

# Malaria risk and temperature: Influences from global climate change and local land use practices

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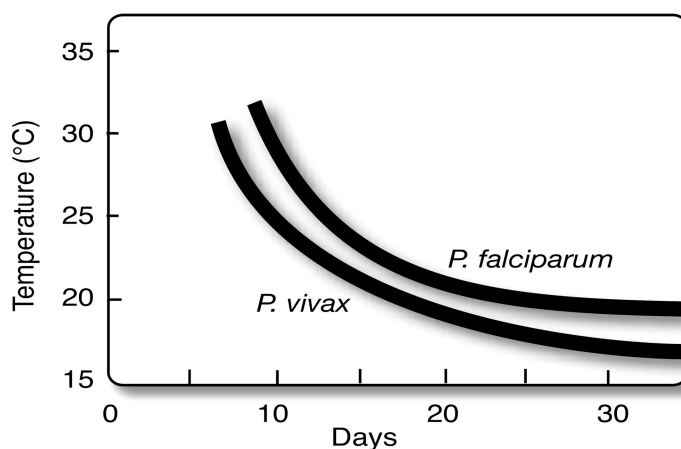
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An estimated 700,000 to 2.7 million people die of malaria each year, and 75% of those are African children ([www.cdc.gov/malaria](http://www.cdc.gov/malaria)). Recent resurgence in the East African highlands involves multiple factors, from climate and land use change to drug resistance, variable disease control efforts, and other socio-demographic factors (1). But malaria is an extremely climate-sensitive tropical disease, making the assessment of potential change in risk due to past and projected warming trends one of the most important climate change/health questions to resolve. Pascual *et al.* (2) now provide important new insights toward answering this malaria/climate question in their article in this issue of PNAS.

## Warming Trends and Malaria

Pascual's research team used a detrended time series of temperature and documented a warming trend in the East African highlands from 1950 to 2002, concomitant with increases in malaria incidence. Moreover, their findings confirm the importance of the well recognized nonlinear and threshold responses of malaria (a biological system) to the effect of regional temperature change (Fig. 1). For example, showing that the biological response of mosquito populations to warming can be more than an order of magnitude larger than the measured change in temperature represents a stunning finding, critical in advancing risk assessment of climate change impacts. Those who argue that we need not worry about small shifts in temperature should pause after considering the findings of Pascual *et al.* (2) that a mere half-degree centigrade increase in temperature trend can translate into a 30–100% increase in mosquito abundance, in other words “biological amplification” of temperature effects. In the African highlands, where mosquito populations are relatively low compared with lowland areas (3), such biological responses may be especially significant to determining the risk of malaria.

As a general rule, temperatures decrease on average by 6°C for every 1,000 m of elevation gained. Referring to Fig. 1, minimum temperature for parasite



**Fig. 1.** Relationship between temperature and malaria parasite development time inside the mosquito (“extrinsic incubation period” or EIP). EIP shortens at higher temperatures, so mosquitoes become infectious sooner. Note the nonlinear response to temperature, as well as relative threshold limits for malaria parasite development ( $\approx 18^{\circ}\text{C}$  and  $15^{\circ}\text{C}$  for *P. falciparum*, and *P. vivax*, respectively) (adapted from ref. 16).

development of *Plasmodium falciparum* and *Plasmodium vivax* approximates  $18^{\circ}\text{C}$  and  $15^{\circ}\text{C}$ , respectively, limiting the spread of malaria at higher altitudes. There is also a relationship between increasing altitude and decreasing mosquito abundance in African highlands (4). Projecting into the future, Ebi *et al.* (5) have compared climate suitability maps for malaria in the topographically diverse country of Zimbabwe and found that the projected warming from global climate models would make the country's entire highland area climatologically more favorable to support malaria by year 2050 (Fig. 2).

Large epidemics of malaria elsewhere have been associated with climate and temperature anomalies, such as in the Indian subcontinent (6), Colombia (7), and Uganda (8). Thomson *et al.* (9) recently showed that, in Botswana, indices of El Niño-related climate variability can serve as the basis of malaria risk prediction and early warning.

## Malaria and Local Effects on Climate from Land Use Change

Changing landscapes can significantly affect local weather more acutely than long-term climate change. Land cover change can influence microclimatic conditions, including temperature, evapotranspiration, and surface runoff (10,

11), all key to determining mosquito abundance and survivorship. In Kenya, Yan and colleagues (12) have found that open, treeless habitats experience warmer midday temperatures than forested habitats and also affect indoor hut temperatures. As a result, the gonotrophic cycle of female *Anopheles gambiae* was found to be shortened by 2.6 days (52%) and 2.9 days (21%) during the dry and rainy seasons, respectively, compared with forested sites. Similar findings have been documented in Uganda where higher temperatures have been measured in communities bordering cultivated fields compared with those adjacent to natural wetlands, and the number of *A. gambiae s.l.* per house increased along with minimum temperatures after adjustment for potential confounding variables (13).

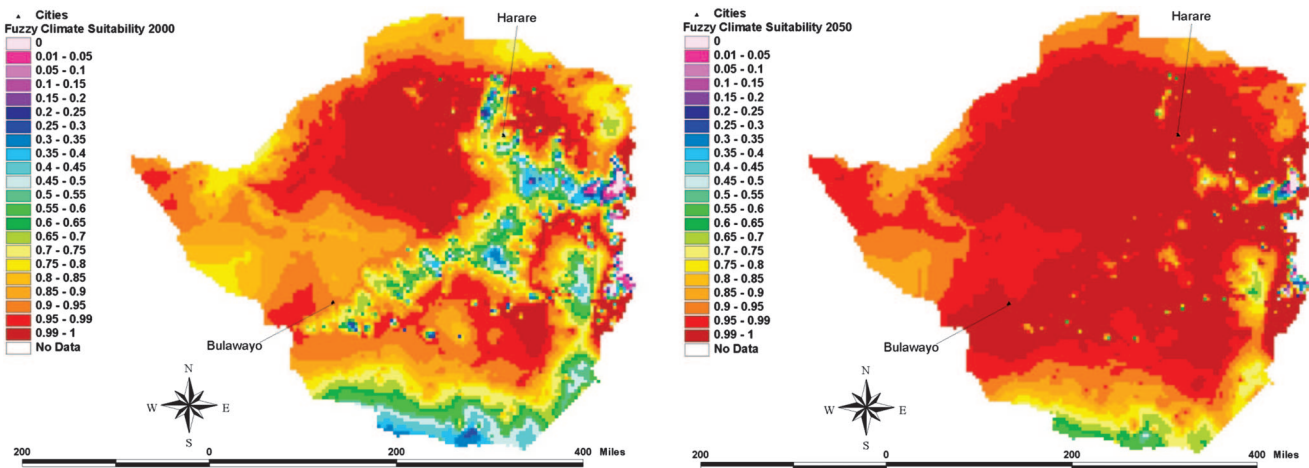
Higher maximum and mean temperatures of aquatic breeding sites found in farmlands also hasten larval development and pupation rates (14). Increased canopy cover in western Kenya is negatively associated with the presence of *A.*

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**Fig. 2.** Climate suitability for stable malaria transmission across the diverse topography of Zimbabwe, determined by fuzzy logic analysis and based on United Kingdom Meteorological Office (UKMO) global climate scenarios for year 2000 (Left) and with warming to the year 2050 (Right). Orange-red colors indicate more suitable climate conditions for malaria transmission. [Adapted from Ebi *et al.* (5) and Hartman *et al.* (17); maps provided by K. Ebi.]

*gambiae* complex and *Anopheles funestus* larvae in natural aquatic habitats (3). In artificial pools, survivorship of *A. gambiae* larvae in sunlit open areas was 50 times the survivorship in forested areas and also related to assemblages of predatory species (15). In short, deforestation and cultivation of natural swamps in the African highlands create conditions favorable for the survival of *A. gambiae* larvae, making analysis of land use change on local climate, habitat, and biodiversity central to malaria risk assessments.

### Conclusions

Studies of the association of malaria and past climate in the African highlands

have been controversial in part due to the varying quality of long-term disease data across sites in Africa, as well as the difficulty in adequately controlling for sociodemographic and biological (drug resistance) data. Not only have Pascual and her team (2) improved upon temperature trend analysis in the region, but, by inclusion of an entomological model, they have enhanced the predictability of how changing temperature trends may alter malaria risk. Accurate risk prediction, of course, still requires improved monitoring and modeling of mosquito populations and human malaria epidemiology, as well as effects on the parasite and disease itself.

The relentless expansion of malaria in the highlands is exacerbated by rapid

population growth and massive land use changes (such as deforestation) that can favor mosquito breeding. Combined with poor access to effective health care and inefficient vector control measures, these challenges demand collaboration across ministries of health, environment, and finance/development at the local, national, and regional levels to best address malaria in the African highlands. At the international level, industrialized nations must confront the deleterious health effects that their greenhouse gas emissions (causing global warming) are having around the world.

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- Patz, J. A., Hulme, M., Rosenzweig, C., Mitchell, T. D., Goldberg, R. A., Githeko, A. K., Lele, S., McMichael, A. J. & Le Sueur, D. (2002) *Nature* **420**, 627–628.
- Pascual, M., Ahumada, J. A., Chaves, L. F., Rodó, X. & Bouma, M. (2006) *Proc. Natl. Acad. Sci. USA* **103**, 5829–5834.
- Minakawa, N., Sonye, G., Mogi, M., Githeko, A. & Yan, G. (2002) *J. Med. Entomol.* **39**, 833–841.
- Bodker, R., Akida, J., Shayo, D., Kisinza, W., Msangeni, H. A., Pedersen, E. M. & Lindsay, S. W. (2003) *J. Med. Entomol.* **40**, 706–717.
- Ebi, K. L., Hartman, J., Chan, N., McConnell, K. J., Schlesinger, M. & Weyant, J. (2005) *Clim. Change* **73**, 375–393.
- Bouma, M. J. & van der Kaay, H. J. (1996) *Trop. Med. Int. Health* **1**, 86–96.
- Poveda, G., Rojas, W., Quinones, M. L., Velez, I. D., Mantilla, R. I., Ruiz, D., Zuluaga, J. S. & Rua, G. L. (2001) *Environ. Health Perspect.* **109**, 489–493.
- Lindblade, K. A., Walker, E. D., Onapa, A. W., Katungu, J. & Wilson, M. L. (1999) *Trans. R. Soc. Trop. Med. Hyg.* **93**, 480–487.
- Thomson, M. C., Doblas-Reyes, F. J., Mason, S. J., Hagedorn, R., Connor, S. J., Phindela, T., Morse, A. P. & Palmer, T. N. (2006) *Nature* **439**, 576–579.
- Foley, J. A., Defries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., *et al.* (2005) *Science* **309**, 570–574.
- Patz, J. A., Campbell-Lendrum, D., Holloway, T. & Foley, J. A. (2005) *Nature* **438**, 310–317.
- Afrane, Y. A., Lawson, B. W., Githeko, A. K. & Yan, G. (2005) *J. Med. Entomol.* **42**, 974–980.
- Lindblade, K. A., Walker, E. D., Onapa, A. W., Katungu, J. & Wilson, M. L. (2000) *Trop. Med. Int. Health* **5**, 263–274.
- Munga, S., Minakawa, N., Zhou, G., Mushinzimana, E., Barrack, O. O., Githeko, A. K. & Yan, G. (2006) *Am. J. Trop. Med. Hyg.* **74**, 69–75.
- Tuno, N., Okeka, W., Minakawa, N., Takagi, M. & Yan, G. (2005) *J. Med. Entomol.* **42**, 270–277.
- Gilles, H. M. (1999) *Epidemiology* (Oxford Univ. Press, Oxford).
- Hartman, J., Ebi, K., McConnell, K. J., Chan, N. & Weyant, J. (2002) *Glob. Change Hum. Health* **3**, 42–54.