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Government actions/public policy shifts Effects Impact on human health Establish sustainable dietary guidelines Eliminate subsidies for commodity crops Add cost of environmental degradation to foods with high environmental footprint Reduce demand for beef Reduced meat consumption Shift to more plant-based diets Make improvements in urban design Eliminate subsidies for fossil fuels Increased use of public transportation Impact on climate change Reduced greenhouse gases FIGURE 473-8 Strategies to mitigate the impact of climate change on human nutrition. (Reproduced with permission of Journal of Clinical Investigation from Climate change and malnutrition: we need to act now. WH Dietz 130:556, 2020.) ■ ■INFECTIONS AND DIARRHEAL DISEASE (See Chap. 474.) POTENTIAL SOLUTIONS Reductions in GHG emissions will require health professionals to voice their evidence-based understandings of climate-sensitive pathologies to lobby for political action. Other important systemic interventions in health care include achieving universal health coverage (including financial risk protection); equitable access to quality essential health care services as well as safe, effective, and affordable medicines and vaccines; making health care and health systems net-zero carbon; add ing a climate-change lens to existing lines of research; improving data quality and enhancing, standardizing, and integrating data collection in LMICs; and anticipating and correcting disaster-related health care system failures, such as impacts to supply chains or loss of electric power resulting from extreme weather events. PART 15 Disorders Associated with Environmental Exposures Interventions related to environmental policy include advocat ing for a tighter particulate-matter air-quality standard, supporting institutional divestment from fossil fuels, and advocating for the rapid drawdown of emissions and negative emissions strategies. Ecosocial interventions, supported by national or global institutions, include the distribution of clean cookstoves globally, switching to plant-based diets, decreased air travel, reducing air conditioner use, and increased access to more public transportation. Finally, advocating for wealth-redistribution schemes (e.g., reparations, progressive taxation, debt cancellation, improved safety nets, underemployment insurance) to empower dis advantaged populations to cope with climate hazards will have positive ancillary effects on the social determinants of health, the administration of health services, and the outcomes of clinical interventions. CONCLUSIONS Without sweeping reductions in GHG emissions, over the next 50 to 100 years, models predict increases in average global temperature of 2–5°C (with localized highs), rising sea levels, and more frequent and severe extreme-weather events, with resultant complications for population health globally. The hostile consequences of climate change will dis proportionately affect vulnerable and marginalized groups, particularly those whose ability to cope with climate hazards is curtailed by systemic racism, colonial legacies, illicit financial flows, and human rights failings. Health care professionals find themselves on the front line of the climate crisis and remain, in many settings, sources of information and counsel. In order to mitigate the impact of climate-sensitive diseases and resulting health disparities, they must continue to extend their clinical purview to socioecological determinants and structural interventions.

Reduced risk of cardiovascular disease, T2D, stroke, cancer, obesity Increased biking/walking Impact on nutrition Improved food security Preservation of protein and micronutrient content of crops Acknowledgment Paul Farmer contributed to this chapter in the 21st edition and some material from that chapter has been retained here. ■ ■FURTHER READING Bekkar B et al: Association of air pollution and heat exposure with preterm birth, low birth weight, and stillbirth in the US: A systematic review. JAMA Netw Open 3:e208243, 2020. Brief of Amici Curiae Public Health Experts, Public Health Organiza tion, and Doctors In Support of Plaintiffs-Appellees' Petition for Hearing En Banc, Juliana v. United States of America, No. 18-36082 (9th Cir. Mar. 13, 2020). Centers for Disease Control and Prevention: Climate Effects on Health. Available from https://www.cdc.gov/climateandhealth/effects/ default.htm. Accessed January 19, 2024. Hoffman JS et al: The effects of historical housing policies on resident exposure to intra-urban heat: A study of 108 US urban areas. Climate 8:12, 2020. The Lancet: Countdown on health and climate. Available at https:// www.thelancet.com/countdown-health-climate- Accessed January 19, 2024. The New England Journal of Medicine: Climate Change. Available from https://www.nejm.org/climate-crisis Accessed January 19, 2024. Rajagopalan S et al: Air pollution and cardiovascular disease: JACC state-of-the-art review. J Am Coll Cardiol 72:2054, 2018. Aaron S. Bernstein, Jonathan A. Patz

Climate Change and

Infectious Disease Since the late nineteenth century, humans have released greenhouse gases—mainly carbon dioxide and methane—into the atmosphere, creating a new climate unseen in human times. This new climate has already altered the epidemiology of infectious diseases, and the accu mulation of more greenhouse gases in the atmosphere will further alter the incidence and severity of infections. In certain instances, climate

change may establish conditions promoting the emergence of infec tious diseases, while in other instances, it may render areas that are presently suitable for certain diseases unsuitable. This chapter presents the current state of knowledge regarding the known and prospective infectious-disease consequences of climate change. OVERVIEW The term climate change refers to multidecadal alterations in temperature, precipitation, wind, humidity, and other components of weather outside of the natural climate variability seen in comparable time periods. Over the past 2.5 million years, the earth has warmed and cooled, cycling between glacial and interglacial periods during which average global tem peratures moved up and down by 4–7°C. During the last glacial period, which ended roughly 12,000 years ago, global temperatures were, on aver age, 5°C cooler than in the mid-twentieth century (Fig. 474-1). The present climate period, known as the Holocene, is remarkable for its stability: temperatures have largely remained within a range of

2–3°C. This stability has enabled the successful population and cultivation of much of the earth's landmass by humanity. Current climate change differs from that in the past not only because its primary cause is human activities but also because its pace is faster. The current rate Observed warming Contributions to warming based on two complementary approaches (a) Observed warming 2010–2019 relative to 1850–1900 (b) Aggregated contributions to (c) Contributions to 2010–2019

2010–2019 warming relative

warming relative to 1850–1990,

to 1850–1990, assessed from

assessed from radiative

attribution studies

forcing studies °C 2.0 1.5 1.0 0.5 0.0 –0.5 –1.0 Internal variability Solar and volcanic drivers Other human drivers Well-mixed greenhouse gases Total human influence FIGURE 474-1 Assessed contributions to observed warming in 2010–2019 relative to 1850–1900. Assessed contributions to observed warming in 2010–2019 relative to 1850– 1900. A. Observed global warming (increase in global surface temperature). Whiskers show the very likely range. B. Evidence from attribution studies, which synthesize information from climate models and observations. Temperature change attributed to total human influence; changes in well-mixed greenhouse gas (GHG) concentrations; other human drivers due to aerosols, ozone, and land-use change (land-use reflectance); solar and volcanic drivers; and internal climate variability. Whiskers show likely ranges. C. Evidence from the assessment of radiative forcing and climate sensitivity. Temperature changes from individual components of human influence: emissions of GHGs, aerosols, and their precursors; land-use changes (land-use reflectance and irrigation); and aviation contrails. Whiskers show very likely ranges. Estimates account for both direct emissions into the atmosphere and their effect, if any, on other climate drivers. For aerosols, both direct effects (through radiation) and indirect effects (through interactions with clouds) are considered. (Used with permission from IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [V Masson-Delmotte et al (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001. Reproduced with permission of the Licensor through PLSclear.)

of warming on Earth is unprecedented in the last 50 million years. The 5°C of warming that occurred at the end of the last ice age about 12,000 years ago took roughly 5000 years, whereas such a temperature increment may occur within the next 150 years unless the release of greenhouse gases is substantially reduced in coming decades.

■ ■GREENHOUSE GASES Greenhouse gases (Table 474-1) are a group of gases in Earth's atmosphere that absorb infrared radiation and thus warm the planet. Essentially, greenhouse gases act as a blanket on the earth to keep more of the sun's solar radiation in the atmosphere. Carbon dioxide, released into the atmosphere primarily from fossil fuel combustion and deforestation, has had the greatest effect on climate since the Industrial Revolution. Other greenhouse gases, such as methane, nitrous oxides, and fluorinated gases, are more potent than carbon dioxide, but make up a smaller proportion of greenhouse gases. Both carbon dioxide and methane have increased considerably from the nineteenth century until 2023, with methane concentrations more than doubling. Water vapor is the most abundant and a highly potent greenhouse gas but, given its short atmospheric life span and sensitivity to temperature, is not a major factor in recently observed warming. °C 2.0 °C 2.0 CHAPTER 474 1.5 1.5 1.0 1.0 Climate Change and Infectious Disease 0.5 0.5 0.0 0.0 –0.5 –0.5 –1.0 –1.0 Aviation contrails Land-use reflectance and irrigation Black carbon Ammonia Organic carbon Sulphur dioxide Volatile organic compounds and carbon monoxide Nitrogen oxides Halogenated gases Nitrous oxide Methane Carbon dioxide Mainly contribute to changes in anthropogenic aerosols Mainly contribute to changes in non-CO2 greenhouse gases

TABLE 474-1 Greenhouse Gases: Sources, Sinks, and Forcings GAS HUMAN SOURCES SINKa RADIATIVE FORCINGb (95% CONFIDENCE INTERVAL) Carbon dioxide (CO2) Fossil fuel combustion, deforestation Uptake by oceans (~30%), plants 1.68 (1.33–2.03) Methane (CH4) Fossil fuel production, ruminant animals, decomposition in landfills Hydroxyl radicals in the troposphere 0.97 (0.74–1.20) Nitrous oxide (N2O) Fertilizer, fossil fuel combustion, biomass burning,

livestock manure Halocarbons Refrigerants, electrical insulation, aluminum production Hydroxyl radicals in the troposphere, sunlight in the stratosphere aIn this table, a sink refers to the place where greenhouse gases are naturally stored or the mechanism through which they are destroyed. bRadiative forcing, measured in watts per meter squared, refers to how much an entity can alter the balance of incoming and outgoing radiation to and from Earth’s atmosphere. It is measured relative to a preindustrial (i.e., 1750) baseline. Greenhouse gases have a positive “forcing”; that is, on balance, they increase the amount of radiation (and specifically infrared radiation) that is retained in Earth’s atmosphere. Source: Intergovernmental Panel on Climate Change Fifth Assessment Report, Working Group 1, Chapter 8; American Chemical Society “Greenhouse gas sources and sinks,” available at www.acs.org/content/acs/en/climatescience/greenhousegases/sourcesandsinks.html. The atmosphere, some of the aerosols suspended in it, and clouds reflect a portion of incoming solar radiation back toward space. The remainder reaches Earth’s surface, where it is absorbed and some is emitted back into the atmosphere. The earth emits energy absorbed from the sun at longer wavelengths, primarily infrared, that green house gases can absorb. The change in wavelength that occurs as solar radiation is absorbed and re-emitted from the earth’s surface is funda mental to the greenhouse effect (Fig. 474-2). ■ ■TEMPERATURE Climate change has clearly caused global warming with the average surface temperature of Earth increasing 1.09°C from 1880 to 2020. Moreover, the rate of global warming is faster now than at any time in the last 1000 years. Yet, this mean warming fails to show that warming is occurring much faster in certain regions. The Arctic has warmed twice as fast overall, and winters are warming faster than summers. Nighttime minimum temperatures are also rising faster than daytime high temperatures. Each of these nuances bears upon the incidence of infectious diseases in general and vector-borne disease specifically. PART 15 Disorders Associated with Environmental Exposures Due to climate change, extreme heat waves are expected to be more common, longer, and more severe in the future. The hottest 5-year Incoming solar radiation 342 W m–2 Reflected solar radiation 107 W m–2

Reflected by clouds, aerosol and atmosphere

Reflected by the surface

Absorbed by the surface Thermals

FIGURE 474-2 Earth’s energy balance. (Kiehl’s Earth’s Annual Global Mean Energy Budget, Bulletin of the American Meteorological Society, Vol. 78, No. 2, 1997 (Figure 7, page 206). © American Meteorological Society. Used with permission.)

Photolysis in the stratosphere 0.17 (0.14–0.23) 0.18 (0.01–0.35) period ever recorded since records started in the mid-nineteenth cen tury was 2016–2020. Besides contributing directly to morbidity and mortality in human populations, heat waves wilt crops and are pre dicted to contribute substantially to agricultural losses. For example, the 2010 heat wave in Russia, which was unprecedented in its severity, contributed to hundreds of forest fires that generated enough air pol lution to kill an estimated 56,000 people and that burned 300,000 acres of crops, including roughly 25% of the nation’s wheat fields. Nutritional deficiencies underlie a substantial portion of the global burden of many infectious diseases. ■ ■PRECIPITATION In addition to changing temperature, the emission of greenhouse gases and the consequent increase in energy in Earth’s atmosphere have influenced the planet’s water cycle. Since 1950, substantial increases in the heavi est precipitation events (i.e., those above the 95th percentile) have been observed in Europe and North America. Moreover, in 2022, floods harmed an estimated 58 million people globally. Other areas have seen greater drought, notably southern Australia and the southwestern United States. A warmer atmosphere holds more water vapor. Specifically, air holds 6–7.5% more water vapor per degree (Celsius) of warming in the lower Outgoing longwave radiation 235 W m–2

Emitted by the atmosphere Atmospheric window

Absorbed by the atmosphere

Greenhouse gases Latent heat

Back radiation

Surface radiation Evapotranspiration

Absorbed by the surface

atmosphere. For areas that have traditionally had more precipitation on average, warming tends to promote heavier precipitation events. In contrast, in regions prone to drought, warming tends to result in greater periods between rainfalls and in the risk of drought. Floods and droughts have been associated with outbreaks of waterborne infectious diseases. ■ ■HURRICANES The world’s oceans have absorbed 90% of the excess heat that green house gases have kept in Earth’s atmosphere since the 1960s. Ocean heat provides energy for hurricanes, and warmer years tend to have greater hurricane activity. Stronger hurricanes (category 4 and 5) are expected with climate change, though climate change influence on hurricane frequency is uncertain. Modeling of future tropical cyclones suggests that their intensity may increase 2–11% by 2100 and that the average storm will bring 20% more rainfall. ■ ■SEA LEVEL RISE Between 1901 and 2010, the global sea level rose ~200 mm, or ~1.7 mm per year on average. From 1993 to 2010, the rate of rise nearly doubled—i.e., to 3.2 mm annually. Most of this sea level rise has resulted from the thermal expansion of water. Glacial ice melt is the second greatest factor, and its contribution is accelerating. By 2100, global sea level may rise by 0.8–2 m, with an annual rate of rise of 8–16 mm at the century’s end. Sea level rise is not uniform. The rate of rise on the eastern seaboard of North America has been roughly double the global rate. Compounding sea level rise is the subsidence of coastal areas due to human settlement. In the absence of levee upgrades, an estimated 300 million people living near coasts worldwide will be at risk of flooding in 2050 because of the combined effects of subsidence, erosion, and sea level rise. Along with extreme storms and overuse of coastal aquifers, rising seas also contribute to salinization of coastal groundwater. About 1 billion people rely on coastal aquifers for potable water. ■ ■EL NIÑO SOUTHERN OSCILLATION The El Niño Southern Oscillation (ENSO) refers to periodic changes in water temperature in the eastern Pacific Ocean that occur roughly every 4–5 years. ENSO cycles have dramatic effects on weather around the globe. Warmer-than-average water temperatures in the eastern Pacific define El Niño events (see below), whereas cooler-than-average water temperatures define La Niña periods. Evidence is accruing that climate change may be increasing the frequency and severity of El Niño events. El Niño events drive alterations in weather worldwide (Fig. 474-3) and are associated with extreme events and consequently higher rates of morbidity and mortality. Hurricane Mitch, one of the most powerful hurricanes ever observed, with winds reaching 290 km/h, dropped 1–1.8 m (3–6 feet) of rain over 72 h on parts of Honduras and Nicaragua. As a result of this storm, 11,000 people died and 2.7 million were displaced. FIGURE 474-3 Characteristic weather anomalies, by season, during El Niño events. (Source: Climate Prediction Center, https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/warm_impacts.shtml.)

Outbreaks of cholera, leptospirosis, and dengue occurred in the storm’s aftermath.

■ ■POPULATION MIGRATION AND CONFLICT The final common outcome of all climate-change effects is human displacement. Sea level rise, extreme heat and precipitation, droughts, and salinization of water supplies all conspire to make regions, including some inhabited by humans for millennia, uninhabitable. The 8 million inhabitants of low-lying South Pacific islands are vulnerable to sea level rise and could be a major source of climate migrants. Climate change may also be contributing to humanitarian crises and conflicts. A severe 2011 drought in East Africa may have incited the Somali famine that resulted in 1 million refugees; mortality rates reached 7.4/10,000 in some refugee camps. EFFECTS OF CLIMATE CHANGE ON INFECTIOUS DISEASE The incidence of most, if not all, infectious diseases depends on climate. For any given infection, however, climate change is but one of many factors determining disease epidemiology. In instances in which climate change creates conditions favorable to the spread of infections, CHAPTER 474 Climate Change and Infectious Disease

diseases may be kept in check through interventions such as vector control or antibiotic treatment.

Detecting the influence of climate change amid the many competing forces that bear on infectious disease emergence and spread can be challenging. Research on animal pathogens, which in most instances are less intervened upon than that with their human counterparts, has suggested how climate change may independently influence disease spread. Avian malaria in Hawaii, for example, has clearly moved to higher elevations where warmer temperatures have enabled disease transmission. Many putative pathways have been identified that con nect greenhouse gas emissions to infectious disease risk in people. Cli mate change influences extend beyond contagious diseases and include diseases from microbial toxins, such as those that result from harmful algal blooms. Warmer ocean temperatures cause Pseudonitzschia spp., blue–green cyanobacteria, and dinoflagellates to grow faster, resulting in concurrent disease outbreaks. ■ ■VECTOR-BORNE DISEASE Because insects are cold-blooded, ambient temperature dictates their geographic distribution. With increases in temperatures (in particular, nighttime minimum temperatures), insects are freed to move pole ward and up mountainsides. At the same time, as new areas become climatically suitable, current mosquito habitats may become unsuitable because of heat extremes. In addition, insects tend to be sensitive to water availability. Mos quitoes that transmit malaria, dengue, and other infections may breed in pools of water created by heavy downpours. As has been observed in the Amazon, breeding pools can also appear during periods of drought when rivers recede and leave behind stagnant pools of water for Anopheles mosquitoes. These circumstances have raised interest in the potentially favorable impact of water-cycle intensification on the spread of mosquito-borne disease. PART 15 Disorders Associated with Environmental Exposures Malaria • TEMPERATURE Higher temperatures promote higher mosquito-biting rates, shorter parasite reproductive cycles, and the potential for the survival of mosquito vectors of Plasmodium infection in locations previously too cold to sustain them. Modeling experiments have identified highland areas of East Africa and South America as perhaps most vulnerable to increased malarial incidence as a result of rising temperatures. In addition, an analysis of interannual malaria in Ecuador and Colombia has documented a greater incidence of malaria at higher altitudes in warmer years. Highland populations may be more vulnerable to malaria epidemics because they lack immunity. Although rising temperature has the potential to expand the viable range of disease, malaria incidence is not linearly associated with temperature. While mosquitoes and parasites may adapt to a warm ing climate, the present optimal temperature for malaria transmission is ~25°C, with a range of transmission temperatures between 16°C and 34°C. Rising temperatures can also have differential effects on parasite development during external incubation and on the mosqui toes’ gonotrophic cycle. Asynchrony between these two temperaturesensitive processes has been shown to decrease the vectorial capacity of mosquitoes.1 PRECIPITATION The abundance of Anopheles mosquitoes is strongly correlated with the availability of surface-water pools for mosquito breeding, and biting rates have been linked to soil moisture (a surrogate for breeding pools). Research in the East African highlands has docu mented that increased variance in rainfall over time has strengthened the association between precipitation and disease incidence. These disease-promoting effects of precipitation may be countered by the potential for extreme rainfall to flush mosquito larvae from breeding sites. 1rVc is the vectorial capacity relative to the vector-to-human population ratio and is defined by the equation rVc = a2bhbme–μmn/μm where a is the vector bit ing rate; bh is the probability of vector-to-human transmission per bite; bm is the probability of human-to-vector infection per bite; n is the duration of the extrinsic incubation period; and μm is the vector mortality rate.

PROJECTIONS Climate models have begun to deliver output on regional scales, permitting projections of climate-suitable regions to assist national and local health authorities. Climate models speak to the temperature and precipitation ranges necessary for malaria transmis sion but do not account for the capacity of malaria control programs to halt the spread of disease. The global reduction in malaria distribution over the past century makes it clear that, even with climate change, malaria occurs in far fewer places today because of public health inter ventions. Recent vaccine trials also show promise in further reducing malaria risk. Despite intensive efforts, malaria remains the single greatest vectorborne disease cause of morbidity and death in the world. Particularly in regions that are most affected by malaria and where the public health infrastructure is inadequate to contain it, climate modeling may pro vide a useful tool in determining where the disease may spread. Mod eling studies in sub-Saharan Africa have suggested that, although East African nations may encompass regions that will become more climati cally suitable for malaria over this century, West African nations may not. By 2100, temperatures in West Africa may largely exceed those optimal for malaria transmission, and the climate may become drier; in contrast, higher temperatures and changes in precipitation may allow malaria to move up the mountainsides of East African countries. Cli mate change may create conditions favorable to malaria in subtropical and temperate regions of the Americas, Europe, and Asia as well. Dengue Like malaria epidemics, dengue fever epidemics depend on temperature (Fig. 474-4). Higher temperatures increase the rate of larval development and accelerate the emergence of adult Aedes mos quitoes. The daily temperature range may also influence dengue virus transmission, with a smaller range corresponding to a higher trans mission potential. Temperatures <15°C or >36°C substantially reduce mosquito feeding. In a Rhesus model of dengue, viral replication can occur in as little as 7 days with temperatures of >32–35°C; at 30°C, rep lication takes ≥12 days; and replication does not reliably occur at 26°C. Research on dengue in New Caledonia has shown peak transmission at ~32°C, reflecting combined effects of a shorter extrinsic incubation period, a higher feeding frequency, and more rapid development of mosquitoes. Along with temperature, peak relative humidity is a strong predictor of dengue outbreaks. The association between dengue epidemics and precipitation is less consistent in the peer-reviewed literature, possibly because of the mos quito vector’s greater reliance on domestic breeding sites than on natu ral pools of water. For instance, in some studies, increased access to a piped water supply has been linked to dengue epidemics, presumably because of associated increased domestic water storage. Nonetheless, several studies have established rainfall as a predictor of the seasonal timing of dengue epidemics. The current global distribution of dengue largely overlaps the geographic spread of Aedes mosquitoes (Fig. 474-5). The presence of Aedes without dengue endemicity in large regions of North and South America and Africa illustrates the relevance of variables other than climate to disease incidence. Nevertheless, coupled climatic–epidemiologic modeling suggests dramatic shifts in the relative vectorial capacity for dengue by the end of this century should little or no mitigation of greenhouse gas emissions occur (Fig. 474-6). Other Arbovirus Infections Climate change may favor increased geographic spread of other arboviral diseases, including Zika virus disease, chikungunya virus disease, West Nile virus disease, and east ern equine encephalitis. Zika virus moved to the Western Hemisphere from French Polynesia around 2013 and rapidly spread in Brazil in 2016. Although air travel was essential for the delivery of the virus to the Americas, the available evidence suggests that the 2015 El Niño event provided an optimal climate for the infection to take root and spread (see “ENSO-Related Outbreaks,” below). Aedes aegypti is the primary vector for Zika virus. Chikungunya virus disease emerged in Italy in 2007, having previously been mostly a disease of African nations. Climate models predict that, should competent vectors be present, conditions will be suitable for the chikungunya virus to gain a foothold in Western Europe, especially France, in the first half of

Days (EIP length and development to adult)

Temperature (°C)

FIGURE 474-4 Effects of temperature on variables associated with dengue transmission. Shown are the number of days required for development of immature Aedes aegypti mosquitoes to adults, the length of the dengue virus type 2 extrinsic incubation period (EIP), the percentage of Ae. aegypti mosquitoes that complete a blood meal within 30 min after a blood source is made available, and the percentage of hatched Ae. aegypti larvae surviving to adulthood. (Reproduced from CW Morin et al: Climate and dengue transmission: Evidence and implications. Environ Health Perspect 121:1264, 2013.) the twenty-first century. In North America, areas favorable to West Nile virus outbreaks are expected to shift northward in this century. Current hotspots in North America are the California Central Valley, southwestern Arizona, southern Texas, and Louisiana, which have both compatible climates and avian reservoirs for the disease. By midcentury, the upper Midwest and New England will be more climatically suited to West Nile virus; by the end of the century, the area of risk may shift even further north to southern Canada. Whether the disease will ultimately move northward will depend on reservoir availability and mosquito control programs, among other factors. Lyme Disease In the past few decades, Ixodes scapularis, the primary tick vector for Lyme disease as well as for anaplasmosis and FIGURE 474-5 Distribution of Aedes aegypti mosquitoes (turquoise) and dengue fever epidemics (red). (Map produced by the Agricultural Research Service of the U.S. Department of Agriculture.)

babesiosis in New England, has become established in Canada because of warming temperatures. With climate change, the range of the tick is expected to expand further (Fig. 474-7).

Development to adult

EIP length Percent (survival to adult and blood fed) Blood fed

Survival to adult Lyme disease, caused by the spirochete Borrelia burgdorferi, is the most commonly reported vector-borne disease in North America, with ~60,000 cases annually. In Europe, Lyme disease has also increased and expanded geographically. Furthermore, the timing and peaks of cases have been affected, with the annual peak case numbers in 2019 arriving 6 weeks earlier than 25 years prior.

■ ■WATERBORNE DISEASE Many microorganisms, from bacteria to toxinproducing algae, cause waterborne disease (Table 474-2). The outbreaks of waterborne disease are associated with heavy rainfall events. A review of 548 waterborne disease outbreaks in the United States found that 51% were preceded by precipitation levels above the 90th percentile. Since 1900, most regions of the United States except the Southwest and Hawaii have experienced an increase in heavy downpours with the greatest intensification of the water cycle in New England and Alaska. Most disease outbreaks after heavy precipitation occur through contamination of drinking-water supplies. While outbreaks related to surface-water contamination generally occur within a month of the precipitation event, disease outbreaks from groundwater contamination tend to occur ≥2 months later. According to a review of published reports of waterborne disease outbreaks, Vibrio and Leptospira species are the pathogens most commonly involved in the wake of heavy precipitation.

CHAPTER 474 Climate Change and Infectious Disease Combined Sewer Systems Roughly 40 million people in the United States and millions more around the world rely on combined sewer systems in which storm water and sanitary wastewater are conveyed in the same pipe to treatment facilities. These systems were

A PART 15 Disorders Associated with Environmental Exposures B FIGURE 474-6 Trend of annually averaged global dengue epidemic potential (rVc). Differences in rVc are based on 30-year averages of temperature and daily temperature range. A. Differences between 1980–2009 and 1901–1930. B. Differences between 2070–2099 and 1980–2009. The mean value of rVc was averaged from five global climate models under RCP8.5, a scenario of high greenhouse-gas emission. The color bar describes the values of the rVc. (From J Liu-Helmersson et al: Vectorial capacity of Aedes aegypti: Effects of temperature and implications for global dengue epidemic potential. PLoS One 9:e89783, 2014.) designed based on the nineteenth-century climate, in which heavy downpours were less frequent than they are today. The frequency of combined sewer overflows usually into freshwater bodies and resulting in untreated sewage and runoff potentially containing heavy metals and pesticides, has been increasing in cities worldwide. For instance, the channel leading into Lake Michigan from Milwaukee had its high est levels of Escherichia coli, up to 100 times the Environmental Protec tion Agency guidance for recreational waters, after combined sewer overflows (Fig. 474-8). Rising Temperatures and Vibrio Species Warmer temperatures favor proliferation of Vibrio species and disease outbreaks, as has been demonstrated in countries surrounding the Baltic Sea, Chile, Israel, northwestern Spain, and the U.S. Pacific Northwest. Around the Baltic Sea, outbreaks of Vibrio infection may be particularly likely because of faster warming near the poles and the sea’s relatively low salt content. In the United States, levels of vibriosis roughly tripled from 1996–2010, with the highest number of cases occurring each summer. ENSO-Related Outbreaks Weather extremes tied to El Niño events afford a window into a climate-changed future. Recent evidence indicates that climate change itself may be strengthening El Niño events. These events tend to promote epidemic infections in certain regions (Fig. 474-9). Associations of El Niño with outbreaks of Rift Valley fever in east ern and southern Africa have been known since the 1950s. El Niño favors wet conditions suitable for the insect vectors of the disease

in these regions. Given the strong asso ciation between El Niño conditions and disease incidence, models have successfully predicted Rift Valley fever epidemics in humans and animals. In the 2006–2007 El Niño season, for example, outbreaks of Rift Valley fever were accurately predicted 2–6 weeks prior to epidemics in Somalia, Kenya, and Tanzania. 0.21 0.12 0.06 0.03 –0.03 El Niño has had inconsistent associations with malaria incidence in African countries. Some of the strongest associations between El Niño and malaria have been identified in South Africa and Swaziland, where available data on incidence are relatively robust; how ever, even in these instances, the observed increased risk did not reach statistical sig nificance. A stronger link to El Niño has been found in several studies done in South America. Research on malaria incidence in Colombia between 1960 and 2006 found that a 1°C temperature rise contributed to a 20% increase in incidence. –0.06 0.52 0.41 0.26 0.12 In the desert Southwest of the United States, hantavirus erupted following the strong El Niño of 1997. Unseasonal rain fall caused the desert to bloom, providing food resources and resulting in a boon to the mouse population. The following year saw the climate revert back to normal (arid) conditions, and as a result, increased human/mouse contact occurred as mice were forced to seek out food and nest in human dwellings. 0.06 0.03 –0.03 –0.06 –0.12 –0.26 –0.41 –0.52 In Bangladesh, a strong association has been observed between the El Niño Southern Oscillation Index and cholera epi demics. During El Niño, a combination of warmer sea-surface temperatures (SSTs) and rich nutrient runoff lead to phytoplank ton blooms detectable by satellite. These blooms, in turn, feed zooplankton, which can harbor V. cholerae and, therefore, amplify their presence in the environment, causing cholera epidemics in the region (Fig. 474-10). El Niño years are often associated with an increased incidence of dengue. Research on dengue outbreaks in Thailand from 1996 to 2005 revealed that 15–22% of the variance in monthly dengue disease inci dence was attributable to El Niño. In South America, data on dengue outbreaks between 1995 and 2010 showed an increased incidence dur ing the El Niño events of 1997–1998 and 2006–2007. El Niño may have contributed to the emergence of Zika virus in the wake of a very strong ENSO event during the winter of 2015–2016. Temperatures throughout South and Central America were exception ally high and, just prior to the Zika epidemic, the vectorial capacity of Ae. aegypti was at its highest level compared with the previous 60 years. Not surprisingly (because carried by the same mosquito vector), large epidemics of dengue also occurred in Brazil and Colombia at that time. But laboratory studies show that the temperature optimum for Zika virus is 5°C warmer than for dengue. Thus, it is possible the extreme temperature played a role in the extent of the Zika epidemic. CLIMATE CHANGE, POPULATION DISPLACEMENT, AND INFECTIOUS DISEASE EPIDEMICS For many reasons, including freshwater shortages, flooding, food shortages, and climate change–driven conflicts, climate change has and will continue to put pressure on human populations to move. Human migrations have long been associated with epidemic disease in the

2000–2019 2000–2019 N A 2020–2049 2020–2049 N B F 2050–2079 2050–2079 N C G 2080+ 2080+ N D H = High risk = Moderate risk = Low risk = Risk of bird-borne ‘adventitious’ ticks only FIGURE 474-7 Risk maps for the occurrence of the Lyme disease vector Ixodes scapularis. Expansion of I. scapularis–affected census subdivisions (CSDs) in Canada from the present (using 1971–2000 temperature normals) to the 2080s (using temperature conditions predicted by the CGCM2 climate model under emissions scenario A2). In A–D (“slow” scenario), the model assumes that by the end of each time period, only risk CSDs with an algorithm value in the top 10% will contain an I. scapularis population. In E–H (“fast” scenario), the model assumes that by the end of each time period, all CSDs within the “moderate”-risk zone for I. scapularis establishment (risk CSDs) contain an I. scapularis population. For both scenarios, the time steps are 2000–2019, 2020–2049, 2050–2079, and 2080– 2109. “High”-risk regions for I. scapularis population establishment are indicated in red. “Moderate”-risk regions are in orange. “Low”-risk regions are in yellow. Regions with no risk of established populations but some risk from bird-borne “adventitious” ticks are in green. Regions with no predicted risk of either are colorless. (Used from NH Ogden: Risk maps for range expansion of the Lyme disease vector, Ixodes scapularis, in Canada now and with climate change. Int J Health Geogr 7:1, 2008.)

TABLE 474-2 Climate Sensitive Agents of Water-Related Illness PATHOGEN OR TOXIN PRODUCER EXPOSURE PATHWAY SELECTED HEALTH OUTCOMES AND SYMPTOMS Algae: Toxigenic marine species of Alexandrium, Pseudo-nitzschia, Dinophysis, Gambierdiscus; Karenia brevis Shellfish, fish Recreational waters (aerosolized toxins) Gastrointestinal and neurologic illness caused by shellfish poisoning (paralytic, amnesic, diarrhetic, neurotoxic) or fish poisoning (ciguatera). Asthma exacerbations, eye irritations caused by contact with aerosolized toxins (K. brevis). Cyanobacteria (multiple freshwater species producing toxins including microcystin) Drinking water Recreational waters Liver and kidney damage, gastroenteritis (diarrhea and vomiting), neurologic disorders, and respiratory arrest. Enteric bacteria and protozoan parasites: Salmonella enterica; Campylobacter species; toxigenic Escherichia coli; Cryptosporidium; Giardia Drinking water Recreational waters Shellfish Enteric pathogens generally cause gastroenteritis. Some cases may be severe and may be associated with long-term and recurring effects. Enteric viruses: enteroviruses; rotaviruses; noroviruses; hepatitis A and E Drinking water Recreational waters Shellfish Most cases result in gastrointestinal illness. Severe outcomes may include paralysis and infection of the heart or other organs. Leptospira and Leptonema bacteria Recreational waters Mild to severe flu-like illness (with or without fever) to severe cases of meningitis, kidney, and liver failure. Vibrio bacteria species Recreational waters Shellfish Varies by species but include gastroenteritis (V. parahaemolyticus, V. cholerae), septicemia (bloodstream infection) through ingestion or wounds (V. vulnificus), skin, eye, and ear infections

(V. alginolyticus). Source: Climate impacts on water-related illness, in The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, Washington, DC, 2016. https://health2016.globalchange.gov/water-related-illness. migrating populations themselves and in the communities in which they settle. The specific pathogens and patterns of disease that may appear after population migration relate to endemic diseases present in the migrant populations. PART 15 Disorders Associated with Environmental Exposures Large-scale migrations are common after extreme precipitation events. In August 2022, Pakistan experienced over three times the average rainfall, resulting in extensive flooding. Roughly 33 million people were affected, over 1400 people died, and 1.7 million homes were destroyed, all resulting in large-scale displacement. Additionally, standing water provided ideal breeding sites for vectors, and contaminated flood waters in two southern provinces led to outbreaks of diarrhea, cholera, and malaria. Accelerated computing power now allows 1e+5 1e+4 CFU/100 ml 1e+3 1e+2 1e+1 1e+0 CSO Rain with no CSO Base flow FIGURE 474-8 Levels of Escherichia coli in the Milwaukee estuary, which discharges to Lake Michigan, 2001–2007. Levels of E. coli in the Milwaukee estuary, which discharges to Lake Michigan, 2001–2007, during base flow (n = 46); following rain events with no CSO (n = 70); and following CSO events (n = 54). Boxes indicate 75% of values, with median values drawn in each. Whiskers are 95% of values, and outliers are shown as closed circles. There were significant differences in E. coli levels following rainfall and CSOs compared to base flow ($p \leq 0.05$). CFU, colony forming units; CSO, combined sewer overflow. (Reproduced with permission from JA Patz et al: Climate change and waterborne disease risk in the Great Lakes region of the U.S. Am J Prev Med 35:451, 2008.)

MAJOR CLIMATE CORRELATION

OR DRIVER (STRONGEST DRIVERS LISTED FIRST) Temperature (increased water temperature), ocean surface currents, ocean acidification, hurricanes (Gambierdiscus spp. and K. brevis) Temperature, precipitation patterns Temperature (air and water; both increase and decrease), heavy precipitation, and flooding Heavy precipitation, flooding, and temperature (air and water; both increase and decrease) Flooding, temperature (increased water temperature), heavy precipitation Temperature (increased water temperature), sea level rise, precipitation patterns (as it affects coastal salinity) for improved attribution of single weather events to climate change. For Pakistan, climate attribution analysis suggests that intense rainfall over short periods (5 days) has become more extreme with warming temperatures. In low- and middle-income countries, infectious disease outbreaks associated with population displacement may be harder to detect and respond to. People forced to leave their homes en masse are at risk for contracting infections with any pathogen that may be present within the displaced population, including sexually transmitted diseases such as HIV, or airborne or droplet transmitted diseases such as tuberculosis and measles. Reducing disease risk requires overlaying of climaterelated migration risk with foci of disease epidemics. A BROADER VIEW OF CLIMATE

CHANGE AND HEALTH While climate change has far-reaching implications for the distribu tion and severity of infectious diseases worldwide, the greatest disease burdens related to climate change may not be due to infections, at least primarily. Climate change erodes the foundations of health, such as safe drinking water and food security, due to climatic extremes such as flooding or droughts. In addition, resource scarcity and climate instability are increasingly associated with conflicts. For example, severe droughts made more likely by climate change may have been a factor in the revolutions of the Arab Spring and the Syrian civil war. Of course, without adequate nutrition, water, or shelter, infectious disease risks rise. The public health response to climate change entails both mitiga tion and adaptation measures. Mitigation represents primary preven tion and involves the reduction of greenhouse gas emissions into the atmosphere. Although no clear safety threshold of greenhouse gas emissions has been agreed upon, in 2015 at the 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) held in Paris, national governments from the major industrialized countries agreed to set a warming target of <2°C above preindustrial levels by 2050; the attainment of this goal will require reducing greenhouse gas emissions by 40–70% below 2010 levels. At COP21, a framework was established for a global carbon mar ket and nationally determined contributions (NDCs) for countries to commit to greenhouse gas reductions to meet the Paris Climate Agree ment. At the 2023 Conference of the Parties (COP28) held in Dubai,

HPS, PL MAL CHOL RVF DENG RI MAL FIGURE 474-9 Characteristic patterns of disease outbreaks associated with El Niño events, determined on the basis of 2006–2007 conditions. (From A Anyamba et al: Developing global climate anomalies suggest potential disease risks for 2006–2007. Int J Health Geogr 5:60, 2006.) for the first time the “need to transition from fossil fuels” was explicitly included in the final text of the agreement. Mitigation also confers health co-benefits, including better air qual ity and lower incidence and severity of respiratory infections, associ ated with less bio- or fossil fuel combustion. One study estimated that by eliminating air quality pollutants (PM 2.5, sulfur dioxide, nitrous oxides) from energy generation across the United States, >53,000 premature deaths would be avoided. Of note, evidence has shown that long-term air pollution exposure may contribute to mortality risk from COVID-19 and influenza. Dietary and agricultural changes can also afford climate change mitigation and improve human health.

Relevant Units Jan 98 Jan 99 Jan 2000 Jan 2001 Jan 2002

Relevant Units Jan 98 Jan 99 Jan 2000 Jan 2001 Jan 2002 FIGURE 474-10 Predicting cholera rates. Sea surface temperature, sea surface height, and chlorophyll-a predicting cholera in Bangladesh. Top graph illustrates environmental data detected by satellite measurements from the Bay of Bengal from January 1998–January 2002 and includes sea surface temperature (green line), sea surface height (blue line), and chlorophyll-a levels (yellow line), an indicator for the abundance of phytoplankton. Bottom graph illustrates the incidence rate of cholera (red) in Bangladesh over that time period. The black line combines the three environmental parameters and, superimposed over cholera incidence rate, shows a strong correlation. (Reproduced with permission from D Grimes et al: Viewing marine bacteria, their activity and response to environmental drivers from orbit: Satellite remote sensing of bacteria. Microb Ecol 67:489, 2014.)

DENG–Dengue Fever RI–Respiratory Illness CHOL–Cholera MAL–Malaria RVF–Rift Valley Fever HPS–Hantavirus Pulmonary Syndrome PL–Plague CHOL DENG RI Resource-intensive foods, like red meat and dairy, can lead to higher cases of diabetes and cardiovascular disease, so switching to plantbased diets can improve human health and reduce greenhouse gas emissions. CHAPTER 474 Climate adaptation is secondary prevention and seeks to reduce harms associated with sea level rise, heat waves, floods, droughts, wildfires, and other greenhouse gas–driven events. The efficacy of adaptation is constrained by the challenges inherent in predicting the precise location, duration, and severity of extreme weather events and flooding related to sea level rise, among other considerations (Fig. 474-11). Climate Change and Infectious Disease Sea Surface Temperatures Sea Surface Heights Chlorophyll-a Levels Cholera Incident Rate Predicted Cholera Rate

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