

Climate and ENSO variability associated with vector-borne diseases in Colombia

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Abstract

Climatic factors are associated with the incidence of diverse vector-borne diseases (VBDs). Colombia, located in tropical South America, witnesses high precipitation rates and temperatures, varying with elevation over the Andes. We show how temperatures are linked to malaria incidence throughout the country, and we compare those results with those obtained via simple mathematical expressions that represent indices associated with malaria transmission as a function of temperature. Interannual climatic variability in tropical South America is strongly associated with El Niño/Southern Oscillation (ENSO). Most of the region, including Colombia, experiences

prolonged dry periods and above normal air temperatures during El Niño, and generally opposite conditions during La Niña. Through correlation analysis, we show that during El Niño events there are outbreaks of malaria and dengue fever in Colombia. These outbreaks could be explained in terms of a decrease in precipitation and an increase in air temperature, which favor the ecological, biological, and entomological components of these diseases.

We illustrate the ability to predict malaria cases in Colombia by using an epidemiological model based on the concept of vectorial capacity (see Martens et al. 1997). This transmission potential model is driven with surface air temperatures derived from an atmospheric general circulation model (ECHAM3 model, Max Planck Institute for Meteorology) with a spatial resolution of about 300 km. The malarial model produces peaks in *Plasmodium vivax* vectorial capacity during El Niño years and an upward trend with time, in agreement with the Colombian malarial historical record.

These statistical correlations and modeling results may be used for developing health early warning systems of climate conditions conducive to outbreaks, which may facilitate early public health interventions to control and mitigate the incidence of these VBDs.

Introduction

Outbreaks and spreading of vector-borne diseases (VBDs) in human populations are clearly multi-factorial, involving social, biological, and environmental factors, of which climatic variability has long been recognized as important (Gill 1920, 1921). El Niño/Southern Oscillation (ENSO) is the major forcing mechanism of climatic and hydrological variability at interannual timescales, with especially strong impacts on northern South America. El Niño events are related to strong perturbations in global atmospheric circulation and associated anomalies in seasonal-to-interannual weather patterns that can trigger profound societal, economical, and environmental consequences.

Some of the relevant biological/climatic factors that interact to affect human health are (Epstein and Stewart 1995): (1) the quality and distribution of surface water and insect breeding sites (Dobson and Carper 1993); (2) temperature and humidity, affecting the life cycles of disease vectors and of the parasites within the vector (Patz et al. 1996; Martens et al. 1997) and (3) impacts on the ecosystems of predators of insects (Unninayar and Sprigg 1995; Epstein and Chikwenhere 1994). There is diverse evidence relating outbreaks of several waterborne diseases and VBDs with climatic anomalies forced by ENSO events. Malaria outbreaks have been found to be associated with ENSO in Pakistan (Bouma and van der Kaay 1994) and Venezuela (Bouma and Dye 1997), and in Colombia (Poveda and Rojas 1996, 1997). Diseases involving mosquitoes and rodents may cluster after extreme events (especially flooding) in association with the ENSO phenomenon (Epstein et al. 1995); and in Ecuador and Peru epidemics of malaria appear related to flooding associated with El Niño occurrences (Epstein and Stewart 1995). Related research is found in Epstein (1995), Patz et al. (1996), and McMichael and Haines (1997).

In the next section, general features of Colombia's climate and the ENSO phenomenon and its influence on the hydro-climatology of Colombia and tropical South America are discussed. Next, climatic factors associated with the incidence of malaria over Colombia are illustrated, and simple mathematical relationships are used to represent three malaria transmission indices as a function of average temperature. Then we analyze the annual record of malaria and dengue fever cases in Colombia at the national and regional levels, for the period 1959–94, and show the

linkages between those cases and ENSO, through correlation analysis with sea surface temperatures (SSTs) in the equatorial Pacific Ocean. We then present results of a malaria model driven by the results of an atmospheric general circulation model (AGCM), with promising predictability capacity. Finally, we discuss the influence of predictability of ENSO and Colombia's hydroclimatology with respect to malaria and dengue prevention and control campaigns.

Colombia's climate and ENSO

Diurnal, semi-annual, annual and interannual cycles strongly characterize weather and climate variability in Colombia. The annual distribution of rainfall is primarily influenced by the position of the Inter-tropical Convergence Zone (ITCZ), while its spatial variability is controlled by the Andes mountains, the eastern Pacific and western Atlantic oceans, the atmospheric circulation over the Amazon basin, and vegetation and soil moisture contrasts. Mean annual precipitation ranges from less than 300 mm in a small region of the Caribbean coast to regions with 10,000–13,000 mm along the Pacific coast (see Snow 1976, p. 371). Over the three branches of the Andes and the Sierra Nevada de Santa Marta, temperature and precipitation vary with altitude in the range 0–5,800 m, influenced by the strength of the trade winds and local circulation. Over the Andes, precipitation increases with height from the valley floor up to an altitude where the so-called 'Pluviometric optimum' occurs, and decreases upwards. Location of this precipitation maximum over the mountains depends on the valley floor height, the air absolute humidity and local circulation. The relatively cooler and superficial winds that penetrate from the Pacific Ocean into Colombia form a low-level westerly jet (referred to hereafter by the acronym CHOCO jet; see Poveda et al. 1999), that is permanently centered around 5°N throughout the year. The CHOCO jet interacts with the warmer easterlies, thus causing high atmospheric instability that triggers enormous amounts of precipitation over western and central Colombia, and produce large meso-scale complexes that penetrate into Colombia and interact with the ITCZ (Velasco and Frisch, 1987). Northeastern Colombian rainfall is highly influenced by the easterly trade winds coming from the Caribbean Sea, as well as by summertime tropical easterly waves. Southeastern Colombian rainfall is mostly associated with the strength of the southeasterly trade winds from the Amazon basin, and therefore the eastern slope of the Andes experiences high precipitation rates (around 5,000 mm per year) due to orography.

El Niño refers to the unusual warming of SSTs in the eastern and central tropical Pacific. Important components of this anomaly in the global climate system are the deepening of the oceanic thermocline in the eastern Pacific, and the weakening of the dominant surface easterly trade winds. During an El Niño event, there is a shift in the center of convection from the western to the central 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 pressures (SLPs). Negative values of the SOI are associated with warm events (El Niño), while positive values accompany cold events (La Niña). El Niño/Southern Oscillation is an aperiodic oscillation with an average recurrence varying from 2 to 10 years, for an average of about every 4 years (Trenberth 1991). Kiladis and Diaz (1989) recognize the following years for the occurrence of El Niño event during this century: 1902, 1904, 1911, 1913, 1918, 1923, 1925, 1930, 1932, 1939, 1951, 1953, 1957, 1958, 1963, 1969, 1972, 1973, 1976, 1977, 1982, 1983, 1986, 1987, and 1991, 1992. The onset of El Niño events occurs during the Northern

Hemisphere spring, exhibiting a strong locking with the annual cycle (Webster, 1995). El Niño events that comprise two calendar years, are generally characterized by SSTs positive anomalies that increase during the Northern hemisphere spring and fall of the first year (year 0), with the maximum SSTs anomalies occurring during the winter of the following year (year +1), and SSTs anomalies receding during the spring and summer of the year +1. Recently, El Niño occurred during 1994-1995 and 1997-98. Trenberth and Hoar (1996) argue that during the period 1991-1995 there was a 5-year single El Niño event, while Goddard and Graham (1997) suggest that, although that period was marked by generally warmer than normal SSTs in parts of the eastern and central equatorial Pacific, analyses of ocean thermodynamics argue against its characterization as a single extended episode. The physics of ENSO and its climatic consequences can be found in Horel and Wallace (1981), van Loon and Madden (1981), Glantz et al. (1991), Rasmusson and Carpenter (1982), Ropelewski and Halpert (1987), Rasmusson (1991), Diaz and Markgraff (1992), Diaz and Kiladis (1992), and Battisti and Sarachick (1995). El Niño/Southern Oscillation disrupts the normal patterns of the global atmosphere-oceanic circulation, and the 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 and food shortages, infrastructure disruption, forest fires, reduced hydropower generation, electricity shortages, harmful algal blooms, and epidemics.

In general, there is a coherent pattern of climatic and hydrological anomalies in tropical South America during extreme phases of ENSO (Poveda and Mesa 1997). Overall, negative anomalies in rainfall, soil moisture, and river discharges, as well as positive air temperature anomalies, occur during El Niño. The reverse picture is generally valid for the cold phase (La Niña). Figure 1 (top row) shows the annual cycle of air temperature for the difference between El Niño events of 1982-83, 1976-77 and 1991-92, as compared to the 1988-89 cold event in the Pacific Ocean, according to data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project (Kalnay et al. 1996). We conclude that there is an overall increase in air temperature during El Niño in Colombia as compared with the La Niña situation, in particular during December-January-February (DJF) of the mature ENSO phase (referred to as DJF+1). Also, precipitation decreases (figure 1, bottom row) during El Niño as compared with “normal” and La Niña years throughout the country. The first empirical orthogonal function of standardized monthly rainfall over Colombia, for the period 1958-1990, that explains more than 30% of rainfall variability (see Figure 6 of Poveda and Mesa 1997), exhibits the same sign over the entire region, confirming the generalized negative rainfall anomalies associated with El Niño. Western Colombia, and the Andes are the regions of Colombia most strongly affected El Niño, in particular during DJF+1, September-October-November of the ENSO year (referred to as SON-0), and June-July-August of the ENSO year (JJA-0), in decreasing order, and March-April-May of both years 0 and +1 (MAM-0 and MAM+1) are the least affected by ENSO (Poveda et al. 1997 1999). In Figure 1 (bottom row), one can see that the Colombian Orinoco River basin might exhibit an increase in precipitation during JJA-0. Positive anomalies in precipitation during El Niño may also appear in the southernmost fringe of the Pacific coast along the Ecuadorian border. Observations show that negative anomalies associated with ENSO's effect on river discharges occur progressively later for rivers toward the east in Colombia and northern South America. El Niño impact is also felt in the Caribbean plains, and the Orinoco and Amazonian regions of Colombia.

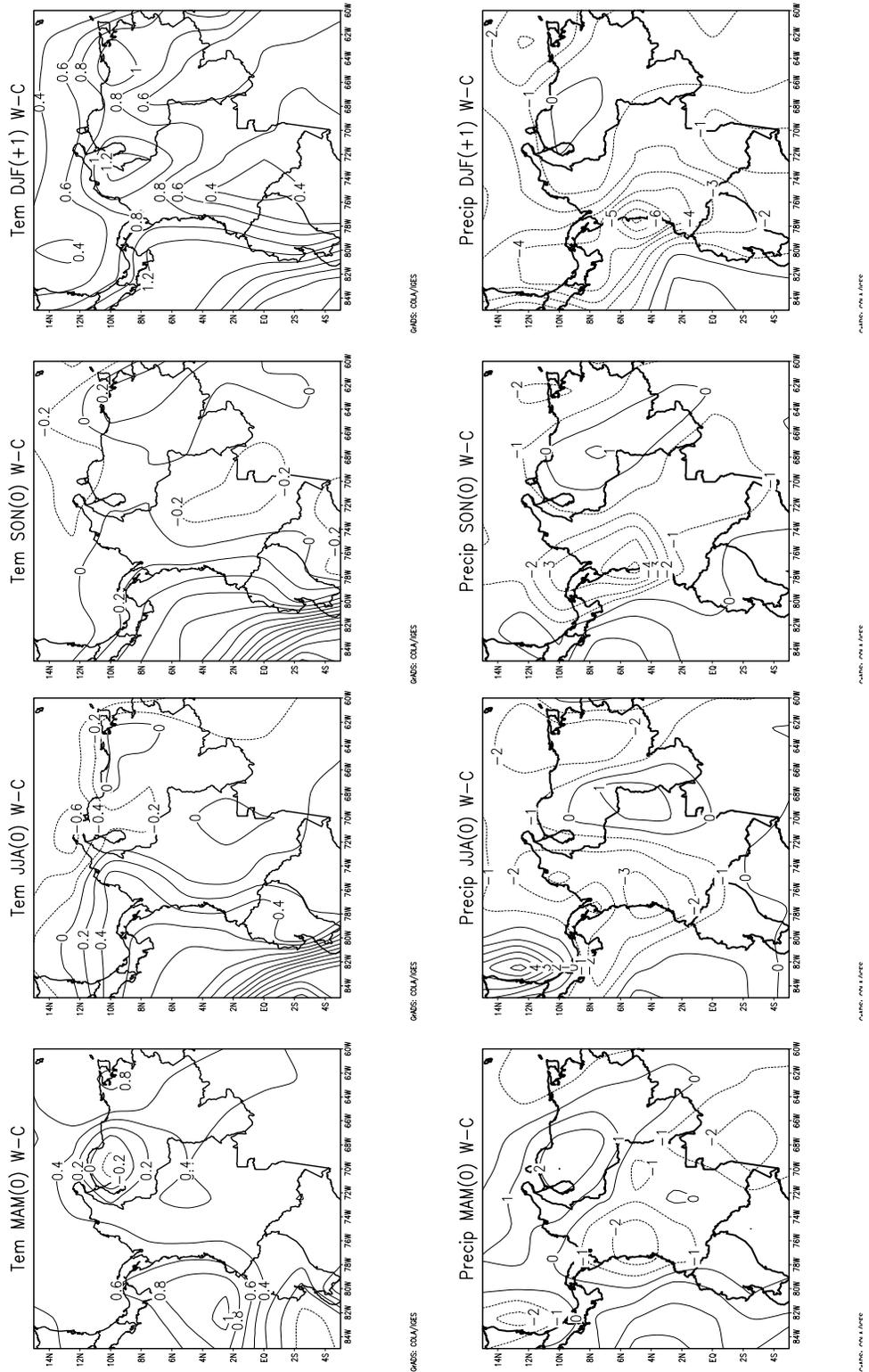


Fig. 1. Annual cycle of air temperature ($^{\circ}\text{C}$) for the difference between warm (1982-83, 1986-87, and 1991-92) and cold (1988-89) phases of ENSO (left column). Analog results for precipitation (mm/d) (right column). Data from the NCEP/NCAR Climatic Reanalysis Project.

Correlation map SSTs vs. PC No. 1 monthly rainfall in Colombia

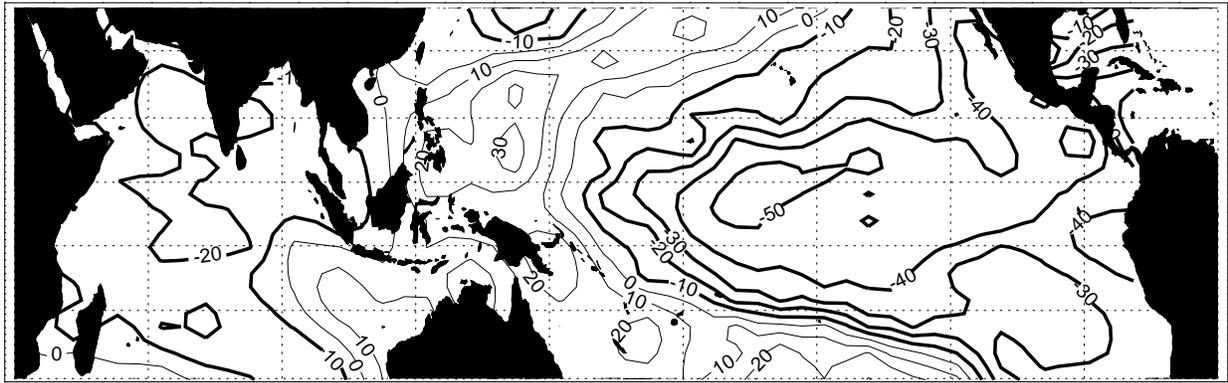


Fig. 2. Correlation map (%) between SSTs at the Pacific and Indian Oceans and the first PC of the Colombian monthly precipitation records (3-month running averages). Note the high values of the correlation coefficients over the Niño-4 and Niño-3 regions, as well as over the Indian monsoon region.

The main mechanisms of the ocean-land-atmosphere system that interact to reduce rainfall during El Niño are: (1) the weakening of the low-level westerly jet ('Chocó Jet') that penetrates from the Pacific Ocean to inland Colombia at 5°N (Poveda et al. 1997 and 1999); (2) the reduction of the 700 hPa equatorial easterly jet; (3) the reduction of moisture advection from the Caribbean Sea; (4) the reduction in number and intensity of easterly waves along the tropical North Atlantic; (5) the displacement of the Intertropical Convergence Zone (ITCZ) to the south-west of its normal position (Pulwarty and Diaz 1993), due to an anomalous Hadley cell over tropical South America (Rasmusson and Mo 1993), and (6) land-atmosphere feedback (Poveda and Mesa 1997).

Figure 2 shows the correlation map between SSTs in the Pacific and Indian Oceans and the first principal component (PC) of Colombia's monthly precipitation field for the 1958–90 period (see Figure 7 of Poveda and Mesa 1997). Figure 2 confirms the strong inverse association between the Pacific Ocean SSTs anomalies and rainfall in Colombia. Regions of greatest negative correlation are the central and eastern equatorial Pacific, and the area of the Indian monsoon. In fact, Colombian precipitation is most highly correlated with SSTs at the Niño-4 region (5°N–5°S, 160°E–150°W), the Niño-3 region (5°N–5°S, 150°W–90°W), and the Niño-1+2 region (0°–10°S, 90°–80°W) of the Pacific Ocean. Interestingly, the Niño-4 region in the Central Pacific returns higher correlations than other regions closer to South America.

Climate and ENSO variability vs. malaria and dengue fever

Malaria

Two-thirds of Colombia's population live in malaria endemic areas, due to climatic and topographic features (Rojas et al. 1992). The most important malaria vectors in the country are *Anopheles albimanus*, *A. darlingi*, and *A. nuñeztovari* (Quiñones et al. 1987), transmitting *Plasmodium falciparum* (46.5%) and *P. vivax* (53.5%), and rare cases (8–10 per year) of *Plasmodium malariae* (Haworth 1988). The geographical distribution of the disease in Colombia is associated with prevalent climatic conditions. As has been stated, temperature and precipitation are related to elevation, in particular over the Andes and the Sierra Nevada de Santa Marta. We use

the association existing between altitude and temperature to represent diverse indices associated with malaria transmission in Colombia as follows. Figure 3 shows the map for the extrinsic incubation period (EIP, or the incubation period of the parasite inside the mosquito) for *P. vivax*, estimated as

$$n = \frac{D_m}{T - T_{min, n}} \quad (1)$$

(MacDonald 1957), where n is the incubation period of the parasite inside the vector (in days), D_m is the number of degree-days required for the development of the parasite (105°C for *P. vivax*), T is the actual average temperature, and $T_{min, n}$ is the maximum temperature required for parasite development (14.5°C for *P. vivax*). The temperature map of Colombia (not shown) considers the regional variability associated with elevation and rainfall. According to equation (1), the Amazon and Orinoco basins and the lowlands of the Pacific and Caribbean coasts exhibit the shortest EIP, while the warmer zones of the Andean region and the Sierra Nevada de Santa Marta in northeastern Colombia (red colors) exhibit the longest EIP for *P. vivax*. In Figure 4 we show a map for the daily survival probability of the *Anopheles* vector, as a function of mean temperature, T . The functional relationship we have used is $p = \exp[-1 / (-4.4 + 1.31T - 0.03T^2)]$, (Martens 1998). Again, almost the same regions of the Andes and the Sierra Nevada de Santa Marta exhibit the highest daily survival probabilities in the country. If we assume that the daily survival probability is an independent event, then p^n can be interpreted as a ‘survival rate’ (SR) of the parasite, as a function of temperature. Figure 5 presents the map of SR for Colombia. The Amazon and Orinoco basins, the lowlands of both the Pacific and the Caribbean coasts exhibit the highest parasite survival rates for *P. vivax*. These modeling results agree with estimations of malarial risk in Colombia for 1996 (see Figure 6, adapted from a map kindly provided by Julio C. Padilla of the Colombian Ministry of Health), confirming that the Colombian Amazon (southeastern), the Orinoco basin (eastern), and the Pacific coast are the regions more prone to malaria in the country. These maps illustrate the association between some indices associated with malaria transmission and temperature, which is related with altitude, but also with precipitation and humidity in Colombia.

Now, we examine the temporal variability of malaria cases. In Figure 7 we present the evolution of the Annual Parasitic Incidence index (API), defined as the ratio between the number of cases reported and the population at risk per 1,000 inhabitants, for the period 1959–94. The API index is computed as the total of cases of both *P. vivax* (represented by the AVI index in Fig. 7) and *P. falciparum* (AFI index), from data reported by the Colombian Ministry of Health. Arrows in Figure 7 indicate El Niño years according to the classification given by Kiladis and Diaz (1989). Three facts emerge from Figure 7: First, outbreaks of malaria are identified during 1961, 1968, 1972, 1977, 1983, 1987, and 1991/1992. Second, there is a clear increasing trend in the number of malaria cases. And third, since the mid-1970s, *P. vivax* has become more predominant than *P. falciparum* nationally. With respect to the first point, it is worth noting that all years but 1961 correspond to ENSO warm events. However, the anomalous dry period from 1957 through 1961 in Colombia was influenced by the 1957–58 El Niño event (Poveda 1994; Poveda and Mesa 1996, 1997). Figure 8 shows the time evolution of the detrended national API index, together with the series of SST anomalies over the Pacific Ocean Niño-4 region, which exhibits the highest correlation with the Colombian hydroclimatology (Poveda 1994; Poveda and Mesa 1997), as well as the series of the (annually averaged) first Principal Component of monthly precipitation in Colombia. A simple detrending procedure for the API series consisted of removing a linear trend

fitted to the historical record. Simultaneous correlation between the API and the SST anomalies over Niño-4 is 0.50, statistically significant at the 95% level, while lag-1-year cross-correlation is 0.49. This result indicates that interannual climatic variability could explain a very important part of the variance of the malaria record in Colombia. The correlation coefficient between the Principal Component No. 1 of precipitation and the detrended API series is 0.42, statistically significant at the 95% level. Analysis performed with regional API series (not shown here) indicate that the association between El Niño occurrences and regional malaria outbreaks is very high, particularly in the Andean, Pacific and Orinoco regions. Figure 9 shows the evolution of the A.P.I. index for the *Departamentos* (States) of Antioquia and Putumayo.

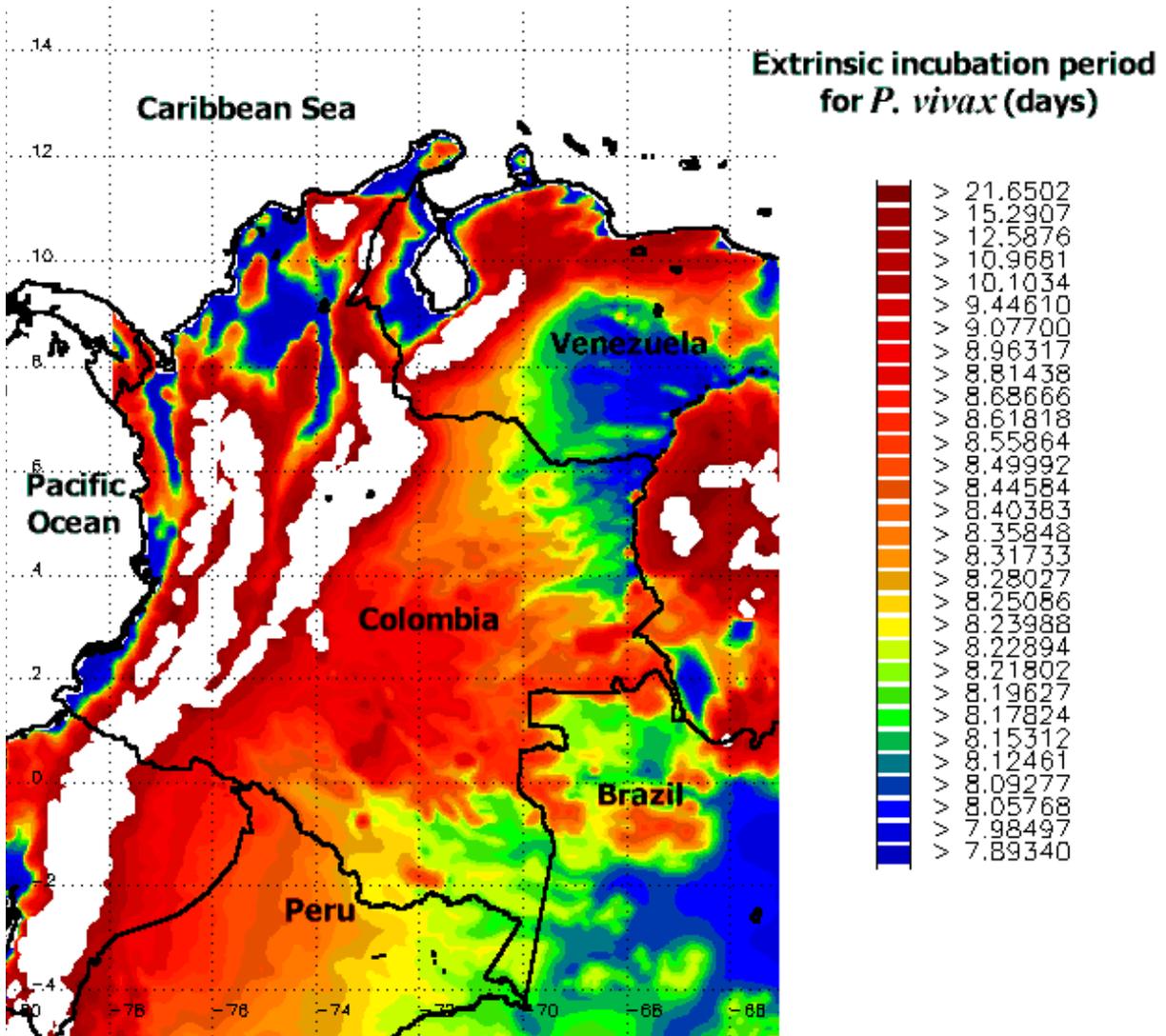


Fig. 3. Distribution of the estimated extrinsic incubation period (equation 1) for *P. vivax* over Colombia. Regions in white do not support *P. Vivax* development due to temperature constraints.

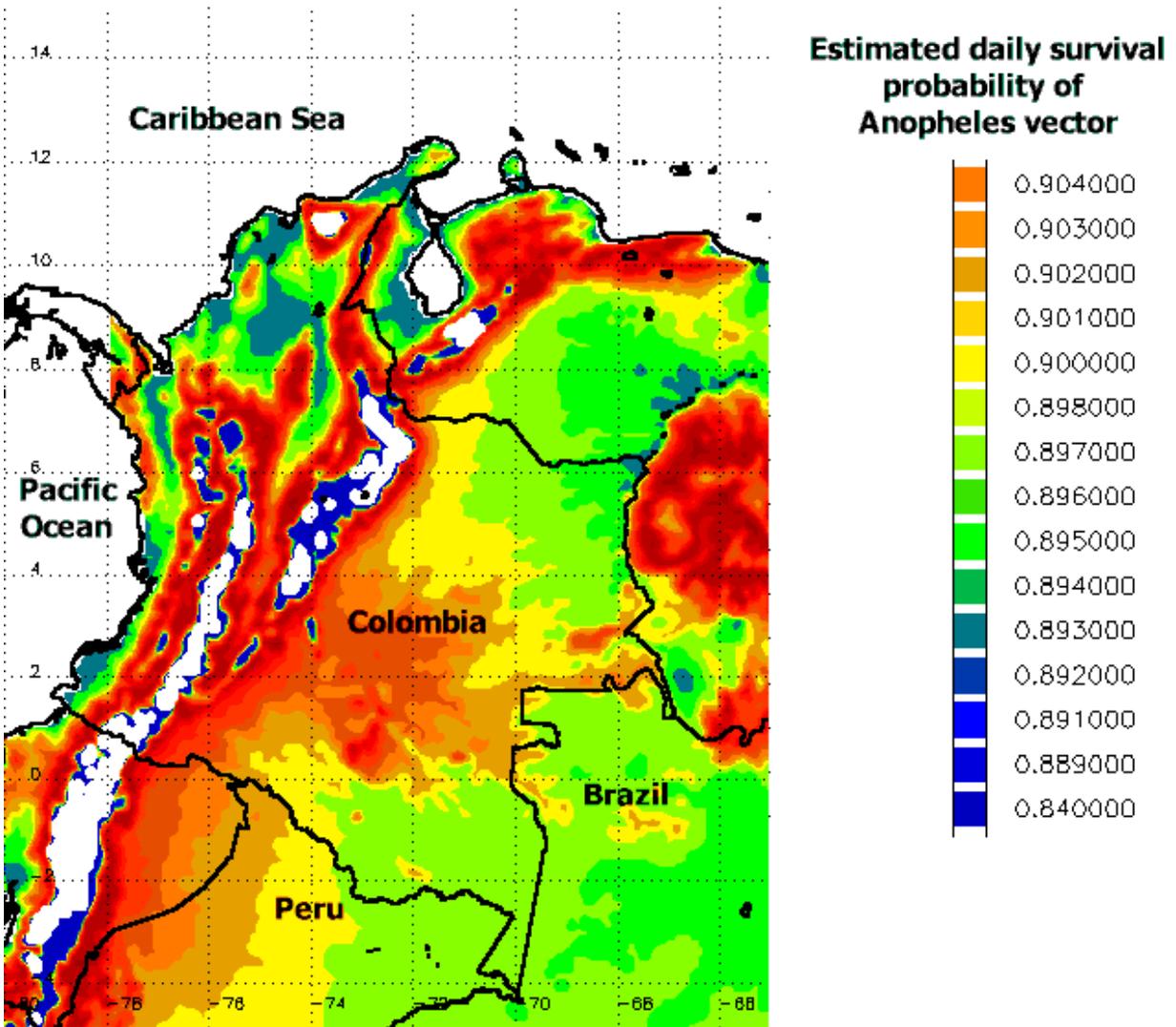


Fig. 4. Distribution of the estimated daily survival probability ($p = \exp[-1/(-4.4 + 1.31T - 0.03T^2)]$, Martens 1998) of the *Anopheles* vector over Colombia. Regions is white are associated with null probability.

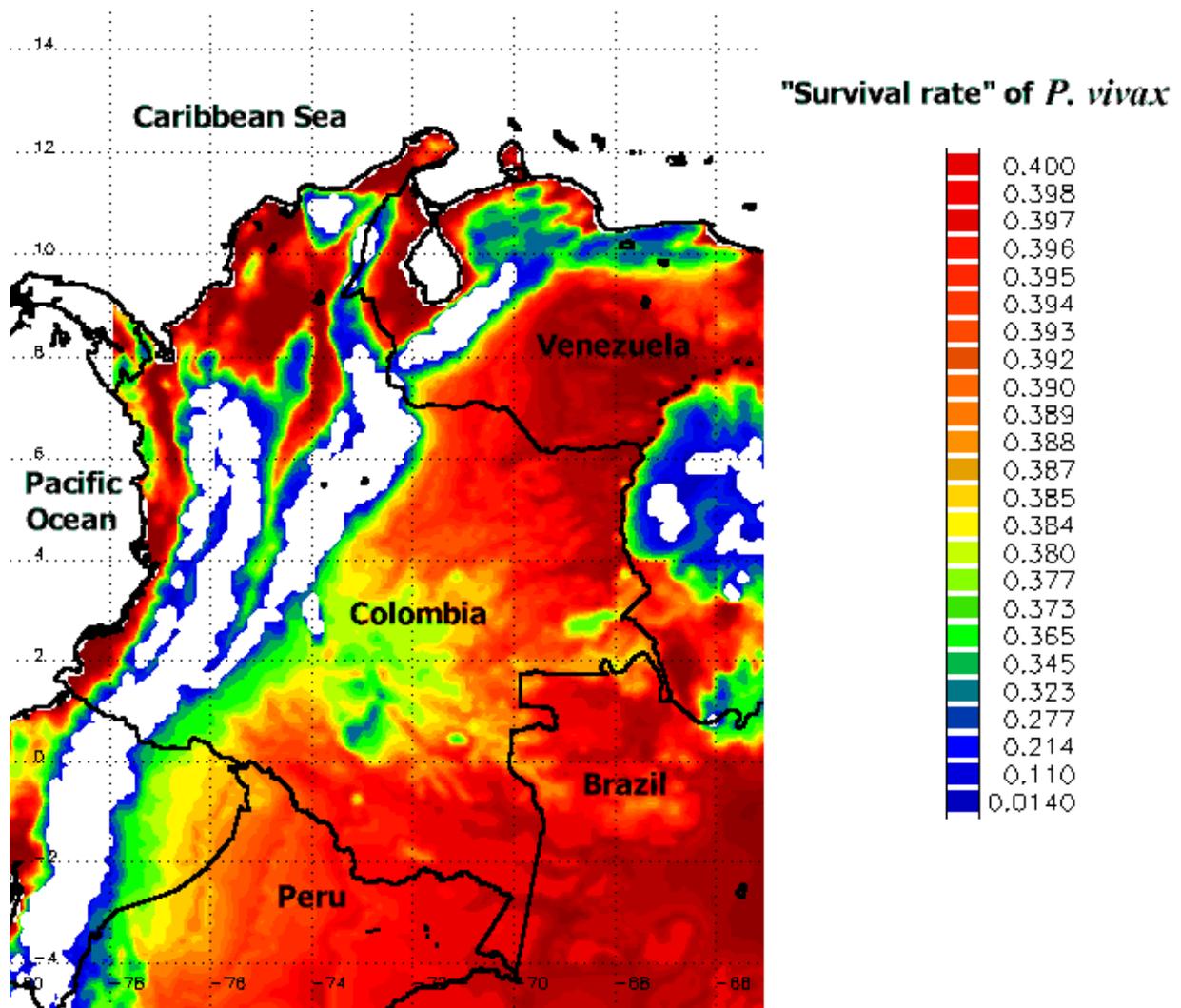


Fig. 5. Distribution of the 'survival rate' of *P. vivax*, defined as p^n , over Colombia. Regions is white are associated with null probability.

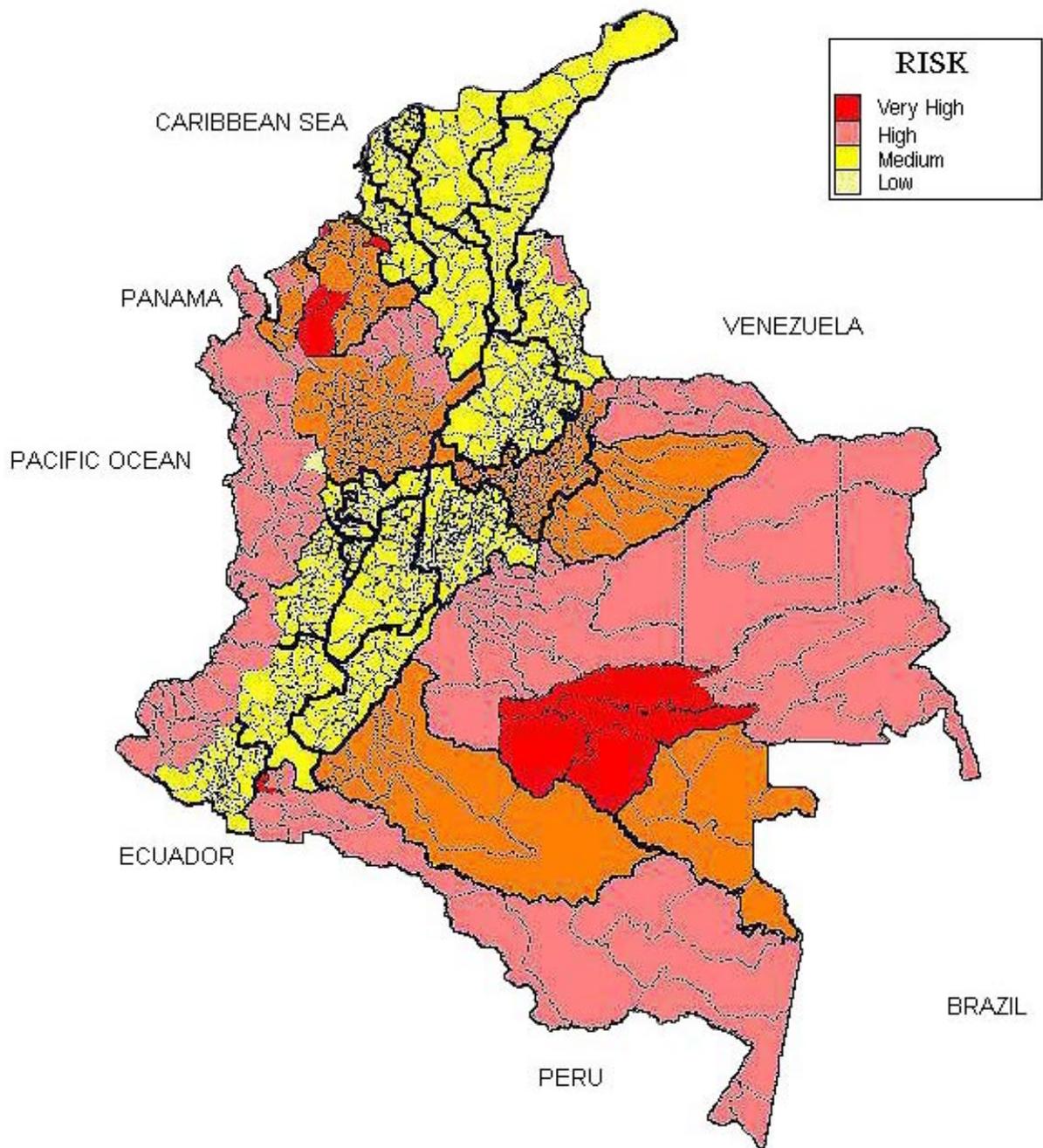


Fig. 6. Distribution of malaria risk over Colombia. Adapted from a map kindly provided by Dr. Julio César Padilla of the Colombian Ministry of Health.

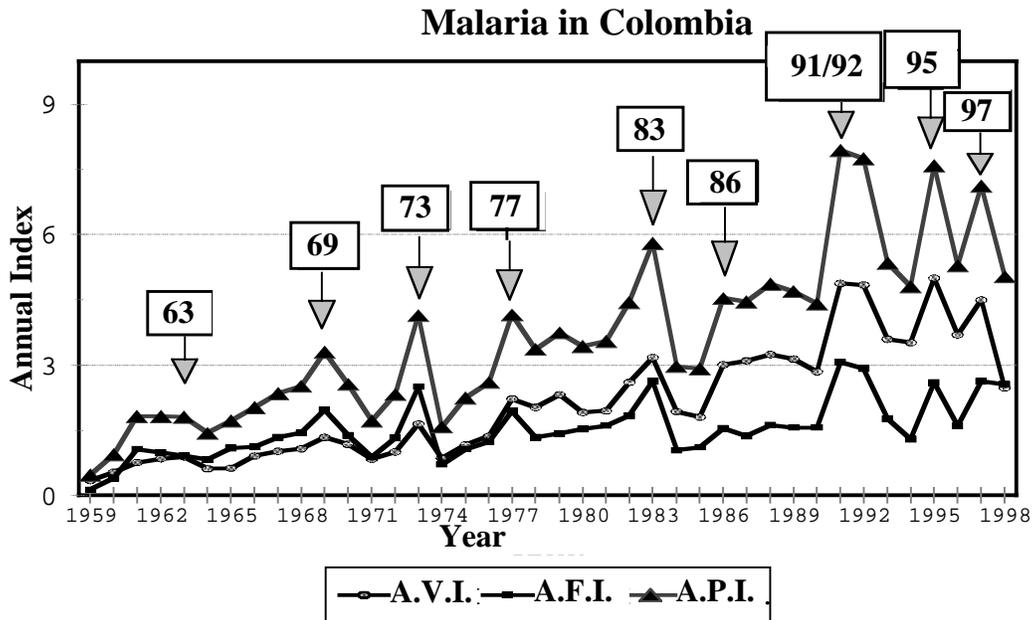


Fig. 7. Evolution of the API, defined as the ratio between the number of cases reported and the population at risk per 1,000 inhabitants, computed as the total of cases of both *P. vivax* (represented by the AVI index) and *P. falciparum* (AFI index). Data reported by the Colombian Ministry of Health.

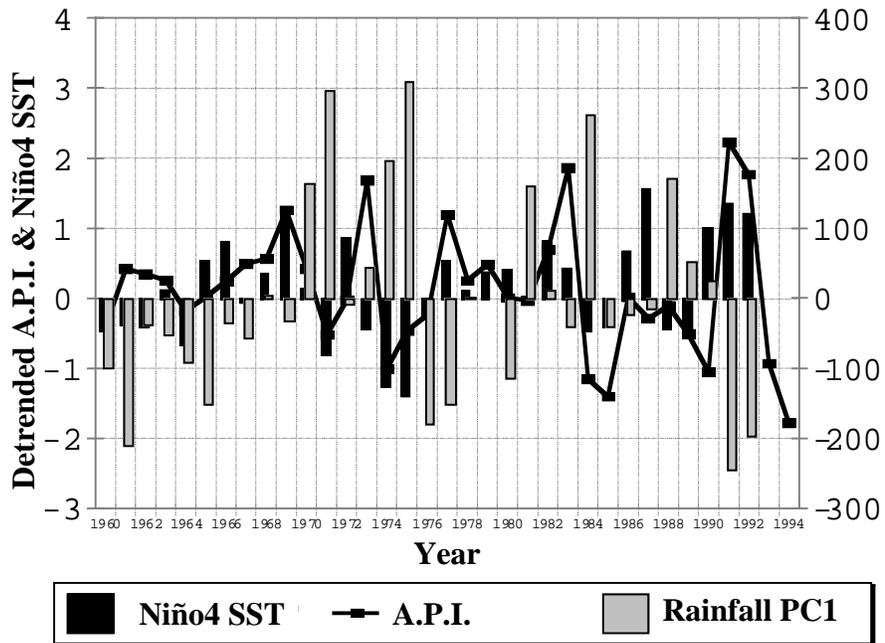


Fig. 8. Series of the detrended API index for Colombia, SST anomalies over the Pacific Ocean Niño-4 region (5°N–5°S, 160°E–150°W), and first Principal Component of Colombia precipitation. Simultaneous correlation is 0.50, and lag-1-year correlation is 0.49, both statistically significant at the 95% level.

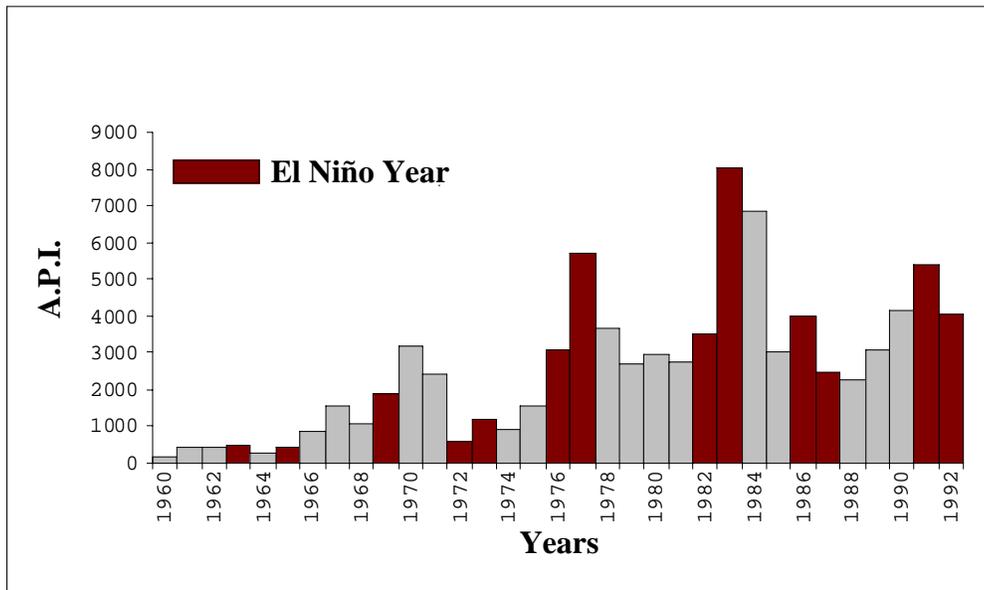
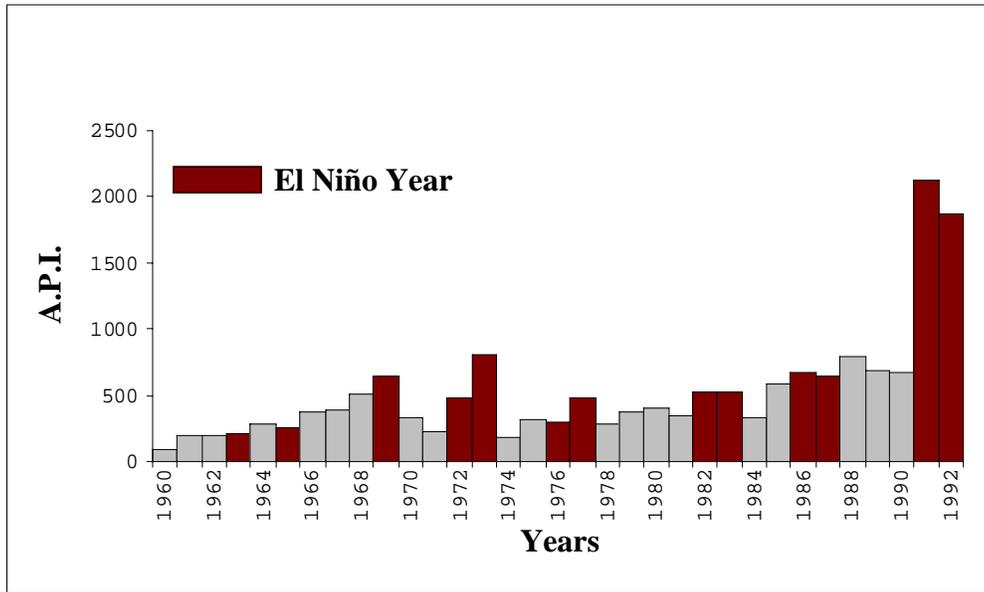


Fig. 9. Evolution of regional API index for (top graph) Antioquia (northwest, Andean region) and (bottom graph) Putumayo (Amazon region).

Dengue fever

Dengue fever (DF), spread by mosquito vectors of the genus *Aedes*, has a worldwide distribution in the tropics. Outbreaks are clearly multifactorial, involving compounding social, biological, and environmental factors. Peri-urban sprawl, poor sanitation, and the proliferation of

nonbiodegradable (and other) water containers, and social inequities in general, provide the setting for the resurgence of dengue fever in Latin America. But meteorological factors also play a role. In general terms, climate circumscribes the range at which VBDs can occur, while weather influences the timing and intensity of outbreaks (Dobson and Carper 1993). Two characteristics of climate change are germane to the distribution: (1) gradual warming and (2) the disproportionate rise in minimum temperatures (TMINs)—i.e., nighttime and winter, in relation to the gradual rise in average global temperatures (Karl et al. 1993; Easterling et al. 1997). Several investigations have linked dengue fever transmission to temperature (Hales et al. 1996; Donald Burke, unpublished data, 1997). The mosquito larvae can develop only at temperatures above a crucial threshold, and freezing kills eggs. Moderately high temperature can also hasten the larval stage, leading to smaller mosquitoes, which require more frequent blood meals. Also, the EIP shortens at higher temperatures. Dengue type 2 virus has an EIP of 12 days at 30°C and only 7 days at 32–35°C (Focks et al. 1995). Koopman et al. (1991) found that decreasing the incubation period by 5 days can lead to a threefold higher transmission rate of dengue, and that raising the temperature from 17°C to 30°C increases dengue transmission fourfold. Higher temperatures may increase the amount of feeding within the gonotrophic cycle (MacDonald 1957), given the smaller body size and enhanced metabolism with increasing temperature.

Dengue fever upsurges in the islands of the South Pacific are associated with ENSO events (Hales et al. 1996). Also, the incidence of dengue fever in Colombia, much of Central America, several Caribbean nations (and in Rio de Janeiro) is strongly influenced by ENSO events. Figure 10 (top) shows the evolution of dengue fever cases in Colombia during 1980–92. Interestingly, peaks are evident for 1983, 1987, and 1992, all of them being El Niño years (+1). Figure 10 (bottom) shows the number of dengue hemorrhagic fever (DHF) cases in Antioquia (northwestern Colombia), for the period 1985–1998, with most of the peaks corresponding to El Niño (+1) years. Notice the extraordinary peak in 1998 (7,368 cases until September 12th). During 1997, there were 3,950 cases of DHF in Colombia (41 deaths), equivalent to 9.82 per 100,000 inhabitants, as compared to the 1,750 cases in 1996 (14 deaths), equivalent to 4.44 per 100,000 inhabitants, as reported by the Colombian Ministry of Health. In Antioquia there were 67 cases of DHF during 1997, and up to the writing of this lines (09/1998) there have been 208 cases of DHF. Again, temperature increases and available stagnant waters may account for the upsurges. Water supply for human consumption becomes a serious problem during El Niño in Colombia, due to the prolonged drought. Many rural towns require the storage of water in cans and tanks, thus creating more breeding sites for the *Aedes* mosquito, and favoring the spreading of dengue fever in the country.

Discussion

Among the reasons that could help explain the strong relationship between El Niño and malaria and dengue fever outbreaks in Colombia are the increased air temperatures and the reduced precipitation during El Niño events. Temperature, precipitation, and humidity affect the epidemiology of malaria (Bouma 1995). Temperature impacts the dynamics of the vector population (reproductive rates, longevity, and biting rates), as well as the duration of the EIP or sporogony of the malaria parasites inside the mosquitoes. Warmer temperatures increase reproductive and biting rates, and decrease the EIP. Very warm (above about 35°C), and to a lesser extent, very cold (below 10°C) temperatures decrease mosquito longevity. Rainfall and humidity impact these dynamics, as well as mosquito breeding sites. For some areas, excessive precipitation

can increase breeding sites. In other areas with many mountain-derived rivers such as Sri Lanka (Bouma 1995) and Colombia, decreased rainfall may help create ponds and stagnant waters along the riverbanks and in the lower valleys (that otherwise would overflow during a non-El Niño year), thus providing adequate breeding sites for the mosquito. The increase in water temperature associated with ENSO years may further favor anopheline mosquito and parasite maturation. Thus, temperature increases and availability of adequate aquatic conditions could be the main factors that explain the observed relationship.

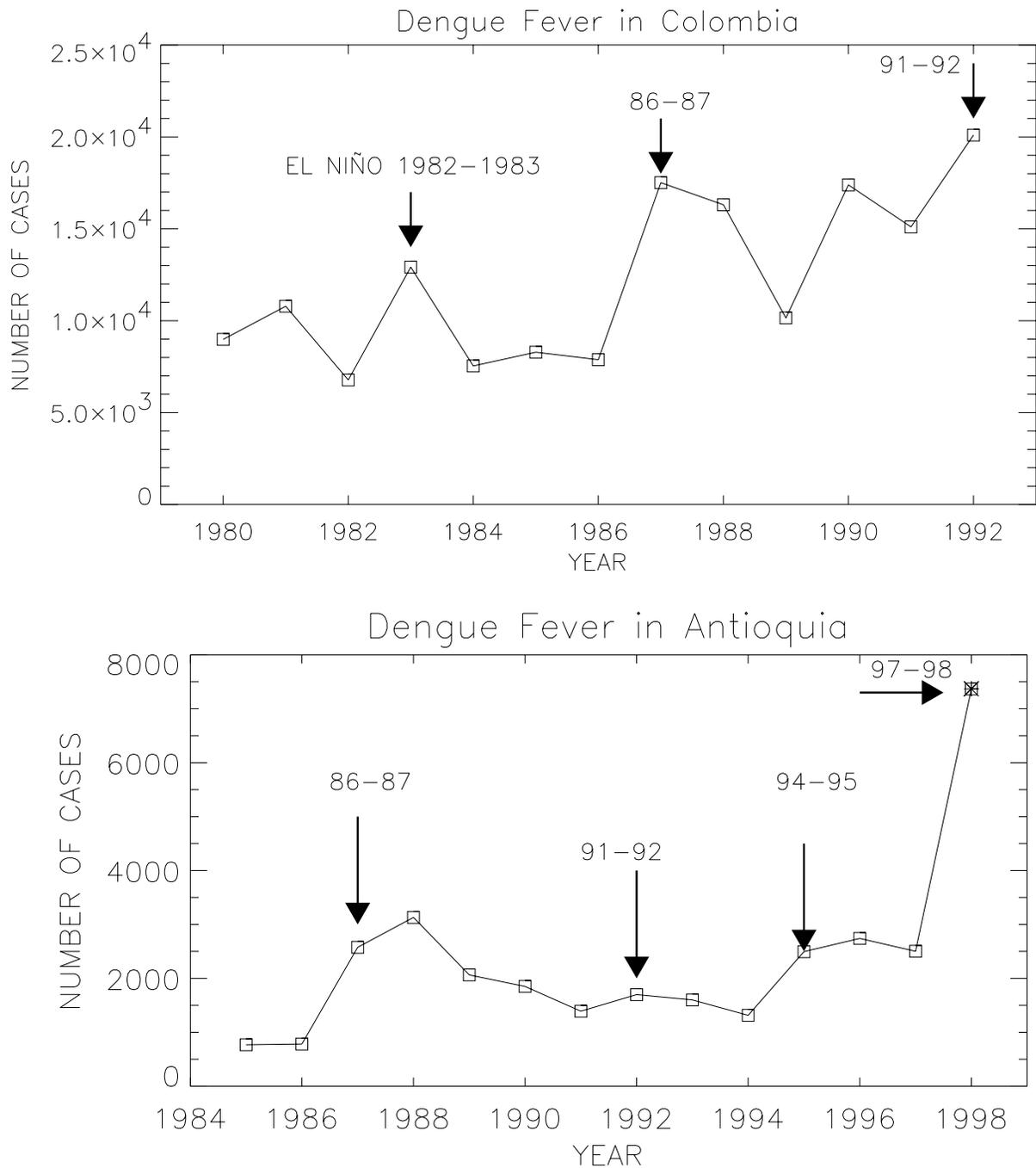
The apparent linkages between the trends in climate variables and the incidence of malaria in Colombia are clear. In particular, the association between increased mean and minimum temperatures (shown in Colombia by Mesa et al. 1997), and increased numbers of malaria cases, are at least consistent with what is known about the biological factors involved in transmission of this disease. In the following section, we use a simple epidemiological model of malaria transmission to test one of these hypothesized linkages.

Climate-malaria modeling: Results for Colombia

We modeled the spread of malaria as a function of important meteorological factors with the Epidemic (or Transmission) Potential Model (Martens et al. 1995a,b; Martens 1998), that is based on the concept of vectorial capacity (MacDonald 1957; GarretJones 1964). Epidemic (or transmission) potential is the reciprocal of the critical mosquito density threshold, and summarizes how climate change would affect the mosquito population directly. This value is obtained by computing the effect of temperature on feeding frequency and longevity, and the incubation period of the parasite in the vector. Within the model, the relation between ambient temperature and latent period is calculated by using a temperature sum as described by Macdonald (1957). The frequency of feeding depends mainly on the rapidity with which a blood meal is digested, which increases as temperature rises, and can also be calculated by means of a thermal temperature sum (Detinova et al. 1962). Between certain temperature thresholds, the longevity of a mosquito decreases with rising temperature (Molineaux 1988). The optimal temperature for mosquito survival lies in the 20–25°C range. The concept of vectorial capacity (VC) involves other factors, including density of mosquitoes, (which in turn depend on temperature and precipitation), blood meals and biting proportions necessary for transmission, and daily survivability, which also depend on temperature and humidity. In these terms, incubation period (probably the most important), mosquito density and survivability, and even host mosquito biting activity are dependent on meteorological conditions.

This epidemiological model was driven with surface air temperatures derived from an AGCM (ECHAM3 model of the Max Planck Institute for Meteorology in Hamburg) with a spatial resolution of about 300 km. The AGCM was run for 1970–92 using observed SSTs as boundary forcing. Previous analyses have shown that the surface air temperature data produced by this AGCM agree well with large-scale spatial averages of observed surface air temperatures and precipitation over Colombia and much of northern South America. In particular, the model correctly show warmer and drier than usual conditions over much of this region during El Niño years, and an upward trend in surface air temperatures during the period since the mid-1970s. Given these temperature signals, the malaria model produces the peaks in vectorial capacity (VC) during El Niño years and an upward trend with time. The qualitative agreement of the model for *P. vivax* and the observed number of cases of malaria in Colombia is also apparent (see Fig. 11),

suggesting the possibility that the malaria model is correctly showing the important role of temperature and precipitation variability in modulating malaria transmission in this region. Nevertheless, one needs to interpret the results with caution and realize that the Epidemic Potential Model may serve as an index ‘for early warning’ in combination with climate forecasts.



* Recorded cases of 1998 until september 12th

Fig. 10. Annual reported dengue cases for Colombia (missing data in 1993–94) (top), and hemorrhagic dengue fever cases in Antioquia, northwest Colombia (bottom).

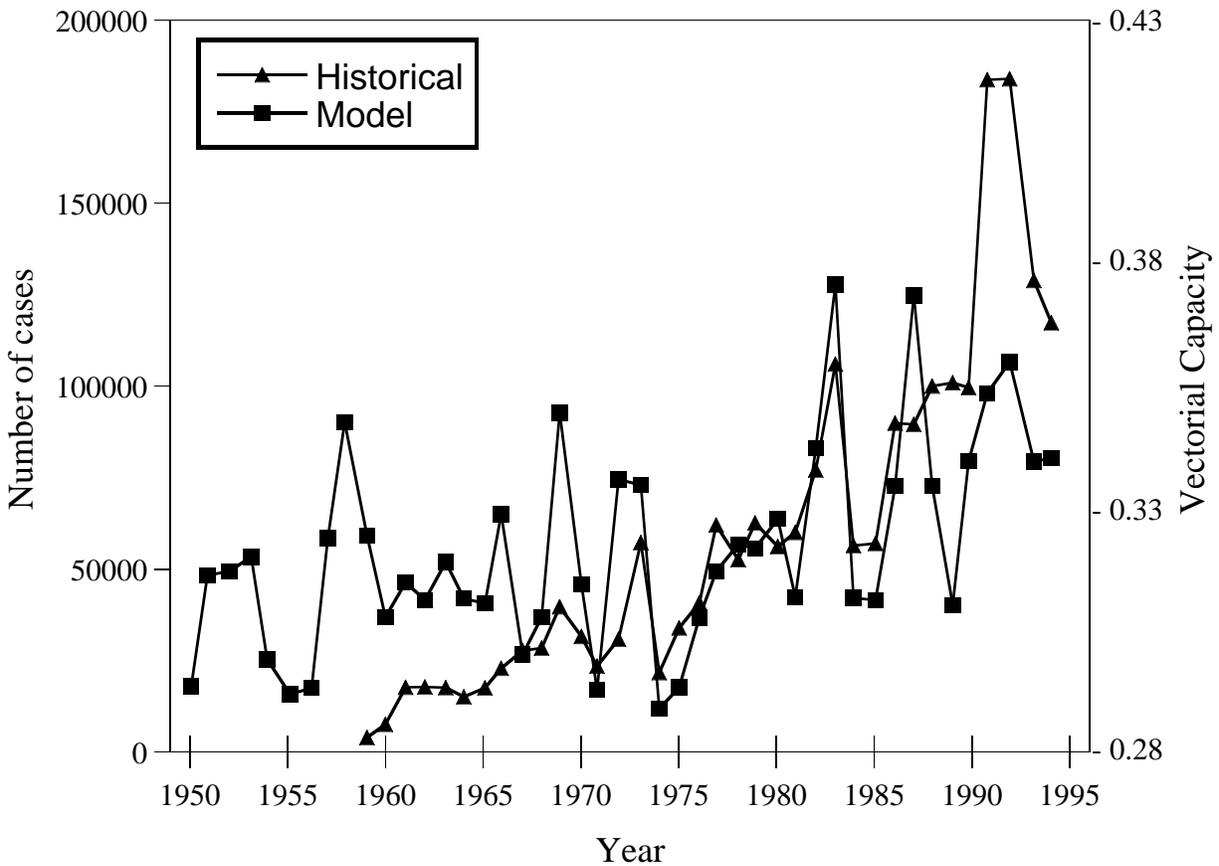


Fig. 11. Comparison between modeled vectorial capacity for *P. vivax* and the historical number of malaria cases in Colombia.

Several remarks must be made concerning the modeling results. The patterns in vectorial capacity are not straightforwardly to be linked with patterns of incidence, given the complexity of the malaria transmission dynamics that include immunity, loss of infection, land use and cover changes, human interventions, etc. We note that the climate data used (on a very large grid level) contain uncertainties that should be borne in mind when dealing with smaller spatial scales. The model's broad geographical spatial scale makes unfeasible to take into account the different *Anopheles* species, although different parts of the country have different species of anopheline vectors (Quiñones et al. 1987). Caution is necessary also in the interpretation of modeling results using surface air temperature data, since mosquitoes can select local microhabitats with different but more suitable temperatures to rest. In these microhabitats, other climatic variables can be 'ideal' for mosquito populations despite apparent adverse climate conditions. This is the case for humidity, which can play a major role in the determination of population longevity, a variable with a higher impact on VC (MacDonald 1957). Also, the model results do not prove that climate is involved with the variability in malaria activity, but are quite consistent with that idea. Indeed, the role of temperature is perhaps overstated in the model and other climatic factors may be involved, but the model is capable to resemble the peaks and the increasing trend existing in the Colombian malarial record. If one thinks in including precipitation projections in the model one should think that they are far less certain than temperature projections, particularly in tropical regions, and recall that some of the largest malaria outbreaks have occurred

during very dry years. In these terms, we would consider that rainfall simply is not a limiting factor, but the air temperature.

Conclusions

There is a strong association between climatic conditions and malarial risk throughout Colombia. Consistently, we have found that the cases of malaria (*P. vivax* and *P. falciparum*) in Colombia exhibit: (1) peaks during El Niño events, which holds true for dengue fever as well; (2) upward trends for the 1959–93 period; and (3) since the mid-1970s, *P. vivax* has become more predominant than *P. falciparum* as a national average. We associate the outbreaks in malaria and dengue fever in Colombia during El Niño to an increase in temperature (minimum and mean) and a decrease in precipitation throughout the country, although changes in other climatic variables such as humidity may play a role, too. Warmer temperatures increase reproductive and biting rates, and decrease the EIP. Diminished rainfall can lead to the formation of ponds and stagnant pools, and thus may create more mosquito breeding sites. The increase in temperature in ponds and stagnant waters associated with El Niño events may increase temperatures and provide breeding sites that further favor anopheline mosquito and parasite maturation. With regard to DF, diminished precipitation causes water shortages in many regions of the country, leading to the storage of water in receptacles and tanks, which constitute preferred breeding sites for *Aedes aegypti*.

Epidemics of these diseases are the result of multiple factors, including socioeconomic determinants, migratory patterns, demographic features, and local environmental constraints. But climatic variability is also an important incidence factor. Thus the statistical correlations may be helpful for developing health early warning systems (HEWS) that inform the public of meteorological conditions conducive to outbreaks. The coupling of epidemiological and climate models produces results that replicate the historical peaks and trends in the Colombian malaria record, thus giving a promising tool for forecasting the disease. Institutional support for HEWS may help to facilitate early, environmentally sound public health interventions. These measures include: increased surveillance and plans for mobilizing public health responses, information dissemination to the public, environmental cleanups for DF, distribution of pesticide-impregnated bed nets and medications for malaria control, targeted spraying of pesticides, stocking of drugs, and applications of biological control measures to mosquito breeding sites. Use of chemical interventions and biological controls can be planned when an El Niño episode is expected or once it is under way.

In addition to ENSO, other large-scale ocean-atmospheric phenomena affect the hydroclimatology of Colombia at interannual timescales. The North Atlantic Oscillation and the Quasi-Biennial Oscillation exhibit a significant influence on Colombia's climatology (Poveda and Mesa 1996, 1997). These findings provide good possibilities of developing adequate climatic predictive models specifically designed for Colombia (Salazar et al. 1994a,b; Poveda and Penland 1994; Carvajal et al. 1998). The improved predictive capability can enhance the planning and decision processes for control of malaria, dengue fever and other VBDs, helping to prevent disease and the associated social and economic troubles. As a matter of fact, the Colombian Ministry of Health implemented a contingency plan to control human health epidemics associated with the 1997-98 El Niño event. Certainly, there were high rates of those diseases during that event, but nonetheless the effect would have been much more intense had those measures not been taken.

The Colombian authors are conducting an ongoing research effort to refine the regional and local aspects of the malaria incidence, and to better understand the relationships with climatic variability at different time scales in Colombia. That research includes the response in the field and in the laboratory of vector and parasite life cycles to the environmental changes associated with extreme phases of ENSO. Further research on climatic patterns and weather parameters may be useful for developing public health priorities throughout Colombia and in other regions. This work can provide a framework for future modeling exercises to investigate the relationship between climatic factors, climate variability, and human health.

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