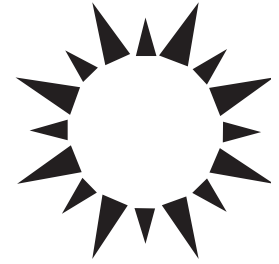


Climate Change and Public Health: Emerging Infectious Diseases



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Glossary

climate change The heating of the inner atmosphere, oceans, and land surfaces of the earth. The warming is associated with more intense extreme weather events and the altered timing, intensity, and distribution of precipitation.

emerging infectious diseases Those diseases new to medicine since 1976, plus old diseases undergoing resurgence and redistribution.

Climate restricts the range of infectious diseases, whereas weather affects the timing and intensity of outbreaks. Climate change scenarios project a change in the distribution of infectious diseases with warming and changes in outbreaks associated with weather extremes, such as flooding and droughts. The hypothesis of this article is that the ranges of several key diseases or their vectors are already changing in altitude due to warming, along with shifts in plant communities and the retreat of alpine glaciers. In addition, more intense and costly weather events create conditions conducive to outbreaks of infectious diseases, as heavy rains leave insect

breeding sites, drive rodents from burrows, and contaminate clean water systems. Conversely, drought can spread fungal spores and spark fires (and associated respiratory disease). In addition, sequences of extremes can destabilize predator/prey interactions, leading to population explosions of opportunistic, disease-carrying organisms. Advances in climate forecasting and health early warning systems may prove helpful in catalyzing timely, environmentally friendly public health interventions. If climate change continues to be associated with more frequent and volatile and severe weather events, we have begun to see the profound consequences that climate change can have for public health and the international economy.

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.

—Rudolf Virchow (1848)

1. BACKGROUND ON 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 (Milankovitch) cycles (e.g., tilt and eccentricity) of the earth about the sun, as revealed by analyses of ice cores and other “paleothermometers” (e.g., tree rings and coral cores), have governed the oscillations of Earth's climate between ice ages and warm periods until the 20th

century. To explain the global warming during the 20th century of approximately 1°C, according to all studies reviewed by the Intergovernmental Panel on Climate Change, one must invoke the role of heat-trapping greenhouse gases (GHGs), primarily carbon dioxide (CO₂), oxides of nitrogen, methane, and chlorinated hydrocarbons. These gases have been steadily accumulating in the lower atmosphere (or troposphere), out to about 10 km, and have altered the heat budget of the atmosphere, the world ocean, land surfaces, and the cryosphere (ice cover).

For the past 420,000 years, as measured by the Vostok ice core in Antarctica, CO₂ has stayed within an envelope of between 180 and 280 parts per million (ppm) in the troposphere. Today, the level of CO₂ is 370 ppm and the rate of change during the past century surpassed that observed in ice core records. Ocean and terrestrial sinks for CO₂ have presumably played feedback roles throughout millennia. Today, the combustion of fossil fuels (oil, coal, and natural gas) is generating CO₂ and other GHGs, and the decline in sinks, primarily forest cover, accounts for 15–20% of the buildup.

1.1 Climate Stability

As important as the warming of the globe is to biological systems and human health, the effects of the increased extreme and anomalous weather that accompanies the excess energy in the system may be even more profound. As the rate of warming accelerated after the mid-1970s, anomalies and wide swings away from norms increased, suggesting that feedback, corrective mechanisms in the climate system are being overwhelmed. Indeed, increased variability may presage transitions: Ice core records from the end of the last ice age (~10,000 years ago) indicate that increased variability was associated with rapid change in state.

Further evidence for instability comes from the world ocean. Although the ocean has warmed overall in the past century, a region of the North Atlantic has cooled in the past several decades. Several aspects of global warming are apparently contributing.

Recent warming in the Northern Hemisphere has melted much North Polar ice. Since the 1970s, the floating North Polar ice cap has thinned by almost half. A second source of cold fresh water comes from Greenland, where continental ice is melting at higher elevations each year. Some meltwater is trickling down through crevasses, lubricating the base, accelerating ice “rivers,” and increasing the potential for sudden slippage. A third source of cold fresh water is

rain at high latitudes. Overall ocean warming speeds up the water cycle, increasing evaporation. The warmed atmosphere can also hold and transport more water vapor from low to high latitudes. Water falling over land is enhancing discharge from five major Siberian rivers into the Arctic, and water falling directly over the ocean adds more fresh water to the surface.

The cold, freshened waters of the North Atlantic accelerate transatlantic winds, and this may be one factor driving frigid fronts down the eastern U.S. seaboard and across to Europe and Asia in the winters of 2002–2004. The North Atlantic is also where deep-water formation drives thermohaline circulation, the “ocean conveyor belt,” considered key to climate stabilization. In the past few years, the northern North Atlantic has freshened, and since the 1950s the deep overflow between Iceland and Scotland has slowed by 20%.

The ice, pollen, and marine fossils reveal that cold reversals have interrupted warming trends in the past. The North Atlantic Ocean can freshen to a point at which the North Atlantic deep-water pump—driven by sinking cold, salty water that is in turn replaced by warm Gulf Stream waters—can suddenly slow. Approximately 13,000 years ago, when the world was emerging from the Last Glacial Maximum and continental ice sheets were thawing, the Gulf Stream abruptly changed course and shot straight across to France. The Northern Hemisphere refroze—for the next 1300 years—before temperatures increased again, in just several years, warming the world to its present state.

Calculations (of orbital cycles) indicate that our hospitable climate regime was not likely to end due to natural causes any time soon. However, the recent buildup of heat-trapping greenhouse gases is forcing the climate system in new ways and into uncharted seas.

1.2 Hydrological Cycle

Warming is also accelerating the hydrological (water) cycle. As heat builds up in the deep ocean, down to 3 km, more water evaporates and sea ice melts. During the past century, droughts have lasted longer and heavy rainfall events (defined as >5 cm/day) have become more frequent. Enhanced evapotranspiration dries out soils in some regions, whereas the warmer atmosphere holds more water vapor, fueling more intense, tropical-like downpours elsewhere. Prolonged droughts and intense

precipitation have been especially punishing for developing nations.

Global warming is not occurring uniformly. It is occurring twice as fast as overall warming during the winter and nighttime, a crucial factor in the biological responses, and the winter warming is occurring faster at high latitudes than near the tropics. These changes may be due to greater evaporation and the increased humidity in the troposphere because water vapor is a natural greenhouse gas and can account for up to two-thirds of all the heat trapped in the troposphere. Warming nights and winters along with the intensification of extreme weather events have begun to alter weather patterns that impact the ecological systems essential for regulating the vectors, hosts, and reservoirs of infectious diseases.

Other climate-related health concerns include temperature and mortality, especially the role of increased variability in heat and cold mortality; synergies between climate change and air pollution, including CO₂ fertilization of ragweed and excess pollen production, asthma, and allergies; travel hazards associated with unstable and erratic winter weather; and genetic shifts in arthropods and rodents induced by warming. This article focuses on climate change and emerging infectious diseases.

2. CLIMATE AND INFECTIOUS DISEASE

Climate is a key determinant of health. Climate constrains the range of infectious diseases, whereas weather affects the timing and intensity of outbreaks. A long-term warming trend is encouraging the geographic expansion of several important infections, whereas extreme weather events are spawning “clusters” of disease outbreaks and a series of surprises. Ecological changes and economic inequities strongly influence disease patterns. However, a warming and unstable climate is playing an ever-increasing role in driving the global emergence, resurgence, and redistribution of infectious diseases.

The World Health Organization reports that since 1976, more than 30 diseases have appeared that are new to medicine, including HIV/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 and 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 (e.g., suburban sprawl).

Waves of infectious diseases occur in cycles. Many upsurges crest when populations overwhelm infrastructures or exhaust environmental resources, and sometimes pandemics can cascade across continents. Pandemics, in turn, can affect the subsequent course of history. 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 another transitional period in the 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.

These conditions bred smallpox, cholera, and tuberculosis. However, society responded with sanitary and environmental reform, and the epidemics abated. How will our society respond to the current threat to our health and biological safety?

2.1 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 and quantified in the 1950s. Excessive heat kills mosquitoes. However, within their survivable range, warmer temperatures increase their reproduction and biting activity 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 days. *Anopheline* mosquitoes, which are 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 *Anopheline*-borne falciparum malaria occurs where temperatures exceed 16°C. 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) are both carried by *Aedes aegypti*, which 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 increase 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 winter temperatures. 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.

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.

3. 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 comprise the immune surveillance system. A suite of messengers and cells also awaits invading pathogens—some that stun them, and others, such as phagocytes, that consume them.

Natural systems have also evolved a set of pheromones and functional groups (e.g., predators, competitors, and recyclers) that regulate the populations of opportunistic organisms. The diversity of processes provides resistance, resilience, and insurance, whereas the mosaics of habitat—stands of trees near 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 be-

coming a dominant theme, disrupting relationships among predators and prey that prevent the proliferation of pests and pathogens.

4. CLIMATE CHANGE AND BIOLOGICAL RESPONSES

Northern latitude ecosystems are subjected to regularly occurring seasonal changes. However, prolonged extremes and wide fluctuations in weather may overwhelm ecological resilience, just as they may undermine human defenses. Summer droughts depress forest defenses, increasing vulnerability to pest infestations. Also, sequential extremes and shifting seasonal rhythms can alter synchronies among predators, competitors, and prey, releasing opportunists from natural biological controls.

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, above Earth's surface and during winter and nighttime. Areas of Antarctica, for example, have already warmed over 1°C this century, and the temperatures within the Arctic Circle have warmed 5.5°C in the past 30 years. Since 1950, the Northern Hemispheric spring has occurred earlier and fall later.

Although inadequately studied in the United States, warm winters have been demonstrated to facilitate overwintering and thus northern migration of the ticks that carry tick-borne encephalitis and Lyme disease. 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.

An accelerated hydrological cycle—ocean warming, sea ice melting, and rising atmospheric water vapor—is demanding significant adjustments from biological systems. Communities of marine species have shifted. A warmer atmosphere also holds more water vapor (for each 1°C warming 6%), insulates escaping heat, and enhances greenhouse warming. Warming and parching of Earth's surface intensifies the pressure gradients that draw in winds (e.g., winter tornadoes) and large weather systems.

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

4.1 Range Expansion of Mosquito-Borne Diseases

Today, half of the world's population is exposed to malaria on a daily basis. Deforestation, drug resistance, and inadequate public health measures have all contributed to the recent resurgence. Warming and extreme weather add new stresses. Dynamic models project that the warming accompanying the doubling of atmospheric CO₂ will increase the transmission capacity of mosquitoes in temperate zones, and that the area capable of sustaining transmission will increase from that containing 45% of to world's population to that containing 60%, although recent statistical modeling projects less of a change. 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. It is important to note, however, that the changes in CO₂ and temperature, and their rates of change, during the 20th century are outside the bounds of those observed during the entire Holocene (the past 10,000 years).

Some of these projected changes may be under way. Since 1976, several vector-borne diseases (VBDs) have reappeared in temperate regions. *Anopheline* mosquitoes have long been present in North America and malaria circulated in the United States in the early 20th century. However, by the 1980s, transmission was limited to California after mosquito control programs were instituted. Since 1990, small outbreaks of locally transmitted malaria have occurred during hot spells in Texas, Georgia, Florida, Michigan, New Jersey, New York, and Toronto. Malaria has returned to South Korea, areas of southern Europe, and the former Soviet Union. Malaria has recolonized the Indian Ocean coastal province of South Africa, and dengue fever has spread southward into northern Australia and Argentina.

These changes are consistent with climate projections, although land clearing, population movements, and drug and pesticide resistance for malaria control have all played parts. However, a set of changes occurring in tropical highland regions are internally consistent and indicative of long-term warming.

4.2 Climate Change in Montane 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 increased approximately 160 m within the tropical belts, equivalent to almost 1°C warming. These measurements are drawn from released weather balloons and satellites.

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

Insects and insect-borne diseases are being reported at high elevations in eastern and central Africa, Latin America, and Asia. Malaria is circulating in highland urban centers, such as Nairobi, and rural highland areas, such as those of Papua New Guinea. *Aedes aegypti*, once limited by temperature to approximately 1000 m in elevation, has recently been found at 1700 m in Mexico and 2200 m in the Colombian Andes.

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. Glaciers in the Peruvian Andes, which retreated 4 m annually in the 1960s and 1970s, were melting 30 m per year by the mid-1990s and 155 m per year by 2000. Many small ice fields may soon disappear, jeopardizing regional water supplies critical for human consumption, agriculture, and hydro-power.

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

4.3 Extreme Weather Events and Epidemics

Although 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.

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 sensitivity to rapid change. Today, the enhanced hydrological cycle is changing the intensity, distribution, and timing of extreme weather events. Large-scale weather patterns have shifted. Warming of the Eurasian land surface, for example, has apparently intensified the monsoons that are strongly associated with mosquito- and water-borne diseases in India and Bangladesh. The U.S. southwest monsoons may also have shifted, with implications for disease patterns in that region.

Extremes can be hazardous for health. Prolonged droughts fuel fires, releasing respiratory pollutants. Floods foster fungi, such as the house mold *Stachybotrys atra*, which may be associated with an emerging hemorrhagic lung disease among children. Floods leave mosquito-breeding sites and also flush pathogens, nutrients, and pollutants into waterways, precipitating water-borne diseases (e.g., *Cryptosporidium*).

Runoff of nutrients from flooding can also trigger harmful algal blooms along coastlines that can be toxic to birds, mammals, fish, and humans; generate hypoxic “dead zones”; and harbor pathogens such as cholera.

4.4 The El Niño/Southern Oscillation

The El Niño/Southern Oscillation (ENSO) is one of Earth’s coupled ocean–atmospheric systems that apparently helps to stabilize the climate system by undulating between states every 4 or 5 years. ENSO events are accompanied by weather anomalies that are strongly associated with disease outbreaks over time and with spatial clusters of mosquito-, water-, and rodent-borne illnesses. The ENSO cycle also affects the production of plant pollens, which are directly boosted by CO₂ fertilization, a finding that warrants further investigation as a possible contributor to the dramatic increase 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. Warm SSTs in the Indian Ocean (that have caused bleaching of more than 80% of regional coral reefs) also contribute to precipitation in eastern Africa. A warm Indian Ocean added moisture to the rains drenching the Horn of Africa in 1997–1998 that spawned costly epidemics of cholera, mosquito-borne Rift Valley fever, and malaria, and warm

SSTs catalyzed the southern African deluge in February 2000.

Weather extremes, especially intense precipitation, have been especially severe 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 more than 11,000 people and caused more than \$5 billion in damages. In the aftermath, Honduras reported 30,000 cases of cholera, 30,000 cases of malaria, and 1000 cases of dengue fever. The following year, Venezuela suffered a similar fate, followed by malaria and dengue fever. In February 2000, torrential rains and a cyclone inundated large areas of southern Africa. Floods in Mozambique killed hundreds, displaced hundreds of thousands, and spread malaria, typhoid, and cholera.

Developed nations have also begun to experience more severe and unpredictable weather patterns. In September 1999, Hurricane Floyd in North Carolina afforded an abrupt and devastating end to an extended summer drought. Prolonged droughts and heat waves are also afflicting areas of Europe. In the summer of 2003, five European nations experienced about 35,000 heat-associated deaths, plus wildfires and extensive crop failures. 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. After 1976, the pace, intensity, and duration of ENSO events quickened, and extremes became more extreme. Accumulating heat in the oceans intensifies weather anomalies; it may be modifying the natural ENSO mode. 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 heat waves and Hurricane Floyd suggest that the costs of climate change will be borne by all.

5. SEQUENTIAL EXTREMES AND SURPRISES

5.1 Hantavirus Pulmonary Syndrome

Extremes followed by subsequent extremes are particularly destabilizing for biological and physical

systems. Light rains followed by prolonged droughts can lead to wildfires, and warm winter rains followed by cold snaps beget ice storms. Warm winters also create snowpack instability, setting the stage for avalanches, which are triggered by heavy snowfall, freezing rain, or strong winds.

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.

The U.S. Institute of Medicine report of 1992 on emerging infectious diseases warned that conditions in the United States were ripe for the emergence of a new disease. What it did not foresee was that climate was to play a significant role in the emergence and spread of two diseases in North America: the hantavirus pulmonary syndrome in the Southwest and the West Nile virus in New York City.

5.1.1 Hantavirus Pulmonary Syndrome, U.S. Southwest, 1993

Prolonged drought in California and the U.S. southwest from 1987 to 1992 reportedly reduced predators of rodents: raptors (owls, eagles, prairie falcons, red-tailed hawks, and kestrels), coyotes, and snakes. When drought yielded to intense rains in 1993 (the year of the Mississippi floods), grasshoppers and piñon nuts on which rodents feed flourished. The effect was synergistic, boosting mice populations more than 10-fold, leading to the emergence of a "new," lethal, rodent-borne viral disease: the hantavirus pulmonary syndrome (HPS). The virus may have already 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.

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.

By summer's end, predators apparently returned (indicating retained ecosystem resilience) and the rodent populations and disease outbreak abated. Subsequent episodes of HPS in the United States have been limited, perhaps aided by early warnings. However, HPS has appeared in Latin America, and there is evidence of person-to-person transmission.

6. CASE STUDY: WEST NILE VIRUS

West Nile virus (WNV) was first reported in Uganda in 1937. WNV is a zoonosis, with "spillover" to humans, which also poses significant risks for wildlife, zoo, and domestic animal populations. Although it is not known how WNV entered the Western Hemisphere in 1999, anomalous weather conditions may have helped amplify this *Flavivirus* that circulates among urban mosquitoes, birds, and mammals. Analysis of weather patterns coincident with a series of U.S. urban outbreaks of St. Louis encephalitis (SLE) (a disease with a similar life cycle) and four recent large outbreaks of WNV revealed that drought was a common feature. *Culex pipiens*, the primary mosquito vector (carrier) for WNV, thrives in city storm drains and catch basins, especially in the organically rich water that forms during drought and the accompanying warm temperatures. Because the potential risks from pesticides for disease control must be weighed against the health risks of the disease, an early warning system of conditions conducive to amplification of the enzootic cycle could help initiate timely preventive measures and potentially limit chemical interventions.

6.1 Background on WNV

WNV entered the Western Hemisphere in 1999, possibly via migratory or imported birds from Europe. Although the precise means of introduction is not known, experience with a similar virus, SLE, as well as the European outbreaks of WNV during the 1990s suggests that certain climatic conditions are conducive to outbreaks of this disease. Evidence suggests that mild winters, coupled with prolonged droughts and heat waves, amplify WNV and SLE, which cycle among urban mosquitoes (*Culex pipiens*), birds, and humans.

SLE and WNV are transmitted by mosquitoes to birds and other animals, with occasional spillover to humans. *Culex pipiens* typically breeds in organically rich standing water in city drains and catch basins as well as unused pools and tires. During a drought, these pools become even richer in the organic material that *Culex* needs to thrive. Excessive rainfall flushes the drains and dilutes the pools. Drought conditions may also lead to a decline in the number of mosquito predators, such as amphibians and dragonflies, and encourage birds to congregate around shrinking water sites, where the virus can circulate more easily. In addition, high temperatures accelerate

the extrinsic incubation period (period of maturation) of viruses (and parasites) within mosquito carriers. Thus, warm temperatures enhance the potential for transmission and dissemination. Together, these factors increase the possibility that infectious virus levels will build up in birds and mosquitoes living in close proximity to human beings.

6.2 Outbreaks of St. Louis Encephalitis in the United States

SLE first emerged in the city of St. Louis in 1933, during the dust bowl era. Since 1933, there have been 24 urban outbreaks of SLE in the United States. SLE as an appropriate surrogate for study because of its similarity to WNV and because of the significant number of SLE outbreaks in the United States, along with accurate weather data (i.e., the Palmer Severity Drought Index [PSDI], a measure of dryness that is a function of precipitation and soil moisture compared with 30 years of data in the same location). The PSDI ranges from -4 (dry) to $+4$ (wet). From 1933 to the mid-1970s, 10 of the 12 urban SLE outbreaks—regionally clustered in Kentucky, Colorado, Texas, Indiana, Tennessee, and Illinois—were associated with 2 months of drought. (One of the remaining outbreaks was associated with 1 month of drought.) After the mid-1970s, the relationship shifted and outbreaks were associated with anomalous conditions that included droughts and heavy rains.

Note that outbreaks of SLE during the 1974–1976 period and after show a variable pattern in relation to weather. Once established in a region, summer rains may boost populations of *Aedes japonicus* and other *Aedes* spp. that function as “bridge vectors,” efficiently carrying virus from birds to humans. The roles of “maintenance” (primarily bird-biting mosquitoes) and bridge vectors in WNV transmission are under study.

6.3 Outbreaks of WNV

6.3.1 Romania, 1996

A significant European outbreak of WNV occurred in 1996 in Romania, in the Danube Valley and in Bucharest. This episode, with hundreds experiencing neurological disease and 17 fatalities, occurred between July and October and coincided with a prolonged drought (May–October) and excessive heat (May–July). Human cases in Bucharest were concentrated in blockhouses situated over an aging

sewage system in which *C. pipiens* were breeding in abundance.

6.3.2 Russia, 1999

A large outbreak of WNV occurred in Russia in the summer of 1999 following a drought. Hospitals in the Volgograd region admitted 826 patients; 84 had meningoencephalitis, of which 40 died.

6.3.3 United States, 1999

In the spring and summer of 1999, a severe drought (following a mild winter) affected the northeastern and mid-Atlantic states. The prolonged drought culminated in a 3-week July heat wave that enveloped the Northeast. Then the pendulum swung in the opposite direction, bringing torrential rains at the end of August (and, later, Hurricane Floyd to the mid-Atlantic states). *Culex* spp. thrived in the drought months; *Aedes* spp. bred in the late summer floodwaters. In the New York outbreak, 7 people died, and, of the 62 people who suffered neurological symptoms and survived, the majority reported chronic disabilities, such as extreme muscle weakness and fatigue.

6.3.4 Israel, 2000

WNV was first reported in Israel in 1951, and sporadic outbreaks followed. Israel, a major stopover for migrating birds, usually receives little precipitation from May to October. In 2000, the region was especially dry as drought conditions prevailed across southern Europe and the Middle East, from Spain to Afghanistan. Between August 1 and October 31, 2000, 417 cases of serologically confirmed WNV were diagnosed in Israel, and there were 35 deaths. *Culex pipiens* was identified as a vector.

6.3.5 United States, 2002

In 2002, much of the western and midwestern United States experienced a severe spring and summer drought. Lack of snowpack in the Rockies (warming winters leading to more winter precipitation falling as rain) contributed. Forest fires burned more than 7.3 million acres, and haze and respiratory disease affected several Colorado cities. There was also an explosion of WNV cases, with human or animal WNV being documented in 44 states and the District of Columbia, reaching to California. Drought conditions were present in June in Louisiana, the first epicenter of WNV in 2002. Widespread drought conditions and heat waves may have amplified WNV and contributed to its rapid spread throughout the continental United States.

(Health officials have also become convinced that WNV can be transmitted via organ transplant and blood transfusion.)

Of greatest concern, however, WNV spread to 230 species of animals, including 138 species of birds and 37 species of mosquitoes. Not all animals fall ill from WNV, but the list of hosts and reservoirs includes dogs, cats, squirrels, bats, chipmunks, skunks, rabbits, and reptiles. Raptors (e.g., owls and kestrels) have been particularly affected; WNV likely caused thousands of birds of prey to die in Ohio and other states in July 2002. Some zoo animals have died.

Note that the population impacts on wildlife and biodiversity have not been adequately evaluated. The impacts of the decline in birds of prey could ripple through ecological systems and food chains and could contribute to the emergence of disease.

Declines in raptors could have dramatic consequences for human health. These birds of prey are our guardians because they prey on rodents and keep their numbers in check. When rodent populations explode—when floods follow droughts, forests are clear-cut, or diseases affect predators—their legions can become prolific transporters of pathogens, including Lyme disease, leptospirosis, plague, hantaviruses and arenaviruses such as Lassa fever and Guaranito, Junin, Machupo, and Sabia, associated with severe hemorrhagic fevers in humans.

As of March 12, 2003, the Centers for Disease Control and Prevention reported the following for 2002:

Laboratory confirmed human cases nationally: 4156
WNV-related deaths: 284
Most deaths: Illinois (64), Michigan (51), Ohio (31),
and Louisiana (25)

There were also 14,045 equine cases in 38 states reported to the U.S. Department of Agriculture APHIS by state health officials as of November 26, 2002. WNV has been associated with illness and death in several other mammal species, including squirrel, wolf, and dog in Illinois and mountain goat and sheep. The largest number of equine cases was reported in Nebraska. Because of the bird and mammal reservoirs for WNV, there is the potential for outbreaks in all eastern and Gulf States and into Canada in the future.

6.3.6 United States, 2003

In the summer of 2003, cases of WNV concentrated in Colorado, the Dakotas, Nebraska, Texas, and Wyoming—areas that experienced prolonged spring drought (and extensive summer wildfires) in association with anomalous conditions in the Pacific Ocean.

The eastern part of the United States (where a cold, snowy winter occurred in association with the North Atlantic freshening and North Atlantic High along with continued warming of tropical waters) experienced a relatively calm summer/fall in relation to WNV. (Both the Pacific and the Atlantic Oceans were in anomalous states beginning in the late 1990s. The state of the Pacific created perfect conditions for drought in many areas of the world.)

6.4 Public Health Implications

Multimonth drought, especially in spring and early summer, was found to be associated with urban SLE outbreaks from its initial appearance in 1933 through 1973 and with recent severe urban outbreaks of WNV in Europe and the United States. Each new outbreak requires introduction or reintroduction of the virus, primarily via birds or wildlife, so there have been seasons without SLE outbreaks despite multimonth drought. Spread of WNV and sporadic cases may occur, even in the absence of conditions amplifying the enzootic cycling. In Bayesian parlance, drought increases the “prior probability” of a significant outbreak once the virus becomes established in a region. Other factors, such as late summer rains that increase populations of bridge vectors, may affect transmission dynamics.

Further investigation and modeling are needed to determine the role of meteorological factors and identify reservoirs, overwintering patterns, and the susceptibility of different species associated with WNV. The migration path of many eastern U.S. birds extends from Canada across the Gulf of Mexico to South America, and WNV has spread to Mexico, Central America, and the Caribbean.

Factors other than weather and climate contribute to outbreaks of these two diseases. Antiquated urban drainage systems leave more fetid pools in which mosquitoes can breed, abandoned tires and swimming pools are ideal breeding sites, and stagnant rivers and streams do not adequately support healthy fish populations to consume mosquito larvae. Such environmental vulnerabilities present opportunities for environmentally based public health interventions following early warnings of conducive meteorological conditions.

State plans to prevent the spread of and contain WNV have three components:

1. Mosquito surveillance and monitoring of dead birds

2. Source (breeding site) reduction through larviciding (*Bacillus sphaericus* and Altocid or methoprene) and neighborhood cleanups

3. Pesticide (synthetic pyrethrins) spraying, when deemed necessary.

The information covering predisposing climatic conditions and predictions of them may be most applicable for areas that have not yet experienced WNV but lie in the flyway from Canada to the Gulf of Mexico. Projections of droughts (e.g., for northeast Brazil during an El Niño event) could help focus attention on these areas, enhancing surveillance efforts (including active bird surveillance), public communication, and environmentally friendly, public health interventions. They may also help set the stage for earlier chemical interventions once circulating virus is detected.

Finally, in terms of the public perception and concerns regarding the risks of chemical interventions, understanding the links of WNV to climatic factors and mobilizing public agencies, such as water and sewage departments, to address a public health threat may prove helpful in garnering public support for the combined set of activities needed to protect public health.

The WNV may have changed because it took an unusually high toll on birds in the United States. Alternatively, North American birds were sensitive because they were immunologically naive. However, the unexpected outbreak of a mosquito-borne disease in New York City and rapid spread throughout the nation in 2002 also serve as a reminder of the potential for exponential spread of pests and pathogens, and that pathogens evolving anywhere on the globe—and the social and environmental conditions that contribute to these changes—can affect us all.

7. DISCONTINUITIES

Climate change may not prove to be a linear process. Polar ice is thinning and Greenland ice is retreating, and since 1976 several small stepwise adjustments appear to have reset the climate system. In 1976, Pacific Ocean temperatures warmed significantly; they warmed 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. Cold upwelling in the Pacific Ocean 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 to Europe and enhancing the Labrador Current that hugs the U.S. east coast. Such paradoxical cooling from warming and ice melting could alter projections for climate, weather, and disease for northern Europe and the northeastern United States. It is the instability of weather patterns that is of most concern for public health and society.

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 cold winters. 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.

8. CONCLUSION

The resurgence of infectious diseases among humans, wildlife, livestock, crops, forests, and marine life in the final quarter of the 20th century may be viewed as a primary symptom of 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 remarkably stable 10,000-year period that 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 must expect 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. However, the consequences of warming and wide swings in weather are projected to 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 damages. Environmental damage from their mining, refining, and transport must be added to direct health effects of air pollution and acid precipitation.

Returning CO₂ to the atmosphere through their combustion reverses the biological process by which plants drew down atmospheric carbon and generated oxygen and stratospheric ozone, helping to cool and shield the planet sufficiently to support animal life.

9. 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 U.S. 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, which rests on environmental and energy policies. Restoration of forests and wetlands, “nature’s sponges and kidneys,” is necessary to reduce vulnerabilities to climate and weather. Population stabilization is also necessary, but World Bank data demonstrate that this is a function of income distribution.

Development underlies most aspects of health and it is essential to develop clean energy sources. 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 nonpolluting sources can be the first step toward the rational use of Earth’s finite resources and reduction in the generation of wastes, the central components of sustainable development.

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 needed to propel clean energy technologies into

the global marketplace. International funds are also needed to support common resources, such as fisheries, and for vaccines and medications for diseases lacking lucrative markets.

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.

Worldviews can also 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 nonpolluting 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 21st century.

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