually estimated lapse/lead times are given Tables 6 and 7. In Jamaica, annual temperature pattern does not exhibit a clear bimodal pattern. The pattern is more unimodal. The term Tep, when applied to Jamaica, corresponds to the maximum monthly temperature in any given year.

(vi) Water (moisture) availability is observed to be necessary for the onset of dengue, as moisture is required for mosquito production. But the amount of water does not appear to be critical for the onset. This can be seen from the pattern shown in Fig. 2, and also from the rainfall values at onset given in Tables 4 and 5.

3.2 Temperature indices useful to gauge the potential for onset of dengue

As mentioned before, the early temperature peak was close to the onset of the disease. One option therefore to gauge the time of onset of the disease is to use both the time of Tep along with an average lapse time and/or an average disease onset temperature. However, from Figs. 2 and 6 it is clear that the monthly temperature follows more or less an oscillatory pattern and the temperature peaks are broad. Because of the oscillatory pattern of the temperature, a country's average onset temperature can be observed on the rising side as well as on the declining side of the early temperature peak and there can be a considerable time gap between the two observations. The results of this work indicate that the more acceptable would be the observation on the declining side of the temperature peak as the probability for onset of dengue after the early peak in temperature was higher than if it was before the peak. This can be inferred from the results for lapse/lead time given in Tables 6 and 7. The broadness of the temperature peak causes less accurate estimation of the time of Tep. Considering the constraints associated with Tep, an alternative scheme is proposed after smoothing the temperature variability.

The smoothing process consisted of calculating MAT using Eq. 1 for every year. Figure 4 shows the monthly variability of reported cases and MAT for Trinidad and Tobago in 1996, 1997, 1998, and 2000. The results for the years 1992, 1994, 1999, and 2001 were similar. MAT values at onset of dengue for different years are also given in Table 6. Onset MAT values vary from 26.9°C to 28.1°C. Also shown in Fig. 4 is the average MAT (hereafter called AMAT) for Trinidad and Tobago, which was calculated using monthly MAT values from 1979 to 2001. The value of the calculated AMAT was 26.9°C and is the same as the lowest MAT at disease onset observed for 1992, 1994, 1996, 1997, 1998, 1999, 2000, and 2001. It appears that AMAT can be treated as a threshold above which the potential for onset of dengue can be expected. Onset can be immediately after or within a few months after the MAT for a given year attains AMAT.

For Trinidad and Tobago, the elapsed time between attaining AMAT and disease onset generally varied from 0 months to about 2.5 months. An exception to this elapsed time range was 1998 (see Fig. 4). In 1998 MAT for the 1st month was 27.1°C and all MAT values for the year exceeded AMAT (26.9°C). Since, the disease onset occurred in the 5th month (MAT = 28.1°C) the estimated elapsed time was 4 months. Possible reasons for this longer elapsed time could be that 1998 was the warmest year in the last decade and therefore the temperature condition necessary for the disease onset, based on MAT values, was satisfied at the beginning of the year. This left only the moisture condition to be satisfied which did not occur until later in the year (around the 5th month).

Also to be noted from Fig. 4 (and 2) is the fact that although the number of dengue cases had been decreasing with the decrease in temperature and rainfall, the number had been fairly high during the first few months in 1998. Possibly the higher temperatures in the later period of 1997 may have been influencing the dengue incidence in the early period of 1998, in addition to the 1998 temperatures themselves. Warmer conditions in the later period of a year may trigger warmer conditions in the early period of the following year, and therefore an epidemic started in the later part of such a year could extend to the following year, as higher temperatures would influence the disease prolongation. This scenario is more favoured during El Niño episodes (El Niño and El Niño + 1 events) (Enfield and Alfaro 1999). One of the strongest El Niño episodes during the last century was in 1997/1998.

Another feature that is apparent from Fig. 4 is that the early approach of AMAT results in an early epidemic and a delayed approach results in a delayed epidemic. An example of an early epidemic was the one in 1998 and a delayed one was in 1997 as seen from Fig. 4 and the CQ values in Table 6. The times of approach of AMAT (At) are also given in Table 6.

Figure 5 illustrates the monthly variability of reported cases and MAT for Barbados during 1997 and 1998. Results were similar during 1995, 1996, and 1999 in Barbados. In Barbados MAT at onset varied from 26.1°C to 26.6°C. MAT at onset for the different years are given in Table 7. The AMAT for Barbados calculated using monthly MAT values from 1979 to 1999 was 26.0°C and is shown in Fig. 5. As in Trinidad and Tobago, AMAT is almost equal to the lowest MAT at onset. Thus in Barbados also, AMAT behaves as a threshold. The approach time to AMAT is almost the same (5th month) for the years investigated except 1998, and so is the time of the epidemic. The elapsed time between attaining AMAT and disease onset varied from 0 to about 2 months. The scenario in Barbados in 1998 is similar to that in Trinidad and Tobago. MAT in the 1st month (26.1°C) exceeded AMAT and dengue onset time was the 4th month. Therefore based on MAT values for the year, temperature conditions for onset were favourable from the beginning of the year. Further, the epidemic had manifested earlier than in other years though the epidemic was much less intense compared to 1997 or to Trinidad and Tobago in 1998 (see Fig. 5 and the CQ values in Table 7).

Figure 6 illustrates the monthly variability of reported cases and MAT for Jamaica. The MAT at onset was about 28.2°C for 1995 and 28.0°C for 1998 (Table 7). In 1995 and 1998 there were fairly strong outbreaks of dengue in Jamaica, as mentioned earlier. AMAT for Jamaica based on the monthly MAT values for 1995 and 1998 was 27.8°C and was close to the MAT at onset in 1998. Also the attainment of AMAT in 1998 was slightly earlier than that in 1995 and so was the epidemic as seen from Fig. 6 and the CQ values in Table 7. The elapsed times between attaining AMAT and disease onset were about 0.5 and 1 month.

In general, MAT has the characteristic that it increases with time and its pattern follows that of reported cases better than that of the monthly temperature. For all three territories examined it is seen that AMAT behaves as a threshold for the onset of dengue, and the onset can be expected anytime after attaining AMAT. The potential time for an epidemic can be judged depending whether the approach to AMAT is early or late. Moreover, the accuracy of judgments can be checked by comparing the present MAT pattern in an analogue fashion with past disease and MAT patterns. Further as MAT is an increasing function of time, the time of approach to AMAT can be estimated more accurately than the timing of Tep or the timing of a country's average temperature at disease onset relative to Tep.

3.2.1 Effectiveness of MAT

The effectiveness of the MAT scheme was examined using dengue and temperature data for years other than the ones used to introduce the scheme. Years 2002, 2003, and 2004 were considered for Trinidad and Tobago. The patterns of MAT and reported dengue cases for 2002 and 2003 are shown in Fig. 7 and similar patterns (not shown) were obtained in 2004. In 2004, temperature data were available only up to the month of March and the dengue epidemic was very weak compared to the other years. The weak epidemic has been attributed to herd immunity (Chadee et al. 2007). Years 2000, 2001, and 2002 were considered in the evaluation of MAT's effectiveness for Barbados. The patterns of MAT and reported dengue cases for 2000 and 2001 are shown in Fig. 8. Similar patterns (not shown) were obtained in 2002. Results derived from both Figs. 7 and 8 together with the results for 2004 in Trinidad and Tobago, and results for 2002 in Barbados are also given in Table 8. Based on these results the following statements can be made about the effectiveness of the MAT scheme.

Comparison of observed At (time of approach to AMAT) with Dot (Dengue onset time) reveals that Dot for the years in Table 8 are greater than At and the elapsed times between At and Dot are less than 2.5 months. This is in agreement with the fact that AMAT behaves as a temperature threshold for dengue onset and that the onset occurs within a month or two after attaining AMAT. Comparison of the CQe (Calendar Quarter-estimated) with CQo (Calendar Quarter-observed) reveals that the overlap between the two is good. CQe in Table 8 was determined by comparing the observed At for the validation years with the MAT patterns in individual years between 1992 and 2001 for Trinidad and Tobago and 1995 and 1999 for Barbados, respectively. Though the number of years used in the evaluation of MAT's effectiveness is small the results show that the MAT scheme is a simple and effective means for judging the potential for onset of dengue and the timing of the epidemics.

4 Discussion and conclusion

The results in this study depicted the following.

(1) A well-defined seasonality of the epidemics.
(2) An association of the disease with climate, especially through temperature and during El Niño episodes (El Niño and El Niño + 1 events). This feature was particularly pronounced in the Trinidad and Tobago data.

(3) Statistically significant positive relationship between temperature and dengue incidence at lags of a few months.
(4) The possibility of a scheme based on the MAT index to effectively gauge the potential for onset of dengue and the timing of an epidemic.

Seasonality, association with El Niño episodes, early onset of the disease in years with warmer early periods, and MAT together with AMAT are useful tools in designing warning systems and formulating suitable adaptation strategies. Based on the seasonality, possibility of outbreaks exists in the 2nd half of any year. The rate of increase of the MAT index and its approach to the average value (AMAT) can be used as a first indicator of the potential for disease onset. The MAT index is easy to obtain as temperatures are measured daily at meteorological stations and average values for months can easily be obtained from meteorological services. The MAT index is especially useful for timing an early or a late epidemic. The epidemics occur earlier if the early part of the year is warmer which leads to an early approach to AMAT. This is more likely to happen in an El Niño + 1 year as the later half of an El Niño year is warmer which influences the temperature field of the following year (Enfield and Alfaro 1999). A slow approach is associated with a late start or onset of the disease. In situations where temperature can be forecasted with some degree of certainty, MAT can be practical and useful in any prediction scheme, especially to issue a dengue watch similar to a hurricane watch. The fact that it is simple to construct enhances its apparent usefulness. Once the start or the onset time of the disease is known, other strategies such as health promotion and education, surveillance, and vector control can be activated. It should be remembered that some moisture is required for mosquito breeding, although the minimum quantity of moisture required was not assessed in this work. Wet breeding places are however generally present in the environment around households. The most common ones are stagnant water pockets after rainfall, unattended/uncovered domestic water storage containers, discarded tyres and containers, and wet flower pots. Household environments are therefore normally not totally dry.

The observed statistical lag needs some attention. The lag was easily visible when one concentrated on the temperature and dengue peaks, for example in Fig. 2. These lags are of the order of a few months. Similar lags have been observed by Wegbreit (1997) in relation to dengue in Trinidad and Tobago. Focks et al. (2003) also have proposed similar lags in relation to dengue epidemics in SE Asia. The work of Focks et al. (2003) on Early Warning Systems for SE Asia indicates that lags of a few months with SST (Sea Surface Temperature) anomalies, which are well correlated with air temperature, are effective in prediction schemes. It is a known fact however that the life time of a mosquito is of the order of a few weeks and, including the time for transmission, the time period that may elapse from hatching of the eggs to disease incidence is of the order of a month. The long lag may be explained in terms of multiple transmissions needed to compound into an epidemic or for the disease to be noted. Alternatively another plausible way of explaining the observed lag and the relevance of the MAT index is to consider the net heat build up (net accumulation of heat) in the mosquito breeding environments over time. Perhaps it is the net heat accumulation that conditions the environment suitable for the onset of the disease and not the temperature directly. A similar view has been hinted by Wegbreit (1997). The net heat build up is dependent on thermal radiation (solar radiation) and other parameters such as rainfall, heat losses and cooling in the nights. Therefore the net heat build up is a slow process and lags of the order of a few months are possible with the lag varying from one year to the next. However, the process has to be associated with a temporal increase in a temperature index. The deduced MAT index, which is increasing with time may be that temperature index.

Projected long-term changes in climate are matters of concern. Projections for 2080 provided by Santer (2001) based on GCMs suggest a Caribbean warmer by 2°C or 3°C, but not much change in precipitation. This magnitude of increase in temperature has been confirmed for Trinidad and Tobago, Barbados, and Jamaica with statistical downscaling (Rhoden et al. 2005). Further, although it is not clear how El Niño phenomena will respond to climate change, some models predict (Timmermann et al. 1999) an increase in El Niño frequency in a globe forced by future greenhouse warming. Both the projected increases in temperature and possible increase in El Niño frequency will pose a serious threat in the future by favouring increased vector abundance, increased disease transmission rates, and perhaps affecting the seasonal patterns observed, unless adaptation and mitigation strategies are made more effective through better planning.

A few important limitations have to also be stated. Firstly, the indices formulated in this work can vary from one country to another and depend on the temperature field. If the temperature fields are similar, indices could be similar. On the other hand if the temperature fields are different, as with Trinidad and Barbados or Jamaica, the indices will be different. In applying the MAT scheme to gauge the potential for onset of dengue and the timing of an epidemic in a given country one has to make sure that a reliable and a continuous set of data for temperature exists for the country. Secondly, the influence of stresses such as socio-economic conditions, population density and herd immunity was not considered in this study. Thirdly, and most importantly, to make the scheme more versatile the viability of the indices has to be examined in relation to mosquito dynamics and virus replication rates using epidemiological data.

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