

Biological and Physical Signs of Climate Change: Focus on Mosquito-borne Diseases



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ABSTRACT

The Intergovernmental Panel on Climate Change concluded that there is “discernible evidence” that humans—through accelerating changes in multiple forcing factors—have begun to alter the earth’s climate regime. Such conclusions are based primarily upon so-called “fingerprint” studies, namely the warming pattern in the midtroposphere in the Southern Hemisphere, the disproportionate rise in nighttime and winter temperatures, and the statistical increase in extreme weather events in many nations. All three aspects of climate change and climate variability have biological implications.

Detection of climate change has also drawn upon data from glacial records that indicate a general retreat of tropical summit glaciers. Here the authors examine biological (plant and insect) data, glacial findings, and temperature records taken at high-elevation, mountainous regions. It is concluded that, at high elevations, the overall trends regarding glaciers, plants, insect range, and shifting isotherms show remarkable internal consistency, and that there is consistency between model projections and the ongoing changes. There are implications for public health as well as for developing an interdisciplinary approach to the detection of climate change.

1. Introduction

According to the World Health Organization (1996), 30 new diseases have emerged in the past 20

years. In addition, there has been a resurgence and a redistribution of old diseases on a global scale. Diseases such as malaria and dengue (“breakbone”) fever, carried by (vectored by) mosquitoes, are among those undergoing resurgence and redistribution (Gubler and Kuno 1997).

Arthropods are exquisitely sensitive to climate. Throughout this century public health researchers have understood that climate circumscribes the distribution of mosquito-borne diseases, while weather affects the timing and intensity of outbreaks (Gill 1920a,b; Dobson and Carper 1993). Paleoclimatic data (Elias 1994) demonstrate that geographic shifts of beetles have been closely associated with changes in climate (see Fig. 1). Their distribution—using the mutual climatic range (MCR) method to map fossilized species assemblages—is particularly sensitive to changes in minimum temperatures (TMINs or nighttime and winter temperatures), as illustrated by shifts in species accompanying the Younger Dryas and those at the end of the last glacial maximum (see Fig. 2). Indeed, the battle between insects and plants may have been key to climate control during the carboniferous period: by developing and coevolving multiple means of defending against herbivory, woody terres-

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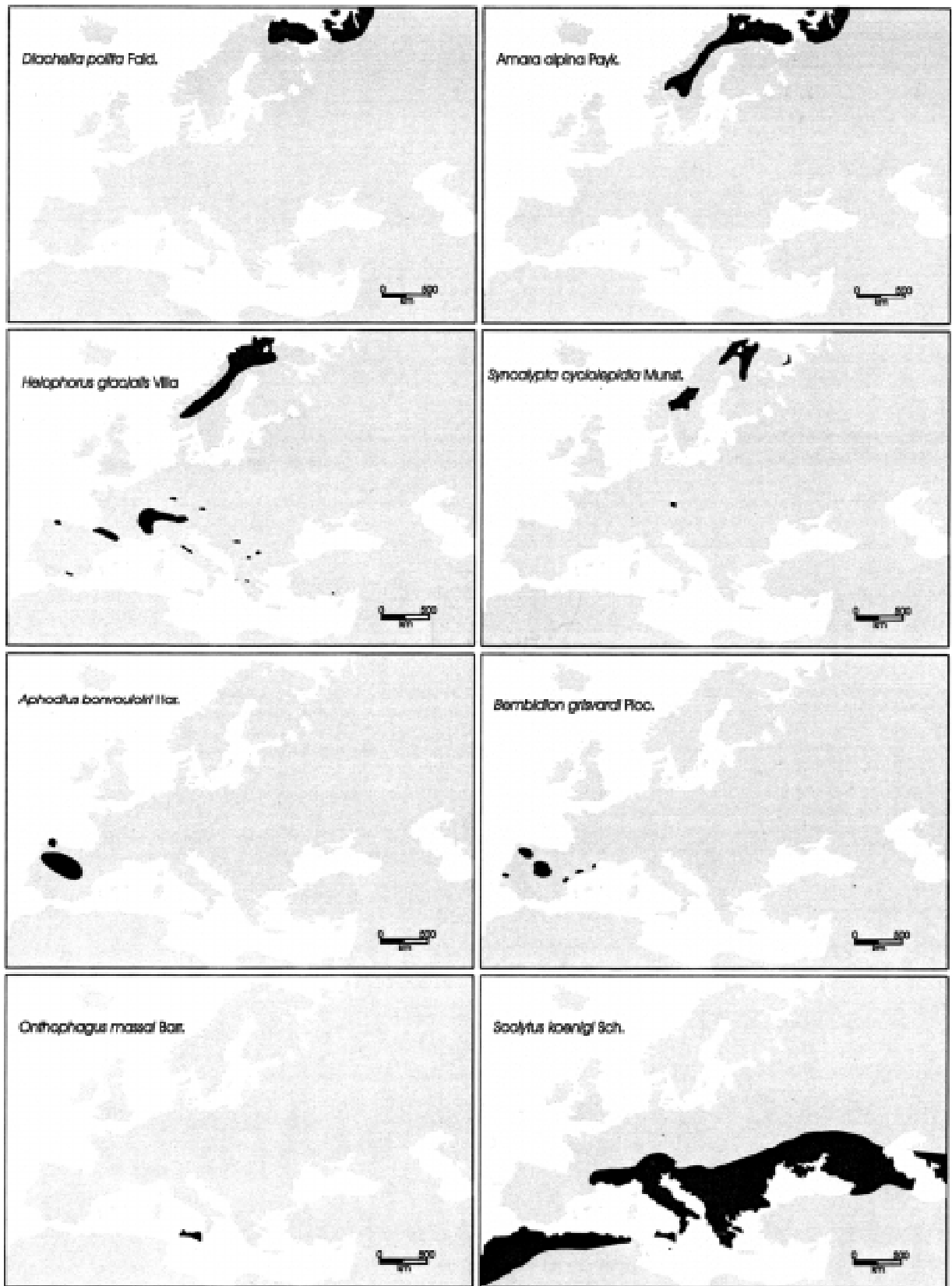


FIG. 1. Maps indicate the European distributions of beetle species found in Britain in late Pleistocene fossil assemblages. *Diacheila polita*, *Amara alpina*, *Helophorus glacialis*, and *Syncalypta cyclolepidia* occurred in fossil assemblages associated with glacial episodes; *Aphodius bonvouloiri*, *Bembidion grisvardi*, *Onthophagus massai*, and *Scolytus koenigi* occurred in episodes of interstadial warming.

trial plants may have thrived, drawing down atmospheric carbon and cooling the biosphere (Retallack 1997).

A growing number of investigators propose that vector-borne diseases (VBDs), (e.g., involving insects and snails as carriers), could shift their range in response to climate change (Leaf 1989; Shope 1991; Patz et al. 1996; McMichael et al. 1996; Carcavallo and de Casas 1996). Models, incorporating vectorial capacity (temperature-dependent insect reproductive and biting rates and microorganism reproductive rates), uniformly indicate the potential for spread of the geographic areas that could sustain VBD transmission to higher elevations and higher latitudes under global warming ($2 \times \text{CO}_2$) scenarios (Maskell et al. 1993; Martens et al. 1997; Matsuoka and Kai 1994; Martin and Lefebvre 1995; Focks et al. 1995) (see Fig. 3). The transmission season may also be extended. Studies in the United States indicate a potential for the northern movement of mosquito-borne encephalitides (e.g., western equine encephalomyelitis and St. Louis encephalitis) within the continental United States and Canada (Reisen et al. 1993; Reeves et al. 1994). Simulations of the changes in malaria virulence due to global temperature increases during the past several decades show patterns strikingly similar to those found in the double CO_2 simulations (N. Graham 1998, unpublished manuscript).

This article examines recent evidence that indicates upward movements in disease-carrying insects, upward plant migration, the retreat of tropical glaciers, and the upward shift in the freezing isotherm in the Tropics, all suggesting the possibility of climatic changes in recent decades. We will focus here on mosquito-borne diseases and the implications for human health and human activities (see McMichael et al. 1996).

2. Evidence of climate change

The most recent and relevant data from the physical and biological sciences indicate a significant warming trend this century [Intergovernmental Panel on Climate Change (IPCC) 1996a,b]. Moreover, Diaz and Graham (1996) report that, since 1970, the elevation of the freezing level (0°C isotherm) in tropical latitudes (30°N – 30°S) has shifted upward approximately 150 m (equivalent to about 1°C of local warming).

The rise in tropospheric temperatures (Santer et al. 1996) is reflected in the mass balance of many glaciers, and ice caps from the Tropics to the midlatitudes

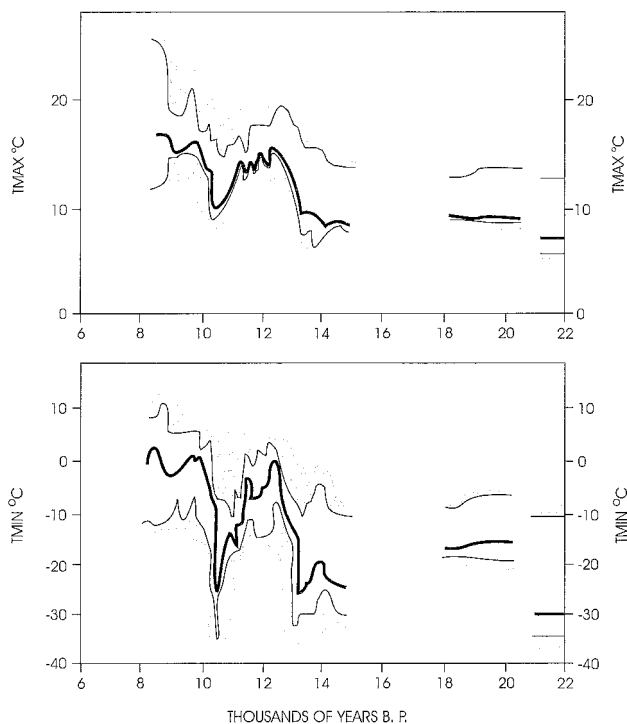


FIG. 2. Mutual climatic range reconstructions of temperatures for the late Devensian interval in the British Isles. Shaded area defines the limits of the MCR; bold line shows the most probable value of paleotemperatures (after Atkinson et al. 1987).

The MCR reconstructions for Britain are remarkable in that they show the rapidity and strength of climatic change at the end of the last glaciation. Extremely rapid warming took place at about 13 000 yr BP, and again at 10 000 yr BP. In between, the marked cooling associated with the Younger Dryas is also demonstrated (from Elias 1994; used by permission of Smithsonian Institution Press).

[South American Andes, African highlands, European Alps, Asian Highlands, Indonesia, and New Zealand] are currently retreating, many at rates that continue to accelerate (Kaser and Noggler 1991; Hastenrath and Kruss 1992; Thompson et al. 1993; Haeberli 1995; IPCC 1996). For example, the edge of the Qori Kalis glacier that flows off the Quelccaya ice cap high in the Peruvian Andes Mountains was retreating at a rate of 4 m (13 ft) annually between 1963 and 1978. By 1995, that rate had grown to 30 m (99 ft) each year (Mosley-Thompson 1997). Many of the smaller ice fields may soon disappear, potentially jeopardizing local water supplies that are critical for human consumption, regional agriculture, and generation of hydroelectric power.

Past and potential displacements of plant distributions in response to climate change has received considerable attention (Jacobson et al. 1987; Davis 1989; Overpeck et al. 1991; Davis and Zabinski 1992; Billings 1995). From a climatic perspective, a small

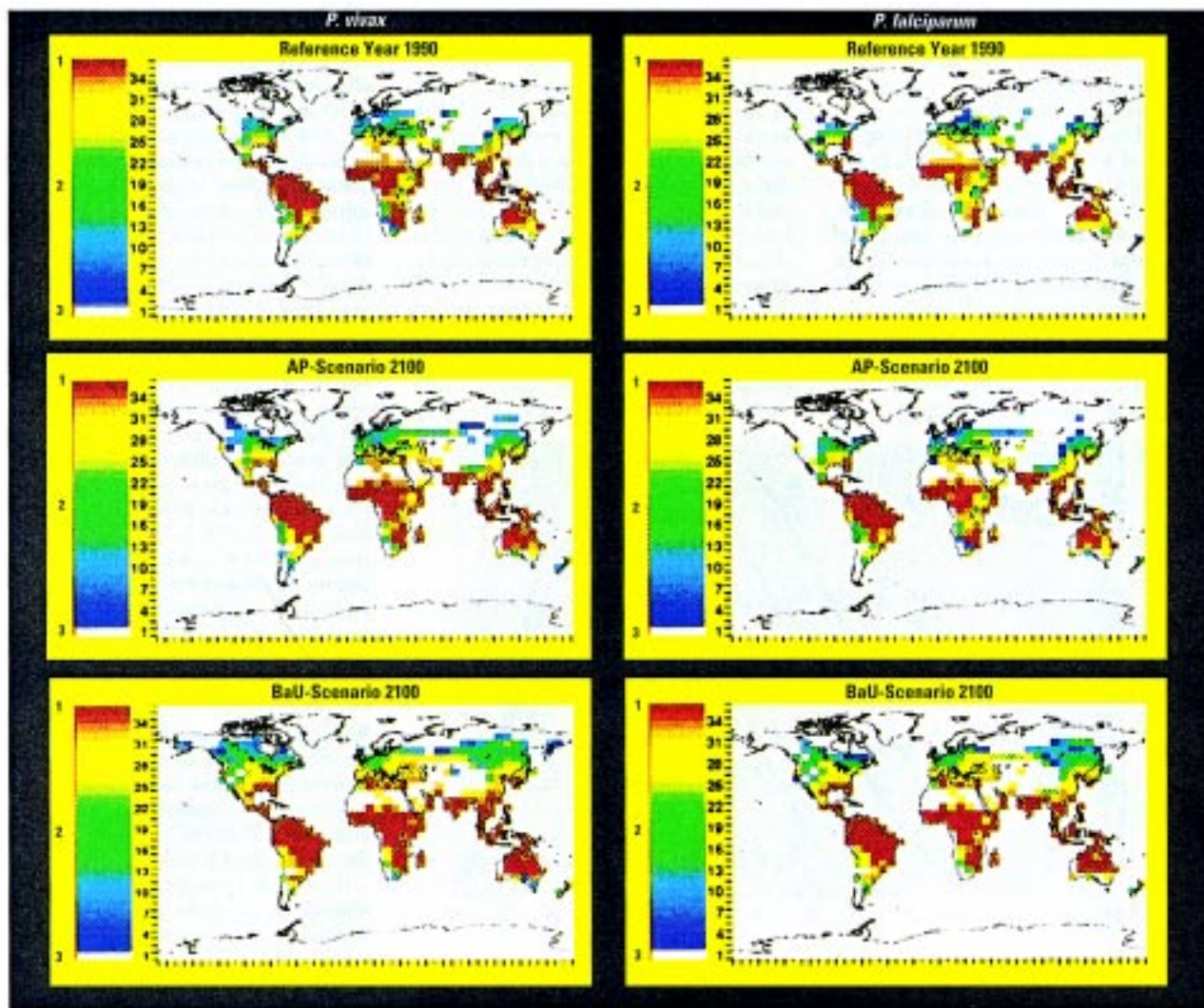


FIG. 3. Potential malaria risk areas in 1990 and 2100 for *P. vivax* and *P. falciparum*, expressed as the logarithm of the epidemic potential [$-10\log(EP)$], based on the climate patterns generated by the U.K. Meteorological Office-General Circulation Model with the accelerated policies (AP) and business-as-usual (BaU) greenhouse gas emission scenarios (Martens et al. 1995).

elevational displacement of plant distribution corresponds to a much larger latitudinal displacement. To accommodate to a 2°C rise in temperature in the Northern Hemisphere, for example, plant distributions may rise 500 m in elevation or shift 300 km poleward (MacArthur 1972; Peters 1991). Upward displacements of plant distributions have been documented on 26 alpine peaks (Grabherr et al. 1994)—recently updated to 30 (Pauli et al. 1996) Maximum upward displacement rates of plant distributions approach 4 m per decade.¹ In extratropical latitudes the evidence is more complex and the influence of changes in storm tracks

¹Similar upward shifts have been observed in Alaska, the U.S. Sierra Nevada, and New Zealand (Yoon 1994).

associated with changes in the westerlies dominates the signal (Hurrell 1995; Hurrell and van Loon 1997).

Insects may also prove to be useful indicator species. Parmesan (1996) found that the distribution of Edith's Checkerspot butterflies (order Lepidoptera) has shifted northward. Population extinctions are four times greater at the far southern end of its range (in Mexico) than at the far northern end of its range (in Canada), and about two and one-half times as great at lower elevations as compared to populations above 8000 feet. Similar changes in range are being observed for other butterfly species in Europe (C. Parmesan 1997, personal communication).

Europeans colonizing Africa were well aware of the benefits afforded by living at higher, cooler elevations

(Lindsay and Martens 1998) separated from *mal aria* [bad air]. Mosquitoes, in particular, are highly sensitive to climatic factors (Gill 1920a,b; Macdonald 1957; MacArthur 1972; Billett 1974; Burgos 1990; Burgos et al. 1994; Carcavallo and de Casas 1994). *Anophele* spp. and *Aedes aegypti* mosquitoes have established temperature thresholds for survival, and there are temperature-dependent incubation periods for the parasites and viruses within them (the extrinsic incubation period or EIP). Provided sufficient moisture, warmer temperatures—within the survivable ranges—increase mosquito populations, biting rates (blood meals), mosquito activity, and abundance, and decrease the EIP or duration of sporogony (Macdonald 1957; Patz et al. 1996; Martens et al. 1997). A rise from 20° to 25°C, for example, reduces EIP for *P. falciparum* parasites from 26 to 13 days (Macdonald 1957). Mosquito survival drops as ambient temperatures approach 40°C.

Bioclimatographs of temperature and humidity levels, and of the geographic distribution of areas permitting mosquito and pathogen development, can be constructed (Dobson and Carper 1993). The aquatic stages of *Anophele* mosquitoes in the Tropics do not develop (Leeson 1939) or breed (DeMeillon 1934) below approximately 16°C, and the minimum temperature for *P. falciparum* malaria parasite development is experimentally between 16° and 19°C and varies among mosquito species (Molineaux 1988). In general, isotherms present boundary conditions, and transmission is generally limited by the 16°C winter isotherm. (Mosquitoes may avoid these restrictions by resting in houses or shaded areas; and biogeographical factors, land-use, dams and irrigation ditches, control measures plus population movements, and the “immunological history” of inhabitants all contribute to the precise areas where transmission occurs.)

In particular, the disproportionate rise in TMINs (Karl et al. 1993) accompanying climate change favors insect overwintering and activity. Easterling et al. (1997) report that since 1950, maximum temperatures have risen at a rate of 0.88°C per 100 years, while TMINs increased at a rate of 1.86°C per 100 years. In both hemispheres TMINs increased abruptly in the late 1970s. A warmer atmosphere holds more moisture (6% more for every 1°C), and these changes may, in part, be attributable to the intensified hydrological cycle (Graham 1995; IPCC 1996) and increasing cloudiness, reducing daytime warming and retarding nighttime outgoing longwave radiation and cooling (Karl et al. 1997).

3. Underlying ocean warming?

Ocean warming may have contributed to the northward shift in marine flora and fauna reported since the 1930s along the California coast (Barry et al. 1995) and to the drop in zooplankton in the same region (Roemmich and McGowan 1995). Ocean warming—along with increased terrestrial evapotranspiration—contributes to the accelerated hydrological cycle, that, in turn, increases temperatures throughout most of the Tropics (Graham 1995), thus altering precipitation patterns that can affect the timing of VBD outbreaks. Warming sea surface temperatures appear related to the isotherm shift (Diaz and Graham 1996), and one may conjecture that the world’s oceans are the repository (capacitor) for the past century’s global warming. Now deep-ocean warming has been reported from subtropical transects in the Atlantic (Parrilla et al. 1994), Pacific (Thwaites 1994), and Indian Oceans (Bindoff and Church 1992) and near the poles (Travis 1994; Regaldo 1995). Indian Ocean waters tested down to 900 m warmed up to 0.5°C between 1962 and 1987, and the Indian Ocean has risen by 3.5 cm in those 25 years from thermal expansion. Also, the Indian Ocean—between 500 and 1500 m deep—contains more fresh water than in the past. More basinwide data are needed to evaluate these trends.

4. Mosquito-borne diseases

Mosquito-borne diseases are now being reported at high elevations in the highlands of Asia, Central Africa, and Latin America. *P. falciparum* malaria is a growing public health threat in the eastern, southern, western, and Chimbu highlands of Papua New Guinea (PNG)(Rozendaal 1996), and in 1997 malaria was reported up to 2100 m in the highlands of Irian Jaya and PNG (ProMED 1997). A steady rise in annual temperatures has been associated with expanding malaria transmission in the Usamabara Mountains in Tanzania (Matola et al. 1987), and highland malaria has been reported in Kenya (Some 1994). The El Niño–Southern Oscillation (ENSO) phenomenon may provide some clues as to the potential future changes in climate because it appears that it affects the distribution (reproduction and mortality) of disease vectors. In association with the warm ENSO event of 1987—and an increase in mean and TMINs (nighttime temperatures)—*P. falciparum* increased significantly in the highlands of Rwanda (Loevinsohn 1994). Satellite

temperature profile data show that temperature anomalies over tropical land areas are in phase with the rise in tropical SSTs due to ENSO, in a manner that increases with height through the troposphere (Susskind et al. 1997; Graham 1995; Diaz and Graham 1996).

Dengue fever—previously limited to about 1000 m in elevation in the Tropics by the 10°C winter isotherm—has appeared at 1700 m in Mexico (Koopman et al. 1991); *Aedes aegypti*—the mosquito that can carry dengue and yellow fever viruses—has been reported at an elevation of 2200 m in Colombia (Suarez and Nelson 1981). There is a growing potential for the resurgence of urban yellow fever in Latin America.

In the 1990s, outbreaks of locally transmitted (as opposed to “airport” or imported cases of) malaria have occurred within the United States: New Jersey in 1991 and Queens, New York, in 1993 during hot, wet summers (Zucker 1996), Michigan (CDC 1996), Texas (CDC 1995), Florida (ProMED 1996), Georgia (CDC 1997), and California (Maldonado et al. 1990). In the 1980s, only California reported local transmission of malaria in the continental United States. Malaria occurred within the United States earlier this century, and these reports lack the supporting documented changes occurring at high elevations in plants, glaciers, and isotherm shift. But these small, localized outbreaks are consistent with model projections that warmer, wetter conditions conducive to greater transmission potential can be expected at higher latitudes.

Montane changes in distribution findings are not only of academic interest. Malaria could threaten elevated urban centers such as Nairobi, Kenya. Mountain ranges that have been barriers to spread may no longer be so.

The distribution of agricultural pests (many cold-blooded stenotherms) can also shift, for they—and the pathogens some transport—also require specific temperatures and environmental conditions for survival (Dahlstein and Garcia 1989; Sutherst 1990). Temperature- and humidity-sensitive crop pests include aphids (Homopteran family Aphididae), locusts (Orthopteran family Acrididae), and whiteflies (Homopteran family Aleyrodidae). *Bemisia tabaci* whiteflies are responsible for injecting numerous *geminiviruses* (18 identified) into the leaves of bean, squash, tomato, and other staple crops in Latin America (Anderson and Morales 1993). Changes in the distribution of plant pests has implications for food security.

While distributional changes are occurring at high elevations, altered weather patterns and more extreme

events (Karl et al. 1995a,b) may be the chief characteristic of climate change on the earth’s surface; and weather extremes also contribute to disease outbreaks. Floods foster fungal growth and provide new breeding sites for mosquitoes, while droughts concentrate microorganisms and encourage aphids, locusts, whiteflies, and—when interrupted by sudden rains—spur explosions of rodent populations (Epstein and Chikwenhere 1994). Because of the strong influence of climatic factors, prediction of weather patterns based on ENSO and other climatic modes such as the North Atlantic Oscillation, integrated with regional SSTs and local topography, may prove useful for anticipating conditions conducive or vulnerable to epidemics and such “biological surprises” (Bouma et al. 1994a,b; Epstein et al. 1995; Hales et al. 1996; Bouma and Dye 1997).

5. Conclusions

There is increasing evidence of decadal-to-centennial warming at high elevations and at deep ocean depths, while many parts of the globe experience increasingly extreme weather patterns. At high elevations, the overall trends regarding glaciers, plants, insects, and temperatures show remarkable internal consistency, and there is consistency between model projections and the ongoing changes. These conclusions elicit several implications:

- Montane regions—where isotherms may first noticeably shift and where physical and biological responses may be most easily ascertained—can serve as sentinel sites to monitor climate change.
- Shifts in mountain isotherms may become evident before shifts in latitudinal isotherms are discernible.
- Physical and biological evidence consistent with decadal-to-century climate change is now present in mountain regions.
- The current and projected expansion of VBDs into the subtropics and to higher elevations warrant heightened vigilance by public health officials in montane areas and for those populations living on the fringes of regions now affected.
- Health early warning systems of climate conditions conducive to outbreaks and disease clusters may become feasible—enabling timely, environmentally sound public health interventions (e.g., immunizations, neighborhood clean-ups, *Bacillus thuringiensis* applications, and others).

Control of insect populations is central to forest, agricultural, and human health. Public health control of insect populations requires surveillance and response capability and is a function of underlying social conditions. Source reduction (elimination of breeding sites) and targeted pesticide use are key measures. Pesticide efficacy, however, is being progressively compromised by several factors: 1) increasing insect resistance, 2) direct human health concerns about food and groundwater contamination, and 3) toxicity to birds, reptiles, fish (that consume mosquito larvae), and friendly insects (e.g., lacewings and ladybugs); this diversity of predators serving to biologically control the proliferation of biting insects (Pimental et al. 1997).

Human activities are altering atmospheric chemistry and changing the earth's heat budget. Together, these chemical and physical changes—compounded by large-scale land use and land-cover changes—have begun to affect biological systems. The public and policy makers must be increasingly concerned with the biological consequences and the societal costs associated with climate change. The waste products of fossil fuel combustion have direct consequences for human and ecological health through air pollution and acid precipitation; now the aggregate of emissions appears to be destabilizing the earth's climate system and changing the conditions under which opportunistic pests and pathogens can thrive.

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