Coupling between Annual and ENSO Timescales in the Malaria–Climate Association in Colombia

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We present evidence that the El Niño phenomenon intensifies the annual cycle of malaria cases for *Plasmodium vivax* and *Plasmodium falciparum* in endemic areas of Colombia as a consequence of concomitant anomalies in the normal annual cycle of temperature and precipitation. We used simultaneous analyses of both variables at both timescales, as well as correlation and power spectral analyses of detailed spatial (municipal) and temporal (monthly) records. During "normal years," endemic malaria in rural Colombia exhibits a clear-cut "normal" annual cycle, which is tightly associated with prevalent climatic conditions, mainly mean temperature, precipitation, dew point, and river discharges. During historical El Niño events (interannual time scale), the timing of malaria outbreaks does not change from the annual cycle, but the number of cases intensifies. Such anomalies are associated with a consistent pattern of hydrological and climatic anomalies: increase in mean temperature, decrease in precipitation, increase in dew point, and decrease in river discharges, all of which favor malaria transmission. Such coupling explains why the effect appears stronger and more persistent during the second half of El Niño's year (0), and during the first half of the year (+1). We illustrate this finding with data for diverse localities in Buenaventura (on the Pacific coast) and Caucasia (along the Cauca river floodplain), but conclusions have been found valid for multiple localities throughout endemic regions of Colombia. The identified coupling between annual and interannual timescales in the climate–malaria system shed new light toward understanding the exact linkages between environmental, entomological, and epidemiological factors conductive to malaria outbreaks, and also imposes the coupling of those timescales in public health intervention programs. *Key words*: climate variability, Colombia, El Niño/Southern Oscillation, ENSO, human health, malaria, tropical medicine, vectorborne diseases. *Environ Health Perspect* 109:489–493 (2001). [Online 4 May 2001]
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More than five million people in Colombia live in endemic malaria regions. During 1996, transmission of malaria reached 42 cases per 1,000 inhabitants in high-risk areas (*1*). In the province of Chocó (along the Pacific coast), there were > 80,000 cases during 1998, when the population at risk was 380,000. The most important malaria vectors in the country are *Anopheles albimanus*, *Anopheles darlingi*, and *Anopheles nuñeztovari* (*2*), transmitting *Plasmodium falciparum* (46.5%) and *Plasmodium vivax* (53.5%), and rare cases (8–10 per year) of *Plasmodium malariae* (*3*). The geographical distribution of malaria in Colombia is associated with prevalent climatic conditions. Mean annual temperature and precipitation are related to diverse factors such as elevation over the Andes, the distance to the Caribbean Sea and the Pacific Ocean, and the influence of the circulation, vegetation, and land-surface feedbacks of the Amazon basin and the tropical Andes, which vary at annual and interannual timescales.

El Niño refers to the unusual warming of sea surface temperatures (SSTs) in the eastern and central tropical Pacific. The accompanying Southern Oscillation, the "seesaw" of the atmospheric mass that produces a pressure gradient between the western and the eastern equatorial Pacific, is quantified by the Southern Oscillation index (SOI), defined as the standardized difference between Tahiti and Darwin sea level atmospheric pressures. Negative values of the SOI are associated with warm events (El Niño), whereas positive values accompany cold events (La Niña). El Niño/Southern Oscillation (ENSO) is an aperiodic oscillation that occurs approximately every 3–7 years, with an average of about every 3–4 years (*4*). The onset of El Niño events occurs during spring in the Northern Hemisphere, exhibiting a strong phase-locking with the annual cycle (*5*). El Niño events, which continue through 2 calendar years, are generally characterized by positive anomalies of SSTs that increase during the Northern Hemisphere spring, summer, and fall of the first year (year 0); the maximum SST anomalies occur during the winter of the next year (year +1), and SST anomalies recede during the spring and summer of the year +1. The physics of the ENSO and its climatic consequences have been reported (*6–11*). ENSO disrupts the normal patterns of global atmosphere–ocean circulation and land surface hydrology, affecting weather events and climate. The associated extreme weather events, including floods, droughts, and heat waves, produce severe socioeconomic and environmental impacts including crop and fishery failures, food shortages, infrastructure disruption, forest fires, reduced hydropower generation, electricity shortages, harmful algal blooms, and epidemics.

ENSO is the main mechanism of Colombia's hydroclimatology at interannual timescales. Overall, negative anomalies in rainfall, soil moisture, and river discharges and evaporation, along with positive air temperature anomalies, occur during El Niño events. The reverse is generally valid for the cold phase (La Niña). The impact of ENSO occurs earlier and stronger in western and central Colombia than in the east. Seasonally, the impacts of ENSO are more pronounced during December–February (year +1), September–November (year 0), and June–August (year 0), in that order; March–May (years 0 and +1) is the least affected period. Colombian precipitation is negatively correlated with sea surface temperature anomalies over the tropical Pacific (*12–14*).

Even though malaria is a highly complex multifactorial disease, previous studies have identified a significant association between the increase in the number of malaria cases in Colombia during the occurrence of El Niño (*15–19*). Such studies have focused on a nationwide level at yearly timescales, whereas no effort has been made to identify the El Niño malaria association at a local level in the endemic regions of rural Colombia at monthly timescales. Such downscaling in time and space will help us understand the complexity of the relationship. In this study

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we used detailed data sets in space (municipal) and time (monthly) to examine how El Niño affects the normal annual cycle of both malaria and climatic indices and to determine their degree of association.

Data and Methodology

We used monthly records for *P. vivax* malaria at 16 towns located in the lowlands of the northwestern province of Antioquia, and estimated the normal annual cycle as well as the anomalous annual cycle observed during historical El Niño events. The Antioquia Health Service provided malaria data for Antioquia for 1980–1997. For operational purposes (to overcome the differences in the definition of the years among continents), the health service split the calendar year into 13 epidemiological periods (EP) of 4 weeks each. Roughly, we can assume that the first EP corresponds to the month of January and the twelfth EP corresponds to the month of December.

We used monthly records of total cases of malaria and diverse hydroclimatic records at two localities in different environmental settings in Colombia: Buenaventura on the Pacific coast (3°54´N, 77°5´W; Figure 1) during 1978–1995, and Caucasia, along the Cauca river floodplain (7°59´N, 75°12´W) during 1990–1997. We estimated seasonal cross-correlations to quantify the degree of linear association between climate conditions and malaria incidence. We also performed power spectral analyses of both raw and standardized malarial and climatic records to examine the coupling between the "normal" annual cycle and the interannual cycles associated with El Niño.

Results

The incidence of malaria in Colombia exhibits clear-cut but different annual cycles during "normal" and El Niño years. Cross-correlations between local climate and malaria in Buenaventura and Caucasia confirm strong statistical associations (Table 1). Buenaventura exhibits significant simultaneous positive seasonal correlations between dew point and *P. vivax* cases for the first half of the year, whereas correlations are higher for the 1-bimonth lag time. This may be due to the coastal location of Buenaventura, which is affected by oceanic moisture that is transported inland by the winds of the CHOCO jet (*20*). The CHOCO jet is a permanent jet of low-level winds that transports large amounts of moisture from the Pacific Ocean into mainland Colombia. In Buenaventura, *P. falciparum* exhibits high positive seasonal correlations with dew point throughout the entire annual cycle. Precipitation exhibits no significant correlation with malaria, possibly due to the fact that precipitation is very high in Buenaventura throughout the year (250–800 mm/month), and therefore it does not constitute a limiting factor for transmission. Malaria in Caucasia exhibits high negative seasonal simultaneous correlations with river discharges of the Cauca river from January to October, but the strongest correlation is observed at lags of 2–4 bimonths (Table 1). In Colombia, with many mountain-derived rivers, decreased rainfall may create ponds and stagnant waters along the river banks and in the lower valleys, thus providing adequate breeding sites for mosquitoes, in particular for *A. albimanus*, a common vector in Colombia.

Cross-correlation analysis between malaria in many localities in Colombia and sea surface temperatures at Niño-3.4 region (120°W–170°W, 5°S–5°N; not shown) indicates maximum correlation coefficients on the order of 0.6 ($p = 0.05$), with a 6–8 month lag. Indeed, increases in the annual cycle of malaria cases during El Niño in many localities appear around September–November (year 0). This may indicate that local climatic and malarial effects associated with ENSO appear stronger between 4 and 6 or more months after the onset of El Niño during the Northern Hemisphere spring (*12,13*).

The "normal" annual cycle of malaria is intensified during El Niño events. Figure 2 shows the spatial distribution of the average annual cycle and during El Niño events for *P. vivax* malaria recorded at 16 locations in the lowlands of Antioquia. In Figure 2, the annual cycle, from the sixth EP (June) year 0 to the fifth EP (May) year +1, shows that malaria cases intensify during El Niño during a "climate-malaria" year from the second half of year 0 to the first half of year +1. This result has also been found in multiple towns in rural Colombia (not shown) and also in malaria-prone regions nationwide (*16,17*). Figure 3 illustrates average total malaria and diverse monthly hydroclimatic records during the annual cycle and during El Niño at Buenaventura and Caucasia. Results suggest that the increase in the number of malaria cases is associated with an increase in air temperature and a decrease in rainfall and river discharges. This association with a decrease

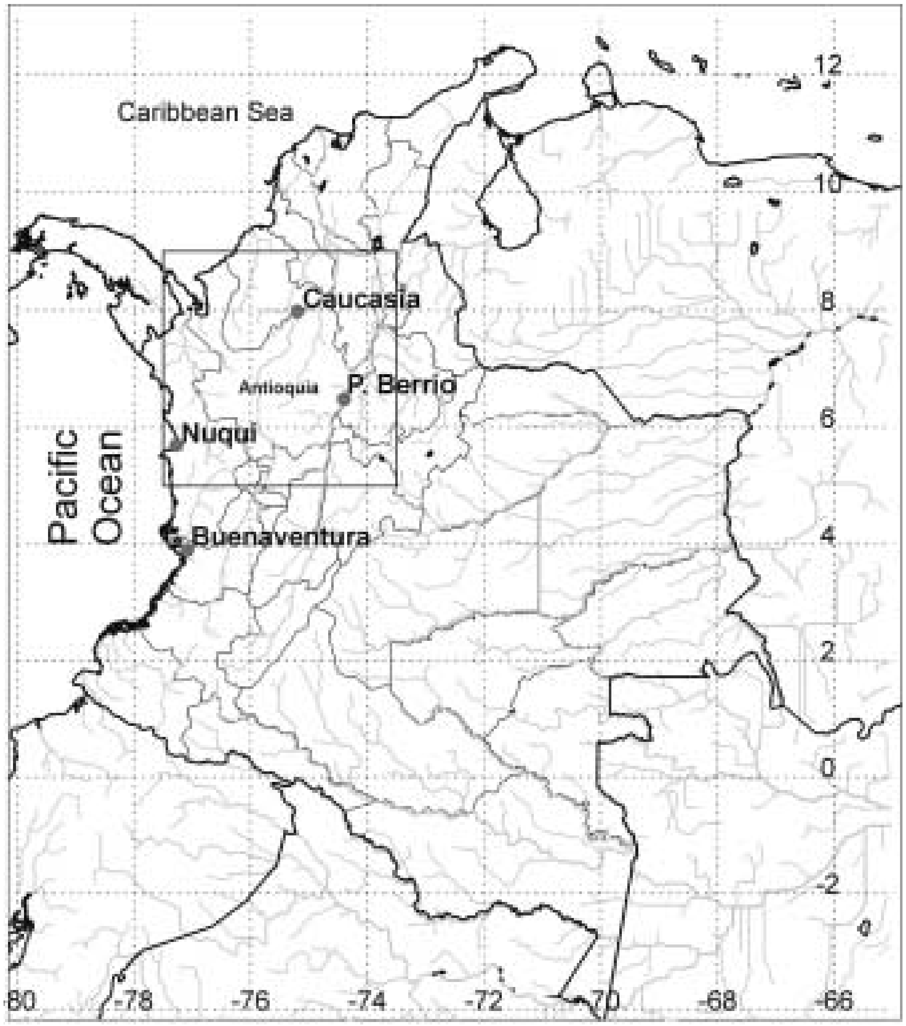

Figure 1. Location of regions included in the study.

in river discharges is common for localities along wide river floodplains. Similar increments in the number of cases of malaria during El Niño are found throughout Colombia; these are usually associated with a consistent pattern of climate anomalies such as an increase in mean temperature, a decrease in precipitation, an increase in dew point, and a decrease in river discharges.

Thus far, we have presented evidence that the endemicity of malaria in rural Colombia exhibits a strong annual cycle that is closely associated with prevalent climatic conditions. Also, we have shown evidence indicating that malaria increments are associated with the concomitant anomalies in climatic variables during El Niño; this refers to an intensification of the annual cycle during El Niño phases rather than a shift in the cycle itself. These observations suggest a strong coupling between the annual and interannual (ENSO) timescales in the malaria–climate association in Colombia. To enhance this conclusion we performed power spectral analysis to both malarial and climatic records in Buenaventura (1978–1995). As long as the annual cycle is such a strong feature of both phenomena in Colombia, the power spectrum is estimated to both raw and standardized climatic records and malaria cases. Standardization is accomplished through subtraction of the monthly mean and scaling by the monthly standard deviation. The standardization process filters out the annual cycle and reveals lower frequencies. Figure 4 presents power spectra for raw and standardized data for the number of malaria cases, mean temperature, precipitation, and dew point in Buenaventura. The power spectrum of the raw number of malaria cases is shown in Figure 4A; arrows indicate the periods (in years) associated with the

Table 1. Cross-correlations between seasonal local climate and malaria in Buenaventura and Caucasia (locations shown in Figure 1) for lag periods 0 (simultaneous) through 5 (bimonths) and climate-leading malaria.

	Lag (bimonth)					
	0	1	2	3	4	5
Buenaventura vs. dew point						
P. vivax malaria						
January–February	0.438	0.632	0.478	0.491	0.554	
March–April	0.490	0.479	0.567	0.452		
May–June		0.535	0.544	0.456		
July–August		0.537		0.418		
September–October						
November–December						
P. falciparum malaria						
January–February	0.421	0.700	0.576	0.565	0.542	0.420
March–April	0.508	0.642	0.606	0.521	0.421	0.462
May–June	0.484	0.611	0.596	0.487	0.479	0.516
July–August	0.441	0.624	0.513	0.575	0.501	0.440
September–October	0.474	0.551	0.552	0.530	0.431	0.468
November–December		0.584	0.560	0.514	0.458	0.473
Caucasia vs. Cauca River discharge						
P. vivax malaria						
January–February	–0.746	–0.693	–0.874	–0.717	–0.756	
March–April	–0.703	–0.777	–0.731	–0.727	–0.821	
May–June	–0.792		–0.760	–0.722	–0.849	
July–August	–0.723	–0.714	–0.671	–0.784	–0.837	
September–October	–0.776		–0.733	–0.765	–0.842	
November–December			–0.711	–0.766	–0.840	
P. falciparum malaria						
January–February	–0.714	–0.740	–0.818		–0.733	
March–April	–0.770	–0.714	–0.786	–0.695	–0.788	
May–June	–0.761	–0.690	–0.790	–0.677	–0.804	
July–August	–0.751	–0.732	–0.693	–0.691	–0.744	
September–October	–0.787				–0.821	
November–December	–0.693			–0.688	–0.756	

All correlation coefficients shown are statistically significant at the 95% level.

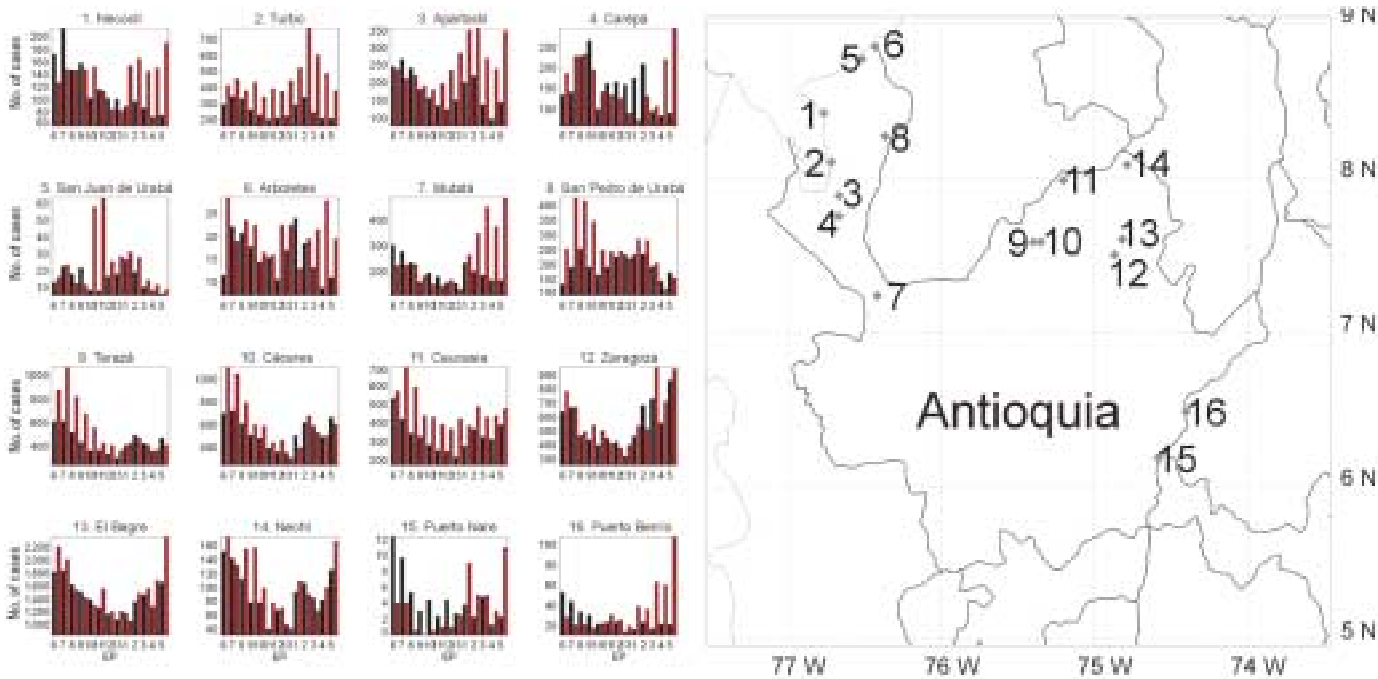

Figure 2. Geographical distribution of *P. vivax* malaria. (*A*) Average annual cycles of *P. vivax* malaria (black bars) in diverse locations in Antioquia (northwestern Colombia) and monthly averages during historical El Niño events (red bars) for 1980–1997. (*B*) Location of each study area indicated by number. The annual cycle is the sixth EP (year 0) to the fifth EP of the next year (year +1). The year is divided into 13 EPs of 4 weeks each; the first EP roughly corresponds to January and the twelfth EP to December. Data from the Antioquia Health Service.

strongest frequencies of the signal (1, 3.6, 4.5, and 6 years). Figure 4C shows the power spectrum of mean temperatures (raw data), with significant spectral peaks at 1, 3.6 and 4.5 years. Figure 4E indicates that the annual cycle of precipitation is highly dominant in Buenaventura. Figure 4G, which shows the power spectrum of raw data for dew point also confirms the presence of important spectral peaks at 1 and 6 years. Analyses of the power spectrum for Buenaventura's standardized records indicate *a*) important spectral peaks at 2, 3.6, 4.5, and 6 years for malaria cases, *b*) important peaks at 3.6 and 4.5 years for precipitation, and *c*) an important peak at 4.5 years for mean temperature, and *d*) an important peak at 3.0 years for dew point. These results confirm the strong coupling that exists between annual and interannual bands for both malaria and climate in Buenaventura; this relationship is also found in many areas in Colombia.

We conclude that the increase in the cases of malaria in Colombia during the months of El Niño events is tightly associated with the concomitant anomalous annual cycle of climatic conditions. Thereby we propose that the well-documented phase-locking that exists between the annual and interannual cycles of the tropical climate (*5*) also exists in the association between climate and malaria incidence in Colombia. Consistently, there is the interest in focusing on the linkages between seasonal climate variability and human health, particularly in endemic regions. Because ENSO is a transient state associated with interannual variability, there is a need to understand the steady state associated with the annual cycle in order to unveil the relationships between ecological, entomological, and epidemiological factors. This is important because mitigation plans and control measures of diseases associated with ENSO must be implemented along with the plans and measures permanently under way to control or mitigate the annual cycle of such diseases.

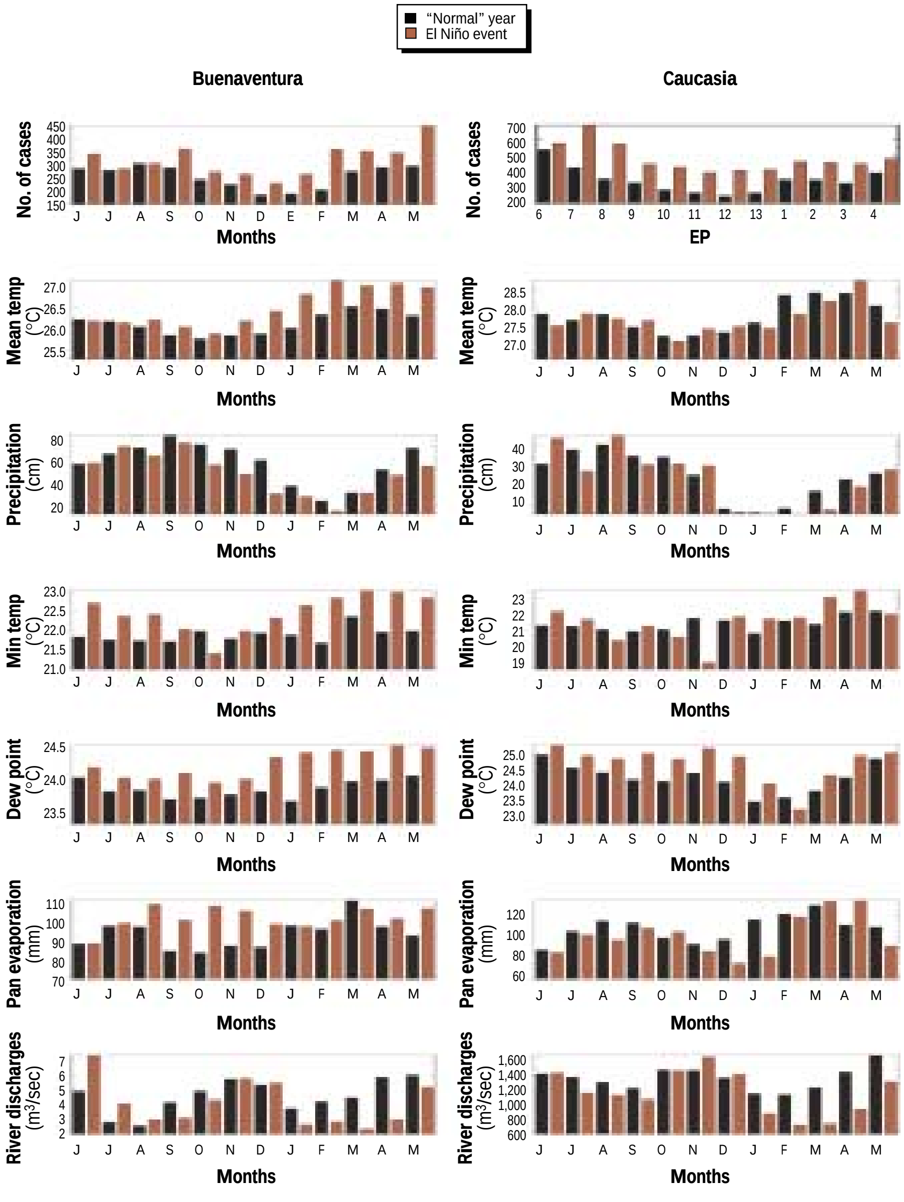

Figure 3. Average annual cycles of total malaria cases from *P. vivax* and *P. falciparum,* mean temperature, precipitation, minimum temperature, dew point, pan evaporation, and river discharges of the nearby Cali and Cauca rivers during "normal" years and during historical El Niño events in Buenaventura during 1978–1995 and Caucasia during 1990–1997. Abbreviations: min, minimum; temp, temperature.

Discussion and Conclusions

Although malaria is a highly complex multifactorial disease, a detailed statistical analysis of the relationship between climate and malaria in Colombia indicates that malaria cases exhibit a strong annual cycle, which is highly associated with the hydroclimatic annual cycle. Both are consistently enhanced, thus augmenting malaria cases, during the occurrence of El Niño; this suggests that coupling mechanisms link the environmental, ecological, and entomological factors of the disease. In many towns throughout rural Colombia, outbreaks of malaria during El Niño are very closely associated with a highly consistent pattern of climatic anomalies. An increase in mean temperature, a decrease in precipitation, an increase in dew point, and a decrease in river discharges characterize such a pattern. Correlation and power spectrum analyses indicate a strong coupling between annual and interanual cycles in the malaria–climate association in Colombia.

Possible explanations for the identified association between climate and malaria in Colombia include the effect of climate on the population dynamics of vectors through changes in population densities or survival rates, but also through availability of adequate breeding sites. In a previous study (*21*), we found no evidence of a significant relationship between climate anomalies and the density and parity of *A. albimanus* and *A. darlingi* at two villages on the Colombian Pacific coast during the 1997–1998 El Niño event and the 1998–2000 La Niña event. Also, no significant association was found between these entomological variables and temperature, humidity, or precipitation. The effect of the ENSO event on malaria vector populations seems to be more complex and probably goes beyond a direct relationship with variables such as density or parity. A reduction in the length of the sporogonic period, due to increments in temperature during El Niño events, probably plays a more important role in the increase of malaria transmission. The field research is still under way.

The nonlinear coupling between annual and interannual scales in both climate and malaria is important in understanding the relationship between ecological, entomological, and epidemiological components of the disease. It is also relevant to setting up mitigation plans and control measures of diseases associated with ENSO, which have to be implemented on top of those measures permanently under way for the annual cycle of such diseases. Accordingly, mitigation and control measures should have annual and interannual cycles, which indicates the need for coupling those two timescales in public health interventions.

Seasonal statistical correlations may be helpful in forcasting outbreaks and for developing health early warning systems (HEWS) of meteorological conditions conducive to outbreaks. Our finding of a strong coupling and phase-locking between the annual and interannual variability of climate and malaria, as well as modeling results that replicate the historical peaks and trends in the Colombian malarial records (*18,19*), provide promising tools for forecasting the disease. Local and international support for HEWS may help to facilitate early, coupled, and environmentally sound public health interventions.

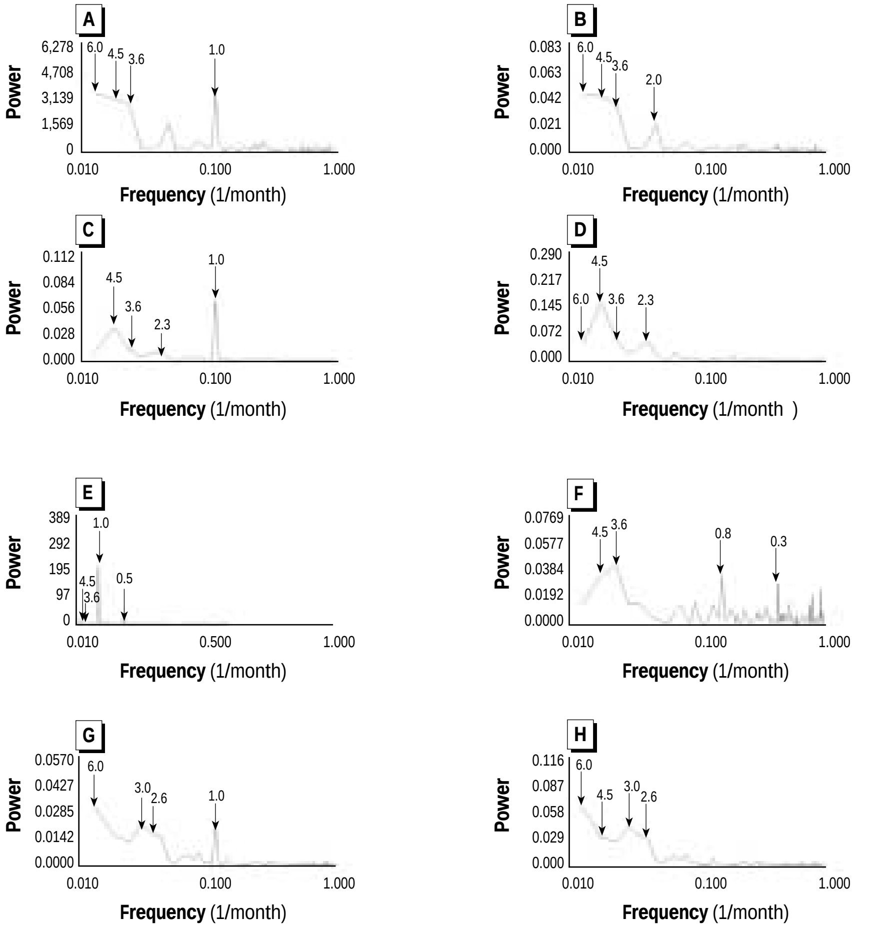

Figure 4. Plots of the power spectrum for monthly series of malaria and climate at Buenaventura for 1978–1995. (*A*) Raw data (arrows indicate those periods associated with the strongest frequencies of the signal) and (*B*) standardized data for cases of malaria. (*C*) Raw data (significant spectral peaks are exhibited at 1, 3.6 and 4.5 years) and (*D*) standardized data for mean temperature. (*E*) Raw data and (*F*) standardized data for precipitation. (*G*) Raw data (with important spectral peaks present at 1 and 6 years) and (*H*) standardized data for dew point.

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