Assessing the roles of temperature, precipitation, and ENSO in dengue re-emergence on the Texas-Mexico border region

Joan M Brunkard, PhD,[1] Enrique Cifuentes, MD, PhD,[2] Stephen J Rothenberg, PhD.[2,3]

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Abstract

Objective. The goal of this study was to assess linkages between microclimate and longer-term ENSO-related weather forcing on the week-to-week changes in dengue prevalence in Matamoros, Tamaulipas, Mexico, over a recent decade of dengue observations. **Material and Methods.** An auto-regressive model to evaluate the role of climatic factors (sea-surface temperature) and weather (maximum temperature, minimum temperature, precipitation) on dengue incidence over the period 1995-2005, was developed by conducting time-series analysis. **Results.** Dengue incidence increased by 2.6% (95% *CI*: 0.2-5.1) one week after every 1°C increase in weekly maximum temperature and increased 1.9% (95% *CI*: -0.1-3.9) two weeks after every 1 cm increase in weekly precipitation. Every 1°C increase in sea surface temperatures (El Niño region 3.4) was followed by a 19.4% (95% *CI*: -4.7-43.5) increase in dengue incidence (18 weeks later). **Conclusions.** Climate and weather factors play a small but significant role in dengue transmission in Matamoros, Mexico. This study may provide baseline information for identifying potential longer-term effects of global climate change on dengue expected in the coming decades. To our knowledge, this is the first study to investigate the potential associations between climate and weather events and dengue incidence in this geographical area.

Key words: climate; El Niño; dengue; border health; United States; Mexico

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Resumen

Objetivo. Evaluar los vínculos entre el microclima, las variables relacionadas al fenómeno de El Niño Oscilación del Sur (ENSO) y los cambios en el reporte semanal de casos de dengue en el área de Matamoros, Tamaulipas, México, a lo largo de una década de observaciones. **Material y métodos.** Se desarrolló un modelo autorregresivo para evaluar la influencia de factores climáticos (temperatura superficial del mar) y tiempo (temperatura máxima, temperatura mínima y precipitación) sobre la incidencia de dengue, a lo largo de 11 años (1995-2005), empleando análisis de series de tiempo. **Resultados**. La incidencia de casos de dengue aumentó 2.6% una semana después de cada 1°C de incremento en la temperatura máxima semanal (95% *IC*: 0.2, 5.1); observamos también que los casos de dengue aumentaron 1.9% dos semanas después de cada centímetro de incremento en la precipitación semanal (95% *IC*: -0.1, 3.9). Cada 1°C de aumento en la temperatura superficial del mar en la región Niño 3.4 fue seguida, 18 semanas después, de un aumento de 19.4% en la incidencia de casos de dengue (95% *IC*: -4.7, 43.5). **Conclusiones**. Los factores de clima y tiempo tienen una influencia menor, aunque significativa, sobre la transmisión del dengue en la ciudad fronteriza de Matamoros, México. Este estudio aporta información basal para identificar efectos potenciales de mayor alcance, relacionados con el cambio climático global sobre los casos esperados de dengue en las próximas décadas. Hasta donde sabemos, este es el primer estudio que evalúa las posibles asociaciones entre los eventos climáticos y tiempos y la incidencia de casos de dengue en la frontera de México con Texas.

Palabras clave: clima; Fenómeno de El Niño; dengue; salud fronteriza; Estados Unidos; México

(1)   Department of Environmental Studies, University of California. Santa Cruz, California, USA.
(2)   Instituto Nacional de Salud Pública. Cuernavaca, México.
(3)   CINVESTAV-IPN. Mérida, México.

Among the most significant anticipated health impacts of climate change is an increased incidence of mosquito-borne infectious diseases including dengue and malaria.[1-3] Dengue is the most serious and prevalent arboviral disease in the world today; two and a half billion people living in the tropics and subtropics are at risk for epidemic transmission. There are an estimated 50-100 million cases of dengue fever each year,[4] although this is probably an underestimate of the true incidence as many cases likely go unreported because the symptoms of dengue are similar to the flu.

At present, dengue and dengue hemorrhagic fever (DHF), a potentially fatal form of dengue, are largely diseases of the tropics; however, many studies project their expansion with global warming.[1,2,5-8] Other studies predict limited or no increase in mosquito-borne disease transmission with global warming.[9,10] There is a growing scientific consensus that humans are affecting the global climate system, primarily by the burning of fossil fuels for energy generation, transportation, mechanized agriculture, and other economic activities. The third assessment report by the Intergovernmental Panel on Climate Change (IPCC) projects an increase in global average temperature of between 1.4°C and 5.8°C by 2100.[11] Other projected climatic changes include a global average increase in both atmospheric water vapor content and precipitation, and an increase in the frequency and magnitude of extreme weather events.[11,12]

The primary human health consequences associated with climate change are increased mortality related to extreme weather events; an increase in deaths resulting from heat waves; and an increased incidence of vector-borne diseases, particularly malaria, dengue and the viral encephalitides.[1,2,13] Increased temperatures directly affect the spread of vector-borne diseases in three critical ways: by expanding the geographic range of the vector, by decreasing the extrinsic incubation period (EIP) of the pathogen (the time required for the virus to replicate inside the mosquito and become infectious to another human), and by increasing the contact rate (the biting rate of female mosquitoes). Climate change is projected to expand the latitudinal and altitudinal range of dengue as well as extend its transmission duration in both the tropics and the temperate zones bordering areas where dengue is currently endemic .[1,2,5-7,14,15]

Probably the most critical effect of climate change on dengue transmission will be the reduction in the EIP of the virus. For example, Watts *et al.* found that the EIP for dengue-2 was 12 days at 30°C but only 7 days at 32°C to 35°C.[16] A related study showed that a five-day decrease in the EIP for dengue translated to a potential three-fold increase in dengue transmission.[17] A shorter incubation time for the disease-causing agent is a critical factor in epidemic potential because it greatly increases the likelihood that a mosquito will live long enough to become infectious and bite a susceptible human, thus continuing the dengue transmission cycle.

Elevated temperatures increase the contact or biting rate of mosquitoes in several ways. First, warmer temperatures reduce the larval size of *Aedes* mosquitoes, resulting in smaller adults that must feed more often to develop their egg batch.[18] Additionally, adult mosquitoes digest blood more quickly at higher temperatures and therefore need to obtain bloodmeals more frequently.[19]

Precipitation variability and more extreme weather events may also increase mosquito-borne disease incidence.[3] Areas that receive increased precipitation or experience an increase in the frequency or magnitude of extreme weather events will likely experience an expansion of vector breeding sites and larval habitat.[20] El Niño events represent the best analog for the impacts of increased frequency of extreme weather events. A number of studies have documented an increased incidence of malaria associated with El Niño events,[20-25] but evidence for dengue-ENSO (El Niño Southern Oscillation) associations is equivocal.[26] Extreme weather events are also likely to facilitate the spread of dengue by disrupting water supply, sewerage and sanitation services. The interruption of basic public health and safety measures that frequently follow such events provides an ideal environment for the vector while leaving humans vulnerable to an increased rate of mosquito biting.[27,28]

Regional studies are needed to explore the potential links between climatic variables and disease emergence.[3] While several studies have looked at links between climatic variables, ENSO, and dengue,[29-31] very few have examined these associations in Latin America. To our knowledge, this is the first study to investigate the potential associations between climate and weather events and dengue incidence on the Texas-Mexico border.

Study objectives

The goal of this study was to assess linkages between microclimate and longer-term ENSO-related weather forcing on the week-to-week changes in dengue prevalence in a restricted geographic area over a single recent decade of dengue observations. This study does not address the issue of climate change effect on dengue incidence, per se. Such studies here and in many other areas will provide baseline information for identifying potential longer-term effects of global climate change on dengue expected in the coming decades.

Material and Methods

Data

An auto-regressive model was developed to evaluate the role of climatic factors on dengue incidence over an eleven year period (1995-2005). We compiled daily data for maximum temperature, minimum temperature, and precipitation from the most reliable weather station in the region, the Brownsville South Padre, Texas airport (WMO# 722500; latitude/longitude: 25(deg) 54' 28.17" N, 97(deg) 25' 29.61" W ; elevation +000 m.a.s.l.). Climate data for the eleven-year series were obtained from the National Climatic Data Center (NCDC).* From 4 017 daily observations at the Brownsville airport weather station, there were a total of 129 missing values in the NCDC database (14 for maximum temperature, 15 for minimum temperature, and 100 for precipitation). The missing values were obtained from the same weather station using a different database, the National Weather Service database.‡ Weekly sea surface temperatures were obtained from the National Oceanic and Atmospheric Administration (NOAA) for Niño 3.4 region (120-170W, 5S-5N)§ and used as an ENSO indicator.

For dengue data, we used weekly incidence data from the city of Matamoros, Tamaulipas, Mexico# because it is the most reliable and thorough dataset in the region. Daily data were transformed into maximum and minimum weekly temperatures and total accumulated weekly precipitation amounts to correspond with weekly epidemiological dengue reporting (Sunday through Saturday), a reporting system standardized across the western hemisphere by the Pan American Health Organization. All dengue case reports (table I) were serologically confirmed at the state lab (Laboratorio Estatal de Salud Pública) in Ciudad Victoria, Tamaulipas, Mexico.

Statistical methods

To measure the effect of temperature, precipitation, and ENSO cycle on dengue incidence using standard regression procedures, serial correlation in the dengue time series must first be removed. We added one case to each weekly dengue count and natural log-transformed

the series to stabilize variance. We then determined lack of temporal trend with the Dickey-Fuller unit root test.[32] Serial correlation was diagnosed with autocorrelation and partial autocorrelation functions, and then empirically reduced by successive additions of lagged autoregressive terms to the series. The process was terminated when the portmanteau test[33] and Bartlett's white noise test[34] indicated no significant autocorrelation among residuals. Using cross-correlation functions, we tested the residuals of the autoregressive series with each weather variable at biologically-plausible time lags to determine optimal time lags maximizing cross-correlations. The autoregressive terms and lagged weather variables were entered into an ARMAX model to calculate variable coefficients and standard errors, and generate model residuals and predictions. ARMAX models are linear regressions (X) with the error term specified with autoregressive (AR) and/or moving average (MA) terms. We used only autoregressive terms without moving average terms. Diagnostics indicated residual heteroscedasticity and the ARMAX model was rerun using standard error estimation that was robust to departure from homoscedasticity. Residuals were symmetrically distributed about a mean of zero.

We tested two models with identical covariate and ARMA structures [AR(2) MA(0)], one using the full 11-year data set, the other using only the first 10 years of data for estimation. We compared predictions with observations of the 11th year of data using both models as a model validation procedure. Data management and statistical procedures were performed with Stata 9.1 (StataCorp, College Station, TX).

Results

From 1995-2005, there were 2 865 reported cases of dengue and 43 reported cases of dengue hemorrhagic fever in Matamoros, Tamaulipas, Mexico.* The highest dengue incidence occurred in 1997, followed by 2005 (table I).

Time series were plotted for all climatic variables and dengue incidence to observe their behavior and patterns of seasonal and inter-annual variability (figures 1-4). Using the full eleven-year dataset (1995-2005), our ARMAX model (table II) showed that dengue incidence increased by 2.6% (95% CI: 0.2-5.1) one week after every 1ºC increase in weekly maximum temperature and increased 1.9% (95% CI: -0.1-3.9) two weeks after

Table I
Reported dengue and DHF incidence
in Matamoros (1995-2005)

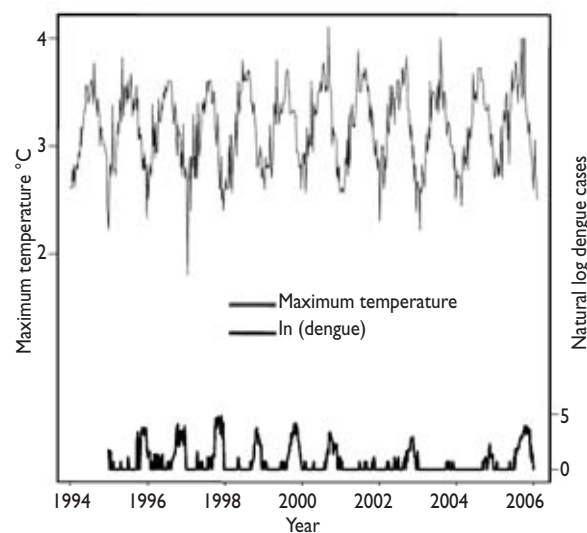| Year	Dengue	DHF	Total dengue
1995	319	0	319
1996	373	19	392
1997	815	10	825
1998	178	5	183
1999	406	0	406
2000	161	2	163
2001	8	0	8
2002	100	4	104
2003	3	2	5
2004	28	1	29
2005	474	*	474‡

* Data are not available for number of hemorrhagic cases in 2005
‡ Incidence data for 2005 represents only those cases that were laboratory-confirmed. Several thousand additional probable cases were reported, including several hundred cases of dengue hemorrhagic fever, but blood samples were not collected (Secretaría de Salud, Tamaulipas, Mexico, unpublished data)
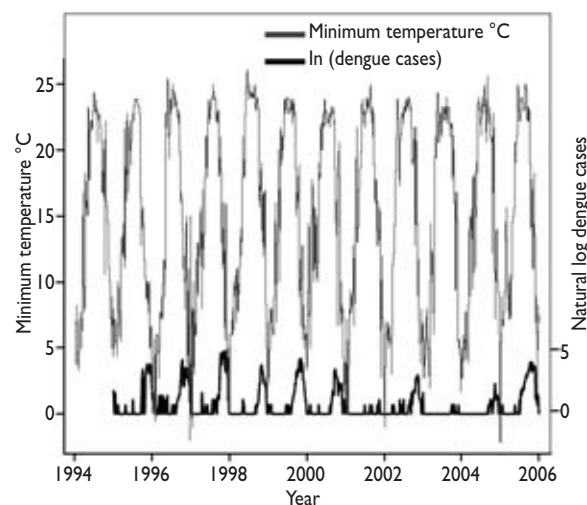

Figure 2: Time series of dengue and maximum temperature (°C)

Figure 1. Time series of dengue and sea surface temperature (°C)

Figure 3: Time series of dengue and minimum temperature (°C)

every 1 cm increase in weekly precipitation. Every 1°C increase in sea surface temperatures in the equatorial Pacific, Nino region 3.4 was associated with a 19.4% (95% CI: -4.7-43.5) increase in dengue incidence 18 weeks later. Minimum temperature was not signifi-
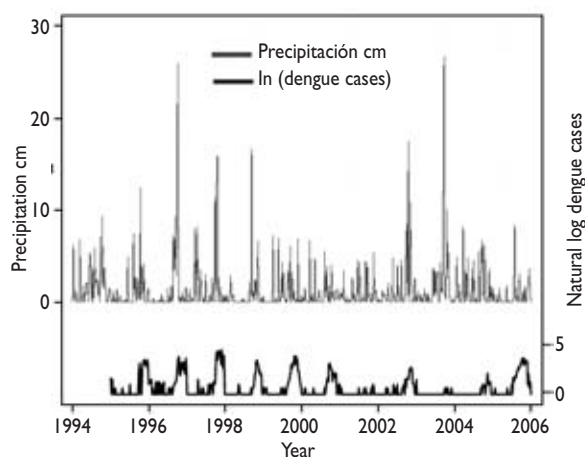
cantly associated with dengue incidence ($p=0.26$) and was dropped from the model.

We validated the basic model by re-estimation using data from the first 10 years, 1995 through 2004 (table III and figure 5), to predict dengue incidence

* Data are in epidemiological weeks, Sunday through Saturday, with each
  year beginning at week 1

FIGURE 4. TIME SERIES OF DENGUE AND PRECIPITATION (CM)

Table II
ARMAX MODEL FOR TIME SERIES 1995-2005

Ln(dengue)	Coef.	z-statistic	p-value	95% Conf. Interval
Max temp °C L1*	.026	2.11	0.035	.002, .051
Precip (cm.) L2*	.019	1.88	0.060	-.001, .039
Sea surface temp L18*	.194	1.58	0.114	-.047, .435
AR(L1)*	.532	7.28	0.000	.389, .675
AR(L2)*	.359	5.04	0.000	.219, .498

Wald Chi square(5) = 1027.2, $p<0.0001$, n=574
L* = number of weeks lag

Table III
ARMAX MODEL FOR TIME SERIES 1995-2004

Ln(dengue)	Coef.	z-statistic	p-value	95% Conf. Interval
Max temp °C L1*	.025	1.83	0.068	-.002, .052
Precip (cm.) L2*	.020	1.93	0.053	-.000, .041
Sea surface temp L18*	.141	1.14	0.255	-.101, .382
AR(1)*	.545	6.91	0.000	.390, .700
AR(2)*	.335	4.35	0.000	.184, .486

Wald Chi square(5) = 748.2, $p<0.0001$, n=522
L*= number of weeks lag

FIGURE 5. ESTIMATION MODEL (1995-2004)

in the eleventh year, 2005 (figure 6). Coefficients did not change significantly between the model estimated with all eleven years and the ten-year model. The predictions in figures 5 and 6 used both the endogenous (the autoregressive variables) and the exogenous (the climate variables) components of the model. Finally we plotted the predictions of the model based on the entire series, 1995-2005 (figure 7), and compared them with the model predictions from the ten-year series, 1995-2004 (figure 6).
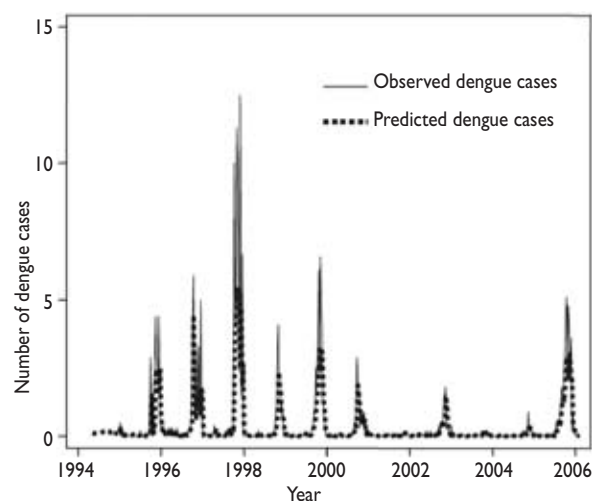
There is very little difference between the within (2004) and out-of-series (2005) model predictions as most of the predictive power comes from the autoregressive terms, whose coefficients are not significantly different in the two models. Despite the strong influence of the autoregressive components in the model, adding the three climate variables resulted in significant improvement in model fit (Chi-squared(3)=11.12, p=0.011) using the full 11-year model.
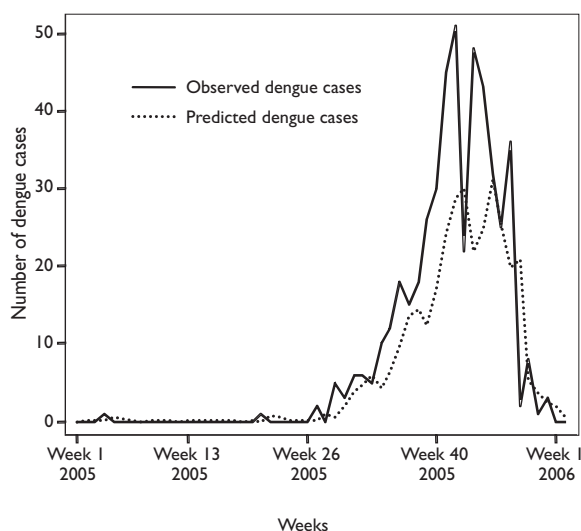
Discussion

Based on this time series analysis, weather and climatic factors together play a significant but small role in dengue transmission in the border city of Matamoros, Mexico. The predictive ability of our models (table II
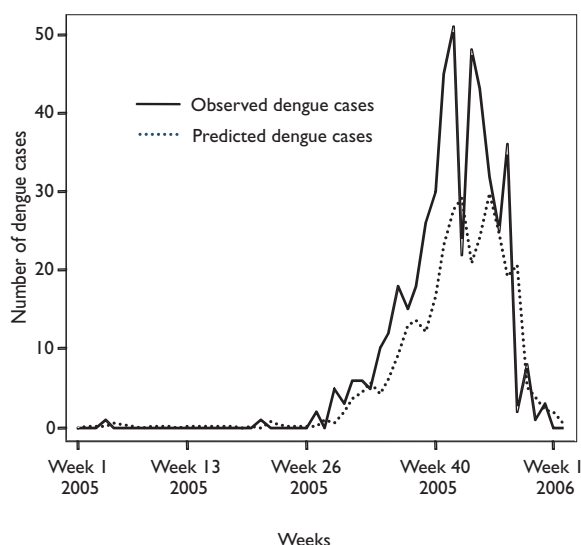
FIGURE 6. OUT OF SERIES (1995-2004) MODEL PREDICTION FOR 2005

FIGURE 7. WITHIN SERIES (1995-2005) MODEL PREDICTION FOR 2005

and III) is largely due to unmeasured endogenous autoregressive factors in the dengue series, which we can not further specify without more information on the full range of factors influencing dengue transmission in this region. Time series modeling is inherently data-driven. Though the autoregressive order determinations and the specific lagged independent variables were selected to optimally condition the series within biological and physical bounds, it is likely that the lags for the variables described here are place-specific and will vary somewhat in locales with other weather conditions and climatic patterns.

We can conclude, however, that endogenous predictive power in the dengue case series does not extend beyond two weeks in Matamoros. Year-to-year variability in dengue seroprevalence is likely a function of herd immunity and the presence of specific dengue serotypes and strains,[35] not measured here. Other studies investigating the relative role of climatic factors on mosquito-borne disease incidence have similarly found that endogenous factors dominate.[36,37]

Our objectives were to determine if the ENSO climate indicator and weather variables played some role in weekly dengue cases. The autoregressive terms in our models were only used to condition the time series of dengue cases so that we could apply the techniques of ordinary least squares regression to test the effect of the climate indicator and weather variables in weekly dengue cases. The addition of maximum temperature, precipitation, and sea surface temperature significantly improved model fit to the data (p=0.011).

Our findings with respect to temperature, precipitation and sea surface temperature are in general agreement with the findings of Hurtado-Díaz et al.[38] who constructed a similar model to study the climate-dengue relationship in the state of Veracruz, Mexico. SSTs were highest in 1997, coinciding with the highest year of reported dengue incidence in Matamoros and in Veracruz, and Hurtado-Díaz et al.[38] detected a small influence of precipitation and minimum temperature. In the Texas-Mexico border region, maximum temperature is more influential than minimum temperature for dengue transmission because its fluctuations cross non-linear thresholds for key biological processes, such as the dramatic reduction in the extrinsic incubation period of the virus at 32°C.[16] As in our model, other studies have found that predictive models under-estimate actual cases of mosquito-borne disease, especially in high incidence years.[39]

Under-reporting of disease incidence is a serious and widespread limitation to modeling climate-disease relationships. Our response variable is almost certainly an underestimate of regional dengue incidence. Even accounting for improved reporting on the Mexican side of the border, we are confident that dengue cases are higher than official incidence reports. For example, a serosurvey in 2004 found that 7.7% of Matamoros

residents had experienced a recent (within 2004) dengue infection.[40] But official statistics place 2004 as one of the lowest years of dengue incidence in the series (table I). A dengue serosurvey in El Salvador found similar pervasive under-reporting.[41] Lopez-Correa *et al.* (1979) calculated that there were at least 46 undiagnosed dengue cases for every reported case from their survey in Puerto Rico.[42] The times series of dengue and precipitation co-variance (figure 4) seems to suggest that 2004 should have been a high incidence year, as it was, but cases were not registered and therefore were not factored into our model. We suspect that the observed influence of precipitation on dengue incidence in our models would have been much stronger if dengue incidence had not been under-reported.

Current evidence suggests that non-climatic factors play the biggest role in mosquito-borne disease incidence.[43,44] However, completely discounting the role of climate in disease emergence is premature;[45] we need better models and more reliable data. In this region of the US-Mexico border, residents and public health officials intuitively know that climate plays a role in dengue transmission. For example, when one resident was asked if she knew how dengue was transmitted, her response was: "I don't know. The mosquito, I think. All of a sudden the rain comes and the dengue is here." Another survey participant commented, "It's warm all the time here, and the mosquitoes don't die off here." And when asked how often the city sprayed for mosquitoes, one resident observed: "during the summer, yes–but sometimes we have mosquitoes during the winter too." Local public health officials likewise commented that with the onset of the rainy season and high temperatures, they were likely to see dengue cases.*

Development of active surveillance for mosquito-borne diseases and Early Warning Systems (EWS) are key public health goals[46] but integrating climate data into predictive frameworks for infectious diseases has not yet been achieved.[3] However, advances in this area are being made. A recent retrospective analysis of malaria prevalence in Botswana, Africa demonstrated that multiple models using ENSO indicators provide a five-month lead time on disease prediction whereas data on precipitation alone only gives a one-month lead,[47] lag times similar to those described in this study. Such findings show promise, but institutional support for integration of climate data into EWS is not yet present in this region.

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* Robles-López JL, personal communication.

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