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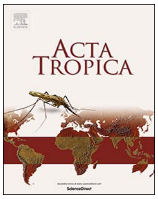

Modelling dengue fever risk in the State of Yucatan, Mexico using regional-scale satellite-derived sea surface temperature

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ABSTRACT

Accurately predicting vector-borne diseases, such as dengue fever, is essential for communities worldwide. Changes in environmental parameters such as precipitation, air temperature, and humidity are known to influence dengue fever dynamics. Furthermore, previous studies have shown how oceanographic variables, such as El Niño Southern Oscillation (ENSO)-related sea surface temperature from the Pacific Ocean, influences dengue fever in the Americas. However, literature is lacking on the use of regional-scale satellite-derived sea surface temperature (SST) to assess its relationship with dengue fever in coastal areas. Data on confirmed dengue cases, demographics, precipitation, and air temperature were collected. Incidence of weekly dengue cases was examined. Stepwise multiple regression analyses (AIC model selection) were used to assess which environmental variables best explained increased dengue incidence rates. SST, minimum air temperature, precipitation, and humidity substantially explained 42% of the observed variation ($r^2 = 0.42$). Infectious diseases are characterized by the influence of past cases on current cases and results show that previous dengue cases alone explained 89% of the variation. Ordinary least-squares analyses showed a positive trend of 0.20 ± 0.03 °C in SST from 2006 to 2015. An important element of this study is to help develop strategic recommendations for public health officials in Mexico by providing a simple early warning capability for dengue incidence.

1. Introduction

Worldwide, dengue fever is a prominent vector-borne disease that has led to more than 500,000 cases reported per year (Bhatt et al., 2013; Murray et al., 2013; Shepard et al., 2011). The main vector is *Aedes aegypti*, a tropical/subtropical mosquito. Dengue virus cases are prominent in urban areas where the mosquito has adapted to develop effectively (Cheong, 1967; Gratz, 1991; Gubler, 2002). Their development typically occurs in both artificial and natural water containers. Increased precipitation, air temperature, and humidity have been shown to promote their development (Brady et al., 2013; Colon-Gonzalez et al., 2011; Descloux et al., 2012; Johansson et al., 2009a; Shuman, 2010). Dengue outbreaks are also influenced by virus serotypes and socio-economic factors including patterns of population distribution, behavior of different age groups, and previous dengue cases (Teurlai et al., 2012; Thomas et al., 2003). Previous dengue cases are defined as those cases that took place weeks before an outbreak. These periods vary depending on geographic location and the dynamics of dengue transmission, and contribute to increasing risk of infection with the virus. The occurrence of previous low or high dengue cases is an indication of the currently circulating virus serotype and the immune status of a population (Focks and Barrera, 2006). Previous studies have shown that humans travelling from areas with known outbreaks and that have been infected with dengue virus also promote the spread of the virus (Hales et al., 2002; Teurlai et al., 2012).

Since the late 1970s Mexico, and the rest of the Caribbean and Latin America, have reported thousands of dengue fever cases annually (Dick et al., 2012). Mexico provides weekly epidemiological panoramas. In particular, the Yucatan State showed a 45% increase in dengue cases from 2014 to 2015 (629 cases in 2014 and 1129 cases in 2015) (Salud, 2016), where serotypes DENV-1, DENV-2, and DENV-4 had been reported. Most of the studies done in the Yucatan State are focused on the development of mosquito larvae and potential breeding sites of *Aedes* species (Dantes et al., 2011; Lorono-Pino et al., 2004). Other

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studies have included environmental variables (i.e., air temperature, precipitation, and humidity) to understand and predict dengue-fever outbreaks in Mexico (Colon-Gonzalez et al., 2013; Hurtado-Diaz et al., 2007). Some of these studies were done at larger geographic areas (i.e., State level) using monthly resolution of dengue data (Colon-Gonzalez et al., 2011; Hurtado-Diaz et al., 2007) or up to one year of data at smaller geographic areas (Garcia-Rejon et al., 2008; Garcia-Rejon et al., 2011). Studies including oceanographic variables (e.g., water temperature) were done at larger geographic areas and used data from the Pacific Ocean and the influence of El Niño Southern Oscillation (ENSO) on dengue fever in the Americas (Brunkard et al., 2008; Colon-Gonzalez et al., 2011; Hurtado-Diaz et al., 2007). It is known that the influence of these parameters on dengue fever is location-dependent (Eastin et al., 2014), and that ENSO influences can be obscured by local variability (Johansson et al., 2009b). Moreover, literature is lacking on studies using long-term epidemiological data together with regional-scale satellite-derived sea surface temperature (SST), and those environmental variables mentioned above, to model dengue fever in Yucatan, Mexico.

Oceanographic variables such as SST are important to include due to their influence on coastal weather patterns (Goddard and Mason, 2002; Thomson et al., 2005; Xie et al., 2010). It has been shown that SST in the Gulf of Mexico region has been increasing (Lluch-Cota et al., 2013; Muller-Karger et al., 2015). Therefore, incorporating SST, together with meteorological parameters, could help improve predictions of dengue cases in coastal areas, especially in the Caribbean-Gulf of Mexico region.

The main objective of this study was to assess the use of regional-scale satellite-derived SST data to model dengue fever incidence rates in the northwest region of the Yucatan Peninsula, Mexico. It was hypothesized that variability and trends in precipitation, air temperature, and humidity were primary drivers of dengue incidence; and that satellite-derived SST would improve dengue risk predictions. An important element of this study is to help develop strategic recommendations for public health officials in Mexico by providing a simple early warning capability for dengue incidence. Epidemiological surveillance has helped track dengue fever patterns in the past and such information, together with inter-disciplinary research and inclusion of oceanographic parameters such as SST, can significantly improve dengue fever surveillance and predictive power of future outbreaks.

2. Material and methods

2.1. Northwest coast, Yucatan Peninsula, Mexico

The study took place in the northwest coastal area of the State of Yucatan, Mexico, located adjacent to the Gulf of Mexico (19.55°N–21.63°N, 87.53°W–90.40°W). The study area has nine municipalities: Chicxulub Pueblo, Dzemul, Hunucma, Ixil, Progreso, Telchac Pueblo, Telchac Puerto, Ucu, and Merida, which is the capital and largest municipality within this region (Fig. 1).

The highest precipitation occurs during the rainy season between July and October (with an average of 400–700 mm of precipitation over the season). The dry season occurs between March and June (0–50 mm for the season). A third season, the “Nortes” season, is characterized by strong ($\sim 80\ \mathrm{km\ h^{-1}}$) winds coming from the continental mass of the U.S. and associated with cold fronts during November–February. Air temperatures generally range from 36 to 40 °C during the dry season, 30–35 °C during rainy season, and 20–23 °C during “Nortes” (Gonzalez et al., 2008; Herrera-Silveira, 1994).

2.2. Satellite-derived oceanographic data and in-situ meteorological data

Day- and night-time SST data were obtained from the U.S. National Oceanic and Atmospheric Administration’s Advanced Very High Resolution Radiometer sensor (AVHRR; $1\ \mathrm{km}^2$ spatial resolution). These images were mapped using cylindrical equidistant projection and are available online at the Institute for Marine Remote Sensing webpage (http://imars.marine.usf.edu/). Data were extracted from January 2006 to February 2015 using the average of three 3 × 3 pixel boxes (centered on 21.37°N, 90.10°W; 21.47°N, 89.72°W; and 21.50°N, 89.24°W) for the northwest coastal area of the Yucatan Peninsula. Interactive Data Language (IDL; v. 7.2) was used to extract data. Monthly and weekly time series were created using the average values of day- and night-time SST images, and climatologies and its anomalies were calculated from 2006 to 2015, which coincides with the time period of the dengue fever data.

Meteorological data (i.e., air temperature, humidity, and precipitation) from 2006 to 2012 were obtained from the National Water Commission (CONAGUA) of the Yucatan State. Both minimum and maximum air temperatures were used to calculate (arithmetic) mean air temperature. Due to the lack of dengue fever data for some of the municipalities for some years, we pooled the nine municipalities in our study area. Moreover, only Merida, Progreso, Telchac Puerto, and Chicxulub Puerto had meteorological data available for the study period. These data sets (i.e., meteorological data) from the aforementioned municipalities were compared and parameters (e.g., precipitation and air temperatures) followed the same patterns across municipalities. There were no significant difference across municipalities of the relatively small geographical area studied ($\sim 2500\ \mathrm{km}^2$). Therefore, we assumed that data from Merida (the largest city in the region) were representative for the entire study area. Climatologies, anomalies, and monthly and weekly means of meteorological data were calculated for the purpose of this study. Environmental and oceanographic data were collected from years prior and after dengue data timeframe in order to calculate trends and lags between dengue incidence rates and environmental/oceanographic data.

2.3. Dengue fever and demographic data

Daily data of confirmed dengue fever cases were obtained from Yucatan’s National Health Information System (Subdirección de Salud Pública, Servicios de Salud de Yucatan; January 2007–December 2010) and from the Universidad Autónoma de Yucatan (January 2011–December 2012). Due to inconsistencies in the data, dengue cases before 2007 were not included in this study. Since we were only interested in dengue cases regardless of the serotype, data for both dengue fever and dengue hemorrhagic fever were pooled for a total of 312 weekly observations. Dengue cases by age class were calculated to determine which age groups were more susceptible to dengue fever. These age-groups were: less than 5 years old, 5–9, 10–19, 20–24, 25–29, 30–34, 35–39, 40–49, and greater than 50 years old. To assess variability and susceptibility to infections during 2007–2012, weekly dengue incidence rates by municipality and age were calculated by dividing number of cases by population each year and multiplying it by 100,000 (i.e., incidence per 100,000 inhabitants). These weekly dengue incidence rates were used in the analyses and not the number of cases. Geographic and demographic data, such as population size, were obtained from Yucatan’s National Institute of Statistics and Geography (2007–2012).

2.4. Non-parametric statistical analyses

Data were analyzed with non-parametric permutation-based statistics, which are a distribution free method. Permutation-based Pearson’s correlation analyses were used to identify lags between predictor variables (i.e., precipitation, SST, humidity, minimum, maximum and mean air temperature, and previous dengue cases), and target variable (i.e., dengue incidence rates). The goal was to identify significant time-lagged (positive or negative) correlations between predictor variables and weekly dengue incidence rates. These time-lags were for all the cases in the study area and these lags comprise the mean of two