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Review

Climate change and emerging infectious diseases

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ABSTRACT – The ranges of infectious diseases and vectors are changing in altitude, along with shifts in plant communities and the retreat of alpine glaciers. Additionally, extreme weather events create conditions conducive to 'clusters' of insect-, rodent- and water-borne diseases. Accelerating climate change carries profound threats for public health and society. © 2001 Éditions scientifiques et médicales Elsevier SAS

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> Epidemics are like signposts from which the statesman of stature can read that a disturbance has occurred in the development of his nation – that not even careless politics can overlook.
> *–Dr Rudolf Virchow, 1848*

1. Background: climate change

The climate system can remain stable over millennia due to interactions and feedbacks among its basic components: the atmosphere, oceans, ice cover, biosphere and energy from the sun. Harmonics among the six orbital (so called Milankovitch) cycles (e.g., tilt, eccentricity) of the Earth about the sun have, as revealed by analyses of ice cores and other 'paleothermometers' (e.g., tree rings, coral cores), governed the oscillations of Earth's climate between ice ages and warm periods. Until the 20th century. To explain the global warming over the 20th century of close to 1 °C, according to all studies reviewed by the Intergovernmental Panel on Climate Change [1], one must invoke the heat-trapping role of greenhouse gases (carbon dioxide, oxides of nitrogen, methane and chlorinated hydrocarbons (CFCs)) accumulating in the lower atmosphere (or troposphere), out to about 10 km. Indeed, the cooling trend of the last 1 000 years has been reversed [2].

For the past 420 000 years, as measured by the Vostok ice core in Antarctica, carbon dioxide (CO_2) has been kept within an envelope of between 180 and 280 ppm in the troposphere [3]. Today, O_2 is 366 ppm and the rate of change surpasses the rates observed in ice core records [1]. Ocean and terrestrial drawing down of CO_2 have presumably played feedback roles. Today, the combustion of fossil fuels (oil, coal and natural gas) is generating carbon and the other greenhouse gases, leading to their buildup. The decline in forest cover accounts for 15–20% of the buildup [4].

Global warming is not occurring uniformly. It is occurring twice as fast as overall warming during the winter and night-time [5], a crucial driver of the biological responses; and the winter warming is occurring faster at high latitudes than near the topics [4]. In addition, heat is building up in the world ocean down to 3 km [6]. The result is a measurable change in the hydrological cycle. The oceans are warming, sea-ice and ice shelves are melting and water vapor in the atmosphere is increasing [7]. In addition, there is now measurable evidence of instability in the climate system, as extreme weather events, such as prolonged droughts and heavy rain events (> 5 cm/day), have increased in intensity and are projected to increase in frequency [8]. It is the rates of change and wide swings in weather that are of chief concern, as ice core records indicate that increased variability may be associated with rapid climate change events and changes in the ocean thermohaline circulation (Paul Meyewski, UNH, personal communication). Together, warming and more extreme weather have begun to alter marine life and the weather patterns that impact infectious diseases, their vectors and hosts.

2. Climate and infectious disease

Climate is a key determinant of health. Climate constrains the range of infectious diseases, while weather affects the timing and intensity of outbreaks [9]. A long-term warming trend is encouraging the geographic expansion of several important infections [10], while extreme weather events are spawning 'clusters' of disease outbreaks and sparking a series of 'surprises' [11, 12]. Ecological changes and economic inequities strongly influence disease patterns. But a warming and unstable climate

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is playing an ever-increasing role in driving the global emergence, resurgence and redistribution of infectious diseases [13, 14].

Since 1975, the World Health Organization [15] reports, over 30 diseases have appeared that are new to medicine. Included are AIDS, Ebola, Lyme disease, Legionnaires'disease, toxic *Escherichia coli*, a new hantavirus, and a rash of rapidly evolving antibiotic-resistant organisms. Of equal concern is the resurgence of old diseases, such as malaria and cholera. Declines in social conditions and public health programs underlie the rebound of diseases transmitted person-to-person (e.g., tuberculosis, diphtheria). The resurgence and redistribution of infections involving two or more species (mosquitoes, ticks, deer, birds, rodents and humans) reflect changing ecological and climatic conditions as well as social changes (such as suburban sprawl).

Waves of infectious diseases come in cycles. Many upsurges crest when populations overwhelm infrastructures or exhaust environmental resources, and, at times, pandemics can cascade across continents. These transitional periods can, in turn, affect the subsequent course of history [16]. The Justinian Plague emerged out of the ruins of the Roman Empire in the 6th century AD, and arrested urban life for centuries. When the plague (carried by rodents and fleas) reappeared in the repopulated and overflowing urban centers of the 14th century, it provoked protests and helped end feudal labor patterns. In *Hard Times*, Charles Dickens describes overcrowded 19th century England:

> *…of tall chimneys, out of which interminable serpents of smoke trailed themselves forever and ever, and never got uncoiled...where the piston of the steam-engine worked monotonously up and down like the head of an elephant in a state of melancholy madness…*

breeding smallpox, cholera and tuberculosis [17]. But society responded with sanitary and environmental reform, and the epidemics abated. Just how will our society respond to the current threat to our health and biological safety?

3. An integrated framework for climate and disease

All infections involve an agent (or pathogen), host(s) and the environment. Some pathogens are carried by vectors or require intermediate hosts to complete their life cycle. Climate can influence pathogens, vectors, host defenses and habitat.

Diseases carried by mosquito vectors are particularly sensitive to meteorological conditions. These relationships were described in the 1920s [18, 19] and quantified in the 1950s [20]. Excessive heat kills mosquitoes, but within their survivable range, warmer temperatures increase their reproduction and biting activity [21], and the rate at which pathogens mature within them. At 20 °C falciparum malarial protozoa take 26 days to incubate, but at 25 °C, they develop in 13 [20]. *Anopheles* mosquitoes (carriers of malaria) live only several weeks. Thus warmer temperatures permit parasites to mature in time for the mosquito to transfer the infection.

Temperature thresholds limit the geographic range of mosquitoes. Transmission of *Anopheles*-borne falciparum malaria occurs where temperatures exceed 16 °C [22]. The range of yellow fever (with a high rate of mortality) and dengue fever (characterized by severe headaches and bone pain, with mortality associated with dengue hemorrhagic fever and dengue shock syndrome), both carried by *Aedes aegypti*, is restricted by the 10 °C winter isotherm. Freezing kills *Aedes* eggs, larvae and adults. Thus, given other conditions, such as small water containers, expanding tropical conditions can enlarge the ranges and extend the season, with conditions allowing transmission.

Warm nights and warm winters favor insect survival. Fossils from the end of the last Ice Age demonstrate that rapid, poleward shifts of insects accompanied warming, especially of these minimum temperatures [23]. Insects, notably Edith's checkerspot butterflies today, are superb 'paleothermometers', outpacing the march of grasses, shrubs, trees and mammals in response to advancing frost lines [24].

In addition to the direct impacts of warming on insects, volatile weather and warming can disrupt co-evolved relationships among species that help to prevent the spread of 'nuisance' species [25].

4. Pest control: one of nature's services

Systems at all scales have self-correcting feedback mechanisms. In animal cells, errors in structural genes (mismatched base pairs) resulting from radiation or chemicals, are 'spell-checked' by proteins propagated by regulatory genes. Malignant cells that escape primary controls must confront an ensemble of instruments that compose the immune surveillance system. A suite of messengers and cells also awaits invading pathogens; some that stun them, and others, like phagocytes, which consume them.

Natural systems have also evolved a set of pheromones and functional groups (like predators, competitors and recyclers) that regulate the populations of opportunistic organisms. The diversity of processes provides resistance, resilience, and insurance, while the mosaics of habitat (stands of trees about farms that harbor birds and nectar-bearing flowers that nourish parasitic wasps) provide generalized defenses against the spread of opportunists. Against the steady background beat of habitat fragmentation, excessive use of toxins and the loss of stratospheric ozone (all components of global environmental change), climate change is fast becoming a dominant theme, disrupting relationships among predators and prey that prevent the proliferation of pests and pathogens [25].

5. Climate change and biological responses

Northern latitude ecosystems are subjected to regularly occurring seasonal changes. But prolonged extremes and wide fluctuations in weather may overwhelm ecological resilience, just as they may undermine human defenses.

Repeated winter thawing and refreezing depresses forest defenses, increasing vulnerability to pest infestations. And sequential extremes and shifting seasonal rhythms can alter synchronies among predators, competitors and prey, releasing opportunists from natural biological controls [26].

Several aspects of climate change are particularly important to the responses of biological systems. First, global warming is not uniform. Warming is occurring disproportionately at high latitudes, just above Earth's surface and during winter and night-time [5]. The Antartic Peninsula has warmed about 2 °C over the last century, while temperatures within the Arctic circle increased 5 °C [27]. Since 1950, northern hemispheric springs have been surfacing earlier, and fall appears later.

While inadequately studied in the US, warm winters have been demonstrated to facilitate overwintering, thus northern migration of the ticks that carry tick-borne encephalitis and Lyme disease [27]. Agricultural zones are shifting northward, but not as swiftly as are key pests, pathogens and weeds that, in today's climate, consume 52% of the growing and stored crops worldwide [28, 29].

An accelerated hydrological (water) cycle is demanding significant adjustments from biological systems along with ocean warming [6]. Communities of marine species have shifted [30]. A warmer atmosphere also holds more water vapor (6% for each 1 °C warming) and insulates escaping heat and enhances greenhouse warming. More evaporation also fuels more intense, tropical-like downpours, while warming and parching of Earth's surface intensifies the pressure gradients that draw in winds (e.g., winter tornadoes) and large weather systems [31–33].

Elevated humidity and lack of night-time relief during heat waves directly challenge human (and livestock) health. These conditions also favor mosquitoes.

6. Range expansion of mosquito-borne diseases

Today, one-half of the world's population is exposed to malaria on a daily basis. Deforestation, drug and pesticide resistance and inadequate public health measures have all contributed to a recent resurgence. Warming and extreme weather add new stresses. Dynamic models project that the warming accompanying the doubling of atmospheric CO_2 will increase the transmission capacity of mosquitoes some 100-fold in temperate zones, and that the area capable of sustaining transmission will grow from that containing 45% of the world's population to 60% [22, 34]; though recent statistical modeling projects less of a change [35]. Notably, all these analyses rely on average temperatures, rather than the more rapid changes in minimum temperatures being observed, and thus may underestimate the biological responses.

In addition, historical approaches to understanding the role of temperature and infectious disease have argued that the relationships do not hold for periods such as the medieval Warm Period and the Little Ice Age [36]. It is important to note, however, that the change of CO_2 and temperature (and their rates of change) over the 20th century are outside the bounds of those observed during the entire Holocene (the last 10 000 years); indeed, the previous 420 000 years [3].

Some of these projected changes may be under way. Since 1975 several VBDs have reappeared in temperate regions. Anopheline mosquitoes have long been present in North America and malaria circulated in the US earlier this century. But by the 1980s, transmission in the US was limited to California, after mosquito control programs. Since 1990, however, small outbreaks of locally transmitted malaria have occurred during hot spells in Texas, Georgia, Florida, Michigan, New Jersey, New York, and in Toronto [10, 12, 37]. Malaria has returned to South Korea, parts of southern Europe and the former Soviet Union. Moving southward, malaria has re-colonized the Indian Ocean coastal province of South Africa, while dengue fever has spread into northern Australia and Argentina [10].

These changes are consistent with projections, though one author has stressed alternative explanations for these changes [36, 38]. Land clearing, population movements and drug and pesticide resistance have all played parts. But a set of changes occurring in tropical highland regions are internally consistent, indicative of long-term warming.

7. Climate change in mountain regions

In the 19th century, European colonists sought refuge from lowland 'mal arias' by settling in the highlands of Africa. These regions are now getting warmer. Since 1970 the height at which freezing occurs (the freezing isotherm) has climbed approximately 160 m within the tropical belts, equivalent to almost 1 °C warming [39]. Local changes, such as mountainside deforestation, cannot account for this global change, for the measurements are drawn from released weather balloons and satellites.

Plants are migrating to higher elevations in the European Alps, Alaska, the US Sierra Nevada and New Zealand [40]. This is a sensitive gauge, for a plant shifting upward 500 m would have to move 300 km northward to adjust to the same degree of global warming [41].

Insects and insect-borne diseases are now being reported at high elevations in east and central Africa, Latin America and Asia. Malaria is circulating in highland urban centers, like Nairobi, and rural highland areas, like those of Papua New Guinea. *Ae. aegypti*, once limited by temperature to about 1 000 m in elevation, have recently been found at 1 100 m in Mexico and 2 200 m in the Colombia Andes [10].

These insect and botanical trends, indicative of gradual, systematic warming, have been accompanied by the hardest of data: the accelerating retreat of summit glaciers in Argentina, Peru, Alaska, Iceland, Norway, the Swiss Alps, Kenya, the Himalayas, Indonesia, Irian Jaya and New Zealand [42, 43]. Glaciers in the Peruvian Andes, retreating at 4 m annually in the 1960s and 1970s, were melting 30 m a year by the mid-1990s and 155 m per year in 2000 [44]. Many small ice fields may soon disappear, jeopardizing regional water supplies critical for human consumption, agriculture and hydropower.

Highlands (where the biological, glacial and isotherm changes are especially apparent) are sensitive sentinel sites for monitoring the long-term impacts of climate change.

8. Extreme weather events and epidemics

While warming encourages the spread of infectious diseases, extreme weather events are having the most profound impacts on public health and society. The study of variability also provides insights into the stability of the climate regime itself.

A shift in temperature norms alters the variance about the means, and high-resolution ice core records suggest that greater variance from climate norms indicates instability. Today, the enhanced hydrological cycle is changing the intensity, distribution and timing of extreme weather events [7, 8]. Over the past century droughts have become longer and bursts of intense precipitation (> 5 cm over 24 h) more frequent [31]. Large-scale weather patterns have shifted. Warming of the Eurasian land surface, for example, has apparently intensified the monsoons [45] that are strongly associated with mosquito- and water-borne diseases in India and Bangladesh. The US southwest monsoons may also have shifted, with implications for disease patterns in that region.

Extremes can be hazardous for health [46, 47]. Prolonged droughts fuel fires, releasing respiratory pollutants. Floods foster fungi, such as the house mold *Stachybotrys atra*, associated with an emerging hemorrhagic lung disease among children [48]. Floods leave mosquito-breeding sites. And floods flush pathogens, nutrients and pollutants into waterways, precipitating water-borne diseases (such as *Cryptosporidium* infection) [49].

Runoff from flooding can also trigger harmful algal blooms along coastlines that a) can be toxic to birds, mammals, fish and humans; b) generate hypoxic 'dead zones', and c) harbor pathogens, like cholera [50].

8.1. The El Niño/Southern Oscillation (ENSO)

The ENSO phenomenon is one of Earth's coupled ocean–atmospheric systems that helps to stabilize the climate system by undulating between states every 4–5 years. ENSO events are accompanied by weather anomalies that are strongly associated with disease outbreaks over time, and spatial 'clusters' of mosquito-, water- and rodent-borne illnesses [12, 46, 51, 52]. The ENSO cycle also affects the production of plant pollens, themselves directly boosted by 'CO_2 fertilization' [53], findings that warrant further investigation as a possible contributor to the dramatic rise in asthma since the 1980s.

Other climate modes contribute to regional weather patterns. The North Atlantic Oscillation is a seesaw in sea surface temperatures (SSTs) and sea level pressures that governs windstorm activity across Europe [54]. Warm SSTs in the Indian Ocean (that have bleached over 80% of regional coral reefs) also contribute to precipitation in east Africa. A warm Indian Ocean added moisture to the rains drenching the Horn of Africa in 1997/98 that spawned costly epidemics of cholera, mosquito-borne Rift Valley fever and malaria [55], and catalyzed the southern African deluge in February 2000.

Weather extremes, especially intense precipitation, have been especially punishing for developing nations, and the aftershocks ripple through economies. Hurricane Mitch, nourished by a warmed Caribbean, stalled over central America in November 1998 for 3 days, dumping precipitation that killed over 11 000 people and left over $5 billion in damages. In the aftermath, Honduras reported 30 000 cases of cholera, 30 000 cases of malaria and 1 000 cases of dengue fever [12]. The following year Venezuela suffered a similar fate, followed by malaria and dengue fever. Then, in February 2000, torrential rains and a cyclone inundated large parts of southern Africa. Floods in Mozambique killed hundreds, displaced hundreds of thousands and spread malaria, typhoid and cholera [11].

Developed nations have also begun to experience more severe and unpredictable weather patterns. Hurricane Floyd in North Carolina, in September 1999, afforded an abrupt and devastating end to an extended spring and summer drought. Prolonged droughts are also afflicting parts of Europe, while growing temperature contrasts between cold poles and warm tropics generate windstorms [53], like the twin winds that raced across the Atlantic over Christmas 1999, destroying France's forests. Extreme weather events are having long-lasting ecological and economic impacts on a growing cohort of nations, affecting infrastructure, trade, travel and tourism.

The 1990s was a decade of extremes, each year marked by El Niño or La Niña (cold) conditions [7, 56]. Since 1976 the pace, intensity and duration of ENSO events have quickened, and extremes have become more extreme. Accumulating heat in the oceans certainly intensifies weather anomalies; it may be modifying the natural ENSO mode itself. Understanding how the various climate modes are influenced by human activities, and how the modes interact, is a central scientific challenge, and the results will inform multiple sectors of society. Disasters, such as the $10 billion European windstorms and Hurricane Floyd, suggest that the costs of climate change will be borne by all [57].

9. Sequential extremes and surprises

Extremes followed by subsequent extremes are particularly destabilizing for biological and physical systems [58]. Light rains (providing kindling) followed by prolonged droughts spark wildfires, and warm winter rains followed by cold snaps beget ice storms. Warm winters also create snowpack instability, setting the stage for avalanches, then triggered by heavy snowfall, freezing rain or strong winds. Krabill et al. reported that 'polar researchers suspect that melting at the base of the Greenland ice sheet may be sculpting fault lines that could diminish its stability. Shrinking of Earth's ice cover (cryosphere) has implications for water (agriculture, hydropower, and for albedo (reflectivity) that influences climate stability' [59].

The US Institute of Medicine report [60] on emerging infectious diseases warned that conditions in the US were ripe for the emergence of a new disease. What they did not foresee was that climate was to play a significant role in the emergence of two of this decade's North American surprises: the hantavirus pulmonary syndrome (HPS) in the southwest and the West Nile virus (WNV) in New York City.

9.1. HPS, US southwest 1993

Prolonged drought in California and the US southwest from 1987 to 1992 reportadly reduced predators of rodents: raptors (owls, eagles, prairie falcons, red-tailed hawks and kestrels), along with coyotes and snakes. When drought yielded to intense rains in the winter of 1993 (the year of the Mississippi floods), grasshoppers and piñon nuts on which rodents feed flourished. The effect was synergistic, boosting mouse populations more than tenfold, and leading to the emergence of a 'new', lethal, rodent-borne viral disease: HPS. The virus may have been present, but dormant. Alterations in food supplies, predation pressure and habitat provoked by sequential extremes multiplied the rodent reservoir hosts and amplified viral transmission [61–63]. Krebs et al. remarked 'controlled experiments with rabbits demonstrate such synergies in population dynamics. Exclusion of predators with protective cages doubles their populations. With extra food, hare density triples. With both interventions, populations increase 11-fold' [64]. By summer's end (1993), predators returned (indicating retained ecosystem resilience) and the HPS outbreak abated. Subsequent episodes of HPS in the US have been limited, perhaps aided by early warnings. But HPS has appeared in Latin America, and there is evidence for person-to-person transmission.

9.2. WNV, New York City 1999

In September 1999 at least 59 people fell ill and seven died from mosquito-borne encephalitis in the New York region. How WNV was introduced into the US remains a mystery. But the conditions favoring diseases that cycle among birds, urban mosquitoes and humans are apparently warm winters followed by summer droughts [65]. A disease with similar ecological dynamics, St Louis encephalitis, first occurred in the US during the 'dust bowl' in 1933, and outbreaks up to 1974 were associated with droughts (unpublished data). For WNV, the 1996 Romanian and 2000 Israeli outbreaks were both associated with droughts and heatwaves (unpublished data). Climatic changes projected for regions in the US include warmer winters and more hot, dry summers [8].

How drought and heat affect the cycle of such diseases is a matter for conjecture. Mild winters and dry summers favor breeding of city-dwelling mosquitoes (*Culex pipiens*), while predators of mosquitoes (amphibians and dragonflies) can decline with drought. Birds may congregate around shrinking water sites, encouraging viral circulation among birds and mosquitoes, while heat accelerates viral maturation. In New York, torrential rains in late August unleashed a crop of *Aedes* spp. mosquitoes that may have provided an additional 'bridge' vector to humans. (The same downpour on August 26 (an extreme weather event) drove farm waste into an underground aquifer supplying an upstate Washington County Fair. Over 1000 became ill with toxic *E. coli*, many suffered from hemolytic uremic syndrome and several children died.)

WNV may have recently evolved in strength, as it took an unusual toll on birds in New York. Alternatively, the North American avians were sensitive, as they were immunologically naïve. But the unexpected outbreak of a mosquito-borne disease in New York City also serves as a reminder that pathogens evolving or emerging anywhere on the globe, and the social and environmental conditions that contribute to those changes, can affect populations elsewhere in the world.

10. Discontinuities

Climate change may not prove to be a linear process [66]. Polar ice is thinning [67] and Greenland ice is retreating [68], and since 1976 several small step-wise adjustments appear to have reset the climate system [69]. In 1976 Pacific Ocean temperatures warmed significantly, still further in 1990, and cooled in 2000. The intensity of ENSO has surpassed the intensity it had 130 000 years ago during the previous warm interglacial period [70]. Cold upwelling in the Pacific in 2000 could portend a multidecadal correction that stores accumulating heat at intermediate ocean layers. Meanwhile, two decades of warming in the North Atlantic have melted Arctic ice, plausibly contributing to a cold tongue from Labrador across to Europe and enhancing the Labrador Current that hugs the US east coast. Such 'paradoxical cooling' from warming and ice melting could alter projections for climate, weather and disease for northern Europe and the northeast of the US.

Winter is a blessing for public health in temperate zones, and deep cold snaps could freeze *C. pipiens* in New York City sewers, for example, reducing the risk of WNV during those years. Thus the greatest threat of climate change lies not with year-to-year fluctuations, but with the potential for a more significant abrupt change that would alter the life support systems underlying our overall health and well-being.

11. Conclusions

The resurgence of infectious diseases among humans, wildlife, livestock [71], crops [29], forests and marine life [72] in the final quarter of the 20th century may be viewed as a primary symptom integrating global environmental and social change. Moreover, contemporaneous changes in greenhouse gas concentrations, ozone levels, the cryosphere, ocean temperatures, land use and land cover challenge the stability of our epoch, the Holocene, a remarkable 10 000-year period that has followed the retreat of ice sheets from temperate zones. The impacts of deforestation and climatic volatility are a particularly potent combination creating conditions conducive to disease emergence and spread. Given the rate of changes in local and global conditions, we may expect more synergies and new surprises.

Warming may herald some positive health outcomes. High temperatures in some regions may reduce snails, the intermediate hosts for schistosomiasis. Winter mortality in the Northern Hemisphere from respiratory disease may decline. But the hazards associated with warming and wide swings in weather, such as more winter precipitation falling as rain, followed by cold snaps, may overshadow the potential health benefits.

The aggregate of air pollution from burning fossil fuels and felling forests provides a relentless destabilizing force on the Earth's heat budget. Examining the full life-cycle of fossil fuels also exposes layers of injury. Environmental damage from their mining, refining and transport must be added to direct health effects of air pollution and acid precipitation. Returning CO_2 to the atmosphere through their combustion reverses the very biological process by which plants drew down atmospheric carbon and generated oxygen and ozone, helping to cool and shield the planet sufficiently to support animal life.

12. Next steps

Solutions may be divided into three levels. First-order solutions to the resurgence of infectious disease include improved surveillance and response capability, drug and vaccine development, and greater provision of clinical care and public health services.

Second is improved prediction. Integrating health surveillance into long-term terrestrial and marine monitoring programs, 'ecological epidemiology', can benefit from advances in satellite imaging and climate forecasts that complement fieldwork. Health early warning systems based on the integrated mapping of conditions, consequences and costs can facilitate timely, environmentally friendly public health interventions and inform policies. Anticipating the health risks posed by the extreme conditions facing the US east coast in the summer of 1999 could have a) enhanced mosquito surveillance; b) heightened sensitivity to bird mortalities (that began in early August); and c) allowed treatment of mosquito breeding sites, obviating large-scale spraying of pesticides.

The third level is prevention, and rests upon environmental and energy policies. Restoration of forests and wetlands ('nature's sponges and kidneys') is necessary to reduce vulnerabilities to climate, changing or not. Population stabilization is also necessary, but World Bank figures demonstrate that that is a function of income distribution. The underlying question, then, is not whether to develop, but how?

Developing clean energy sources and improving energy efficiency are the first steps. Providing basic public health infrastructure (sanitation, housing, food, refrigeration and cooking) requires energy. Clean energy is needed to pump and purify water and desalinate water for irrigation from the rising seas. Meeting energy needs with non-polluting sources can be the first step towards the rational use of Earth's finite resources and a reduction in the generation of wastes.

Addressing all these levels will require resources. Just as funds for technology development were necessary to settle the Montreal Protocol on ozone-depleting chemicals, substantial financial incentives are now needed to propel clean energy technologies into the global market. International funds are also needed to support common resources, like fisheries, and for vaccines and medications for diseases lacking lucrative global markets. The HIV/AIDS fund sets an exciting precedent.

Human and ecological systems can heal after time-limited assaults, and the climate system can also be restabilized, but only if the tempo of destabilizing factors is reduced. The Intergovernmental Panel on Climate Change calculates that stabilizing atmospheric concentrations of greenhouse gases requires a 60% reduction in emissions.

World views can shift abruptly. Just as we may be underestimating the true costs of 'business-as-usual', we may be vastly underestimating the economic opportunities afforded by the energy transition. A distributed system of non-polluting energy sources can help reverse the mounting environmental assaults on public health and can provide the scaffolding on which to build clean, equitable and healthy development in the century before us.

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