PERSPECTIVES: CLIMATE CHANGE AND MALARIA

Temperatures Without Fevers?

Chris Dye and Paul Reiter

"And the houses shall be full of swarms of insects, and also the … ground on which they stand…" (*1*). Or maybe not, after all. In the face of repeated prophecies that insect vectors and pathogens causing diseases such as malaria, Dengue, and yellow fever will spread as the world warms up (*2–6*), Rogers and Randolph (*7*) offer a more benign outlook on the future (see page 1763 in this issue). Taking a multidimensional view that combines several climatic variables, they predict that the distribution of the parasite that causes the most severe form of malaria (*Plasmodium falciparum*) is unlikely to change much if the world gets hotter. We may still become victims of crop failures, freshwater shortages, forest diebacks, a rise in sea-level, and all the rest, but if the findings of this latest work are correct, we should at least be spared an increased burden of malaria.

Enhanced online at www.sciencemag.org/cgi/content/full/289/5485/1697

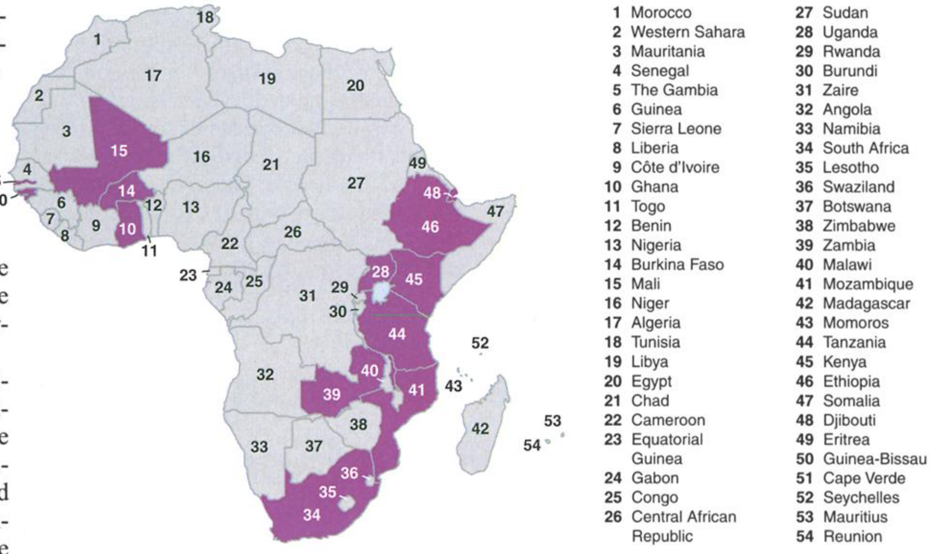
Biologists grappling with the complexity of vector-borne diseases are wary of existing predictions that forecast how disease distribution will change in the future, especially when such predictions are based on an alteration of just one variable—temperature. "Global warming" is about the world's atmosphere getting hotter, but only to a first approximation. More precisely, it is about temperature, rainfall, and humidity covarying spatially and temporally, and how these variables impact the numerous components of the vector and pathogen life cycle. For malaria, these components are not just limited to the temperature-sensitive incubation period of parasites in mosquitoes, but include the abundance, longevity, choice of host, and blood-feeding frequency of the vector, its susceptibility to the parasite, and a plethora of other factors that affect the host-parasite-vector interaction.

Stepping into this multifactorial world, Rogers and Randolph have incorporated five critical measures of temperature, rainfall, and saturation vapor pressure into a multivariate model. They use this model to draw a map of present-day malaria distribution that is 78% correct with respect to the current reported presence or absence of malaria cases—substantially better than any previous fit. They then use the predicted values of these variables to redraw the map as it might appear in 2050. The anticipated distribution of *P. falciparum* in 2050 is strikingly similar to its current distribution. The model predicts an overall change of less than 1% in the number of people suffering from malaria in 2050 compared to today.

One reason that malaria may not claim much new territory is that climatic factors affect mosquito, human host, and parasite populations interactively, rather than independently. Some of these interactions are obvious. A rise in temperature speeds the development of the plasmodia parasites in mosquitoes. But if there is insufficient water for the mosquitoes to breed in, and limited contact with humans, higher temperatures won't matter. The south of England may be getting warmer, but the malaria that was prevalent in the 17th century in the "Dengie marshes" of Essex and other areas has been absent for nearly a century—mosquito habitat has largely been eliminated, and the living conditions of the human population are greatly changed (*8*).

Other interactions are more subtle. High temperatures in the West African country of Mali mean that a 3 month rainy season is enough to sustain transmission of *P. falciparum* by mosquitoes; in contrast, cooler parts of southern and eastern Africa need 5 consecutive months of rain to enable mosquitoes to achieve the abundance and longevity necessary to sustain transmission of malaria (*9*).

Multiple regression with a series of climatic variables may provide a perfect explanation, statistically speaking, for the current distribution of malaria. But it does not follow that the range of the disease is solely determined by climate. *P. falciparum* was endemic in southern Europe (*10*) and the United States (*11*) until the middle of the 20th century. Given the right combination of social, environmental, and climatic changes, these regions could again become vulnerable. Similarly, although the disease has recently become more prevalent in many highland areas of Africa, it has yet to return to the maximum altitudes reported before large-scale control measures were implemented in the 1960s (*12*). Nevertheless, Rogers and Randolph have opened up a new clearing in the methodological jungle of statistical forecasting. Further work emulating their approach need not be restricted to vector-borne diseases; their methods are applicable to any phenomenon that has the potential to be influenced by climate change. Indeed, their results lead us to question whether other climate-related health warnings—for asthma, cholera epidemics, or heat-induced deaths, for example—would stand up to a more sophisticated multivariate analysis.



An in-depth look at malaria. Distribution of INDEPTH field sites (purple) in Africa. Field sites collect data on health and demographics in selected populations that can be used to predict the course of vector-borne diseases such as malaria. [Adapted from (*13*)]

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Rogers and Randolph's results can also be viewed as an attempt to pinpoint areas at greatest risk for new malaria outbreaks. Climatic variables that predict the presence or absence of malaria are likely to be best suited for forecasting the distribution of this disease at the edges of its range (that is, where its existence or nonexistence is most clearly marked). However, detailed ecological and epidemiological studies are still needed to assess the true local risk. Questions to be addressed in such studies should include: How might local species of anopheline mosquitoes extend their breeding ranges in response to altered climate? What is their susceptibility to the malaria parasite? What species interactions—with competitors, predators, and parasites—might influence mosquito abundance? How might changes in abundance affect transmission rates? How do temperature and humidity affect the behavior and longevity of adult mosquitoes? What is the potential for malaria to be imported through human migration?

The resolution and competence of climate models is improving rapidly, and this improvement will be of benefit to future analyses that strive for better explanations of the distribution of malaria. It is less certain that such studies will have access to better disease data, because information on insect vectors and malaria incidence is much harder to collect. This is especially true for the regions of Africa that carry most of the world's malaria burden. Much will depend on the success of new systems for data collection, such as INDEPTH (*13*), a network of field sites that produces information on health and demography by continuously monitoring vital events in selected populations. INDEPTH now has 15 sites in Africa (see the figure) and more than 40 worldwide. The present statistical output lists deaths from all causes, but in the future it may provide estimates of deaths attributable to malaria alone.

In some instances, climate variations do produce a detectable signal in malaria incidence, although the dominant fluctuations in caseload are determined by the ups and downs of control programs (*14*). The goal of those involved in malaria control over the next 50 years should be to make certain that climate change is indeed irrelevant to the distribution and prevalence of the disease. Given adequate funding, technology, and, above all, commitment, the campaign to "Roll Back Malaria," spearheaded by the World Health Organization (WHO), will have halved deaths related to *P. falciparum* by 2010 (*15*). By 2050, the map of malaria distribution should bear little resemblance to the one drawn by Rogers and Randolph.

References

1. Exodus 8:21.
2. A. J. McMichael, A. Haines, R. Slooff, S. Kovats Eds., *Climate Change and Human Health* (WHO, Geneva, 1996).
3. R. T. Watson, M. C. Zinyowera, R. H. Moss, Eds., "Impacts, adaptations and mitigation of climate change: scientific-technical analysis," Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge Univ. Press, 1996).
4. P. R. Epstein, *Sci. Am.* **283**, 50 (2000).
5. R. S. Kovats *et al.*, *Br. Med. J.* **318**, 1682 (1999).
6. UK Meteorological Office, www.met-office.gov.uk/sec5/CR_div/CoP5 (1999).
7. D. J. Rogers and S. E. Randolph, *Science* **289**, 1763 (2000).
8. P. Reiter, *Emerg. Infect. Dis.* **6**, 1 (2000).
9. M. H. Craig, R. W. Snow, D. le Seur, *Parasitol. Today* **15**, 105 (1999).
10. L. J. Bruce-Chwatt and J. de Zulueta, *The Rise and Fall of Malaria in Europe* (Oxford Univ. Press, Oxford, UK, 1980).
11. E. C. Faust, "The distribution of malaria in North America, Mexico, Central America, and the West Indies," in *A Symposium on Human Malaria, with Special Reference to North America and the Caribbean Region*, 1941, pp. 8–18.
12. P. Reiter, *Lancet* **351**, 839 (1998).
13. INDEPTH network, www.indepth-network.org (2000).
14. M. J. Bouma and C. Dye, *JAMA* **278**, 1772 (1997).
15. D. N. Nabarro and E. M. Tayler, *Science* **280**, 2067 (1998).

PERSPECTIVES: PALEOCLIMATE

Taking the Temperature of Past Ocean Surfaces

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Climate can vary substantially over millennial time scales; the most prominent examples are the ice ages that have periodically occurred over the past several hundred thousand years. Variations in the heat exchange through the surface layer of the ocean play a key role in these climatic changes. Reliable sea surface temperatures (SST) are therefore crucial to the reconstruction and modeling of past oceanic salinity and density, water column stratification, thermohaline circulation, and ice volume. Particular emphasis has been placed on obtaining records of SSTs during the last ice age because the climatic scenario during the Last Glacial Maximum is often used to test computer models designed to predict forthcoming climatic changes.

On page 1719 of this issue, Lea *et al.* (*1*) take a convincing step not only toward accurate SST reconstructions but also toward constraining the timing of surface ocean warming with respect to continental ice sheet melting during deglaciations and deciphering changes in continental ice volume. This is important because in order to understand the causal chains that trigger climate change, leads and lags between different ocean and climate proxies need to be defined. Environmental parameters that lead over others and form "the head of the queue" are likely candidates for initiating and changing climate.

In the late 1970s to early 1980s, the Climate/Long-Range Investigation, Mapping, and Prediction Project (CLIMAP) (*2*) generated the first global SST reconstruction for the Last Glacial Maximum on the basis of the statistical evaluation of changes in microplankton assemblages. The project initiated intense paleoclimate research based on deep-sea sedimentary records. Today, the CLIMAP reconstructions still serve as foundations for paleoclimate research, but many of its results remain controversial, for example, regarding the extent of sea ice in high latitudes or the relative change in tropical SSTs.

Since CLIMAP, a whole range of approaches for reconstructing SSTs have been developed. Ice core records from equatorial mountains and records of glacial snow line depression suggest that terrestrial temperatures during the Last Glacial Maximum were cooler than during the Holocene by as much as about 5°C. Noble gas measurements in groundwater also initially implied a 5°C glacial temperature drop, although revision of the data led to only a 1.9° to 2.5°C temperature difference. Data from alkenones (a group of temperature-sensitive lipids found in sediments that are used to reconstruct the paleoenvironment) provide evidence for a 2° to 4°C temperature decline of tropical surface waters. A large tropical SST reduction of around 4° to 5°C is also supported by coral records and, recently, by temperature reconstructions based on planktonic oxygen isotope ($\delta^{18}O$) records.

The inconsistencies between the temperature reconstructions mainly result from the heterogeneity of the applied geochemical and micropaleontological methods, which all rely on different assumptions, are used on different types of samples, and have different limitations. For example, the reconstruction of ocean temperatures from stable oxygen isotope ra-

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