Insights from past millennia into climatic impacts on human health and survival

Anthony J. McMichael[1]

National Centre for Epidemiology and Population Health, Australian National University, Canberra ACT 0200, Australia

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Climate change poses threats to human health, safety, and survival via weather extremes and climatic impacts on food yields, fresh water, infectious diseases, conflict, and displacement. Paradoxically, these risks to health are neither widely nor fully recognized. Historical experiences of diverse societies experiencing climatic changes, spanning multicentury to single-year duration, provide insights into population health vulnerability—even though most climatic changes were considerably less than those anticipated this century and beyond. Historical experience indicates the following. (*i*) Long-term climate changes have often destabilized civilizations, typically via food shortages, consequent hunger, disease, and unrest. (*ii*) Medium-term climatic adversity has frequently caused similar health, social, and sometimes political consequences. (*iii*) Infectious disease epidemics have often occurred in association with briefer episodes of temperature shifts, food shortages, impoverishment, and social disruption. (*iv*) Societies have often learnt to cope (despite hardship for some groups) with recurring shorter-term (decadal to multiyear) regional climatic cycles (e.g., El Niño Southern Oscillation)—except when extreme phases occur. (*v*) The drought–famine–starvation nexus has been the main, recurring, serious threat to health. Warming this century is not only likely to greatly exceed the Holocene's natural multidecadal temperature fluctuations but to occur faster. Along with greater climatic variability, models project an increased geographic range and severity of droughts. Modern societies, although larger, better resourced, and more interconnected than past societies, are less flexible, more infrastructure-dependent, densely populated, and hence are vulnerable. Adverse historical climate-related health experiences underscore the case for abating human-induced climate change.

paleoclimate | analogue | under-nutrition | pandemic

Global climate change poses many risks to human health, safety, and survival—along with some benefits (1). Most environmental systems that sustain human population health are sensitive to climatic conditions: food yields, water supplies, natural constraints on infectious diseases, and protection (by reefs, forests, etc.) against weather extremes. However, public discussion of climate change impacts has focused less on the risks to health than on risks to economies, physical property, and environmental amenity. However, most environmental and social impacts of climate change would (sooner or later) endanger human health—confirming that human impacts on the Earth system are indeed creating an unsafe "planetary operating space" (2).

The threats from heatwaves, floods, and storms are well recognized. Less well understood are the indirect risks to health from climatic influences on food yields, water flows, bacterial and mosquito populations, viability of farm communities, and conflicts over dwindling resources.

Climatic changes have affected human health and survival over long historical time. Beyond impacts of weather disasters, great undulations in the fates and fortunes of societies throughout the Holocene epoch have been associated with seemingly small but sustained climatic changes, affecting crops, livestock, epidemic outbreaks, social unrest, and conflict. There have been both good times and bad times. However, (nonacute) temperature changes in the Holocene have been smaller than those anticipated this century (Fig. 1) (3). Even so, historical insights can enhance understanding of human vulnerabilities and inform today's responses to the prospect of substantial human-induced climate change. The assumption that humans cannot change climate and weather may, in the past, have implied futility of historical analysis. Today, as human actions increasingly influence the climate, that no longer applies.

The history of climatic influences on food shortages is familiar, but consequent impacts on health and survival are less well understood—as are historical climatic influences on infectious disease outbreaks and interconnections between food crises, epidemics, social disorder, and conflict. The causal processes affecting health outcomes are usually complex, variously reflecting social conditions, governance, demographic stresses, militarism, and the superimposed stresses of climatic fluctuations.

Health Risks from Climate Change, Present and Past

Three categories of risk can be differentiated by directness and type of causal pathway (Table 1). Some risks are readily measured and quantified, others are not. Quantifiable risks can be projected in relation to future scenarios of climate change (1).

The amount of available historical information differs among these three categories. In general, there is little explicit information about specific population health benefits (nutrition adequacy, child survival, longevity) during benign climatic periods. Rather, the adverse periods and outcomes customarily attract attention and documentation. However, food supplies, fertility, and population growth typically increased during longer-term stable warmer periods.

Written records from up to 5 millennia ago provide evidence of climatic impacts on food shortages, famines, starvation, and deaths. Skeletal remains may corroborate under-nutrition, micronutrient deficiencies, and increased child mortality. In contrast, for several other types of health risk there is little historical information beyond the past century. For example, information about heatwave impacts in earlier centuries is negligible, although information about deaths and suffering from periods of extreme cold often exists.

Records of major infectious disease epidemics (mostly from dynastic Egypt and Eurasia) extend back 3 to 4 millennia but are rarely explicitly connected with climatic conditions. Such information becomes more detailed and better connected in the past half-millennium. Various plagues in the eastern Mediterranean from 1500 to 500 before the common era (BCE) are in the biblical record. So too (more reliably) are the catastrophic plagues of Athens (5th century BCE) and of Rome (e.g., Antonine and Cyprian plagues in the 2nd and 3rd centuries CE, respectively).

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[1]E-mail: tony.mcmichael@anu.edu.au.

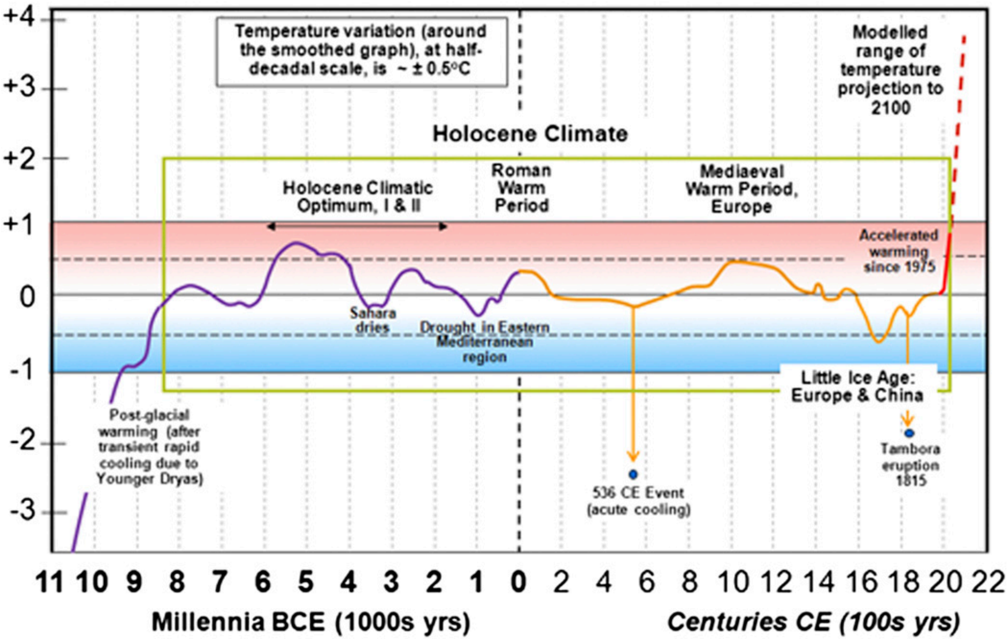

Fig. 1. Variations in northern hemisphere temperature, °C (relative to mean temperature during 1960–1980), averaged from multiple sources published since 2007. Averaging of hemispheric temperature is therefore only indicative. During early–mid Holocene (11–4 thousand years before present), for example, trends in regional temperatures differed, including prolonged cooling of much tropical ocean while warming for over 2 millennia in parts of Europe, China, and Scandinavia (4). Sources for graph include refs. 5–9.

Debate persists over the microbiological identity of most early plagues; historians of the time provided diagnostic clues of variable quality. Generic words such as "plagues" and "poxes" are inevitably obscure; Shakespeare's "agues and fevers" could mean many things. Modern molecular genetics is resolving some of these mysteries, including in relation to three specific strains of the bubonic plague bacterium *Yersinia pestis* as causes of the three pandemics originating in the 6th, 14th, and 19th centuries (10, 11).

Illustrative evidence of climatic influences on major epidemics comes from the Chinese imperial archives, documenting epidemic outbreaks at province level over the past 8 centuries. During the "Little Ice Age" in Eurasia (within the span 1300–1850 CE), 881 epidemics were recorded in China, 32 of which afflicted three or more provinces. That record, from a translated listing assembled in 1940 (12), when matched with estimated annual temperatures in central-eastern China (where the bulk of the population lived), enables analysis of epidemic years in relation to cool and warm periods. Analysis indicates that during colder periods (i.e., temperature below the 1300–1850 mean temperature) there was, approximately, a 35% greater probability of an epidemic and a 40% greater probability of a major (three-plus provinces) epidemic than during the warmer periods.

A larger body of evidence links infectious disease outbreaks with the under-nutrition, starvation, crowding, and social disruption that often resulted from, or were exacerbated by, climatic adversity. A recent analysis of multiple detailed datasets for Europe during the Little Ice Age has shown that the additional cooling of 0.2 °C during the coldest (17th) century was accompanied by marked harvest declines and food price rises, a doubled frequency of famine years, a 1.5-cm decline in adult stature, a tripling in epidemic outbreak rate, and a surge in armed conflicts (7). Other examples of this nutrition–infection linkage include (*i*) the smallpox outbreak in the western Roman Empire in the winter of 312–313 CE "in the midst of famine apparently caused by the lack of winter precipitation" (13); (*ii*) the recurring association of hunger, starvation, and pestilence during very cold episodes in the 8th and 9th centuries in Europe (14); (*iii*) "Cocolitzli" epidemics in postconquest Aztec survivors during mega-drought (see below); (*iv*) dysentery outbreaks in the fledgling Sydney Cove settlement, in eastern Australia, during the drought and food rationing crisis of 1790–1792; and (*v*) epidemics of smallpox in northeast Brazil after starvation caused by the great 1878–1879 drought (see below).

The influence of extremes of climate and weather on (infectious) diarrheal disease is also likely to have long been prominent. Cholera outbreaks in southeastern (British) India during 1901–1940 were strongly correlated with climatic extremes—both with very dry periods (with presumed high bacterial concentration in dwindling drinking-water sources) and with flooding (causing sanitation failure, displacement, and crowding) (15).

Finally, much evidence associates outbreaks of social disorder, conflict, and warfare (and their diverse health impacts) with

Table 1. Three categories of health risks due to changes in climate

1. Direct impacts: health and safety consequences of heatwaves, floods, extreme weather events, increased concentrations of particular air pollutants.
2. Risks due to changes in ecological or biophysical systems: changes in food yields leading to under-nutrition (child stunting and deaths); altered flows, cleansing, and salinity levels of freshwater; changes in range, rates, and seasonality of climate-sensitive infectious diseases (climatic influences on pathogens, vector species, and intermediate-host animals).
3. Impacts arising from social and economic disruptions and hardships: diverse health disorders (including under-nutrition, infections, mental health risks) in climate-displaced groups; depression and despair in failing farm communities and disadvantaged indigenous and other marginalized groups. Health consequences of tension and hostilities due to climate-related declines in water, food, timber, and living space.

climate-related stresses, especially food shortages. In China over the past millennium, multidecadal climatic changes causing food shortages and hunger have often led to social unrest and armed conflict, contributing to most of the dynastic collapses (16). In France, the extreme and erratic climate conditions of the late 1780s exacerbated food shortages, lawlessness, and social uprising that contributed to the French Revolution in 1789 (17). Three decades later in Europe, the cold "years without summer" that followed the massive Tambora (Indonesia) volcanic eruption in 1815 (Fig. 1) led to widespread food crises, starvation, and the overthrow of several minor monarchies (18). During the past half-century, the probability of armed conflict, predominantly within the world's poorer countries, was approximately doubled during times of local climatic stress caused by El Niño events, associated with food shortage and unemployment (19).

In summary, the broad health-risk categories of under-nutrition and starvation, infectious disease outbreaks, and conflict and warfare are the most accessible for historical study in relation to climate.

Learning from History: Opportunities, Cautions

Historical analysis has benefited greatly from two recent advances. First, methods for reconstructing paleo-climates from proxy indicators have progressed markedly. Second, the recent extension of epidemiological research into studying contemporary climate-and-health relations strengthens the knowledge base. This enhanced opportunity is reflected in recent studies of selected aspects of the historical climatic record (20, 21). Nevertheless, four preliminary considerations are relevant.

First, the available information is time-limited. Written ("historical") records extend back no more than 5 millennia, whereas in some cultures such records emerged only later if at all. Some prehistorical health information comes from archaeological and fossil evidence. Information about annual weather patterns was not kept systematically in most of Europe until 14th-century parish-based records emerged (22). In China, systematic observational records of climate and weather extend back a similar period (23). Direct temperature measurement awaited thermometers and their systematic use from the mid-19th century.

Second, today's wealthier and technology-rich societies differ in many ways from earlier societies. Although modern societies might expect to be less vulnerable to climatic stress in view of their stocks of knowledge, physical resources, technological interventions, and good governance, there are limits to that coping capacity. Further, in several respects modern societies may be at heightened vulnerability (Table 2).

Third, the rapid and substantial human-induced warming and associated climatic and environmental changes now anticipated has no obvious historical equivalent. A century-long temperature change of 2–4 °C (perhaps more), as currently seems likely, has no known precedent during the Holocene. Further, rapid climatic shifts during the Holocene mostly entailed cooling (especially due to major volcanic eruptions).

It is important to note, here, that the *direction* of temperature change is not an absolute arbiter of impact on either food yields or infectious diseases. Food yields are affected by both warming and cooling and by changes in rainfall: both excessive rain and the drought that often accompanies temperature change (24). Crop and animal species are attuned, via natural and managed selection, to their usual climate. Two dramatic examples of harvest losses on the order of 25–30%, due to very hot periods, come from Russia in mid-2010 and central-western Europe in 2003 (25).

Infectious disease outbreaks may be triggered either by the biological (e.g., under-nutrition and weakened immunity) and social consequences of a cooler climate (e.g., hunger-related unrest and mobility, crowding, and shared indoors-living with animals) or by the stimulus of a warmer climate (proliferation of bacteria, mosquitoes, and host animal species) and its sometime social consequences (e.g., population growth and movement).

The fourth consideration is to avoid undue attribution of social outcomes to environmental factors such as climate. During much of the 20th century there was energetic debate over the inclusion of climatic factors in social-historical analysis—a practice viewed unfavorably by historians and social scientists as "environmental determinism" (22). However, views moderated in the century's third quarter (26–28); interdisciplinary dialogue emerged (29); and by the 1990s the turning tide favored a more inclusive approach (23, 30).

Time-Scales of Climatic Influences

Climatic changes influence human well-being, biology, health, and survival on six distinguishable time-scales: (*i*) influences on biological evolution (over millennia); (*ii*) great transitions in human culture and ecology (at times of state-changes in climate); (*iii*) long-term climatic changes (multicentury); (*iv*) medium-term climatic changes (multidecade); (*v*) short-term climatic changes (multiyear); and (*vi*) acute climatic/weather events.

Details on the first two items are beyond this article's scope.

For item 1 an extensive literature addresses likely influences of global cooling on hominine biological evolution during the late Pliocene and early Pleistocene epochs. Presumably, both "directed" and "plasticity" selection occurred, with the latter selecting for the behavioral and physiological adaptability needed during the climatically variable period of 2.7–2.0 Mya (31). Meanwhile, climate-related changes in diet "directly" selected for an anatomy and metabolism suited to that diet, including evolution of the jaw and (reciprocally) a shortened colon and enlarged brain (32).

Major climatic shifts propelled two great transitions in human ecology (item 2). From around 80,000 y ago, as glaciation ensued, small bands of *Homo sapiens* drifted north-eastward out of Africa and radiated around and across greater Asia. Human

Table 2. Potential vulnerabilities of modern societies to climatic changes

1. Food-producing systems (land and sea) are already widely under stress from soil degradation and loss, water shortages and over-fishing, plus new vulnerabilities due to a high degree of specialization (hence less resilience), widespread monocultural production, and high dependence on fossil fuel inputs.
2. Today's large populations and dense urban settlements are (*i*) conducive to infectious disease, (*ii*) exposed to urban "heat island" amplification of heatwaves, (*iii*) often located vulnerably (flood-plains, coasts, informal hillside housing, etc.), as population growth and urbanization compound the risks.
3. Urban living depends on much complex infrastructure, vulnerable to disruption.
4. Many large low-income populations, dependent on coastal agriculture, face significant sea-level rise this century.
5. Much of the world is now "full," with little vacant hinterland. Population displacement may exacerbate geopolitical instability.
6. Other human-induced "global environmental changes" (disrupted nitrogen and phosphorus cycles, biodiversity losses, land degradation, etc.) will compound many of the health impacts of climate change (especially food shortages and under-nutrition) (2).
7. International tensions are rising on many fronts—reflecting population pressures, economic crises, water shortages, persistent poverty, and volatile food prices.

culture and biology evolved regionally in response to new climates, foods, and infectious agents. Later, from approximately 11,000 y ago, after postglaciation warming, selective cultivation of cereal-grasses emerged in Southwest Asia's "fertile crescent" and (perhaps soon after) in several other separate centers in East Asia, Southeast Asia, Mesoamerica, and South America. Agrarian village settlement gradually transformed human ecology as the Holocene climate arrived.

The other four time-frames of climate change are applicable to the study of impacts on human population health during the Holocene epoch. Fig. 2 displays examples of these in relation to the main climatic characteristics that applied. The following examples illustrate the possibilities of historical analysis within those four time-frames.

Long-Term Climatic Changes (Multicentury)

Younger Dryas Event: Nile Valley Hunger and Conflict. Between 12.8 and 11.6 thousand years ago the latter stage of the postglaciation warming was interrupted by a major cooling phase, the "Younger Dryas"—probably caused by the sudden massive release of meltwater from Canada's thawing ice sheets into the Atlantic, disrupting that ocean's heat circulation system. Over several centuries the temperature dropped by approximately 4 to 5 °C. At that time early human settlements were forming in several regions with good year-round food sources, including the Natufians in today's northern Syria and the settlements along the Nile Valley.

Archaeological research has identified several dozen Nile settlements that preceded the Younger Dryas. After that climatic shock, however, only a few survived. Regional skeletal remains evince an unusually high proportion of violent deaths, many accompanied by remnants of weapons (33). Meanwhile, in the Natufian region, as food supplies dwindled, most settlements disbanded. The several that managed to survive may have been progenitors of successful settled agriculture once warming resumed, culminating in the relatively stable Holocene climate.

Sumeria: Rise and Decline During Holocene Climatic Optimum. Southern Mesopotamia (Sumeria), encompassing the lower Tigris and Euphrates river flood-plains, was apparently the first region to develop regional-scale agriculture and a polity of multiple connected villages and towns as trading centers. The region's climate reflects a complex, seasonally varying set of weather systems: the "Atlantic" circulation (west winds, warmth, and seasonal rain) driven by the North Atlantic Oscillation (NAO); interdecadal latitudinal fluctuations of the arid subtropical "ridge"; the West Asian monsoon system; and periodic cold dry air from the north (the Siberian High) (34).

During the first, longer phase of the warmer Holocene Climatic Optimum (6000–3800 BCE; Fig. 1), the positive "Atlantic" weather pattern of the NAO predominated (34). This, plus river irrigation, facilitated the spread of agriculture. Then, as Sumeria's climatic configuration began to change in the 4th millennium BCE, increasing food insecurity and hunger emerged. Extended irrigation and substitution of (more salt-tolerant) barley for wheat may have provided some relief. However, the crisis deepened, starvation spread, the authority of rulers dwindled, and local farming communities raided one another. Clay tablets and carvings on stone steles attest to growing misery, conflict, starvation, and several epidemic outbreaks (34).

In this underfed weakened state Sumeria was conquered by the warrior-king Sargon, ruler of the upstream Akkadian empire (northern Mesopotamia). The drying conditions subsequently extended north and, after brief regional domination, the Akkadian empire collapsed around 2200 BCE, largely undone by drought, malnutrition, and starvation.

Classic Maya Civilization. Much has been written about the flowering of the Mayan civilization during 200–750 CE and its progressive decline during the 9th century CE. The "Classic Mayan" civilization, spanning the northern Yucatan Peninsula (in today's northeast Mexico) through to the Guatemala–El Salvador region, has long historical roots. The Mayans had forged a successful way of living, despite heavy tropical forest, mediocre soils, and a paucity of surface water.

Great civilizations decline for complex reasons (30, 35). The drying of the Mesoamerican climate during the 8th to 10th centuries CE has long been a candidate factor. So too have increased population pressure, deforestation, chronic soil erosion, the precarious dependence of agriculture on rainwater, and

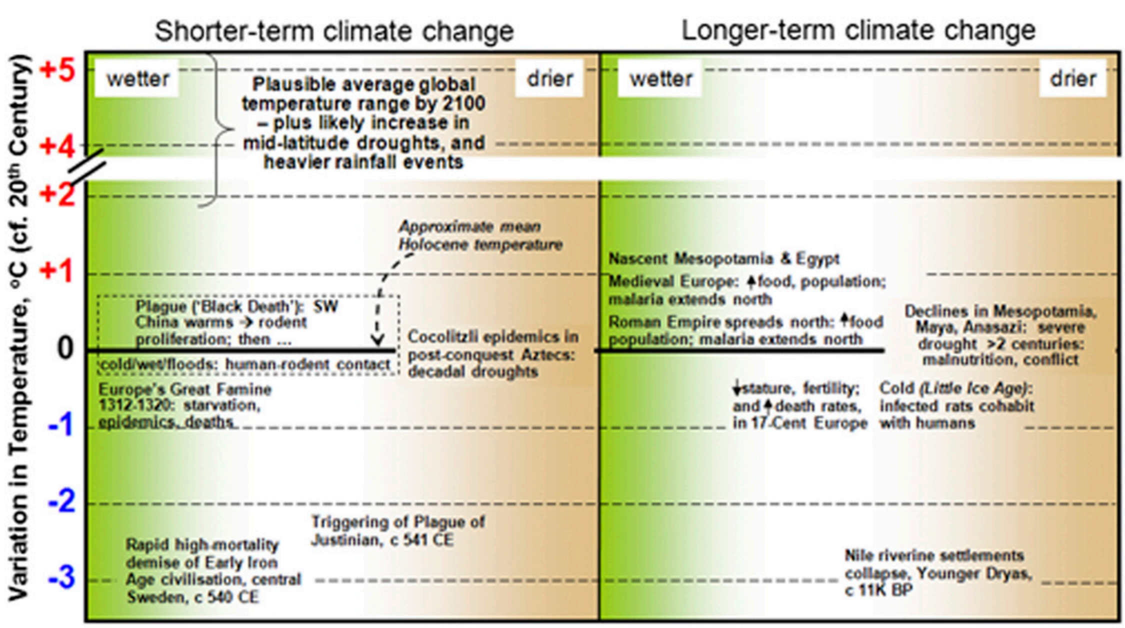

Fig. 2. Selected examples (spanning 12 millennia) of impacts of climate changes, both short-term and long-term, on human health, safety, and survival.

frequent intercity warfare (20, 30). Recent direct evidence of severe regional drought has emerged from chemical analysis of high-grade sedimentary varves in the coastal southern Caribbean seabed, providing bimonthly indicator data on changes in local rainfall levels (36). Supplementary evidence comes from pollen deposits in Yucatan lake-bed sediments (20). Evidently, three great droughts occurred during (approximately) 760–800, 840–870, and 890–920 CE, attributable, in part, to a weakening and shift in the summer monsoon.

Archaeological studies, too, have identified three periods of social stress, architectural decline, and violent conflict close in time to the three "paleo-climatic" droughts (37). Those studies [unlike some earlier research (38)] reported an increased prevalence of nutritional deficiencies and child-age skeletons during the drying period, along with apparent instances of survival cannibalism (39, 40).

Medium-Term Climatic Changes (Multidecade)

Sixteenth Century Droughts in Mesoamerica: "Cocolitzli" Epidemics. In 1521 CE the Aztecs were conquered by Spanish conquistadores, with their lethal stowaway measles and smallpox viruses. Later that century, other epidemics occurred in Aztec survivors. Protracted drought conditions, punctuated by occasional years of intense rainfall, in much of Mesoamerica during the 16th century are thought to have caused spillover of indigenous rodent-borne infections as zoonotic epidemics, compounding the Aztec depopulation (41).

The coincidence, in timing, between the "mega-drought" of 1540–1580 (the longest regional drought for six centuries, clearly identified by tree-ring analysis) and the two major epidemics of 1545 and 1576 (causing 12–15 million and 2 million deaths, respectively) suggests they were caused by "Cocoliztli"—indigenous hemorrhagic viral fevers transmitted by infected rodents (41). The rodents' food-seeking activity during drought, and their proliferation during the ensuing transient rains, would have increased human contact. Recent analogous evidence comes from the acute epidemic of rodent-borne hantavirus pulmonary syndrome in southwestern United States, after the El Niño-related drought of 1992. The rapid postdrought proliferation of fieldmice (hantavirus carriers) amplified human contact with virus from mouse excreta (42).

Black Death, Beginning Mid-14th Century in Europe. The "Black Death" refers to the European component of the Second Pandemic of bubonic plague. That pandemic seems to have begun approximately 1330 CE in the region of eastern Central Asia and southwestern China. Subsequently, it extended west and, from 1347, spread through Europe over the next 5 y. Transmitted by infected fleas feeding on infected rodents, the origin of this great pandemic has long tantalized researchers, including questions about climatic influence.

Much contemporary and historical evidence, worldwide, indicates that the geographic distribution of sylvatic bubonic plague and the timing of outbreaks reflect climatic conditions that favor a "trophic cascade" (43–45). In short, (*i*) over several decades the local climate may stimulate plant-foods eaten by wild rodents, whose numbers grow; (*ii*) weather events can disrupt rodent feeding and underground residence, causing their dispersal; and (*iii*) climatic changes also influence human activities (crowding, trading, conflict) that increase rodent–human contact, either directly or via human-cohabiting black rats.

Evidence suggests that this great pandemic was potentiated by a multidecadal sequence of climatic influences. First, the mild climate during several decades around 1300 CE in the Himalayan foothills of eastern Kazakhstan, adjoining southwestern China, fostered plant-food abundance and hence wild rodent proliferation (45, 46). Second, southern-central China subsequently cooled during 1310–1330, and presumably plant growth declined. In the early 1330s catastrophic floods in central China displaced and drowned many people. These environmental conditions are likely also to have stressed and displaced wild rodents and increased rodent–human contact. Meanwhile, in western China conflict flared between encroaching nomadic Mongol pastoralists (whose numbers had increased on the recently verdant steppes) and Han Chinese farmers. That strife and displacement would have further increased human–rodent contacts (46).

This sequence of climatic influences may thus have potentiated this great Eurasian plague epidemic (46). Before long, trade caravans or (more probably) horse-borne Mongol armies, with "companion" black rats, carried the disease westward into Europe in 1346–1347 via the Black Sea port of Kaffa. Within a dreadful decade, approximately one-third of the European population had perished.

Climatic factors may have also played a more subtle role. A legacy of Europe's Great Famine of 1315–1322 (see below) would have been an undernourished generation of newborns with a weakened immune system—a generation less able to survive infections 3 decades later.

Food Shortages and the Ming Dynasty Collapse, 1640s. In China the colder conditions in early 17th century were extreme. From the 1620s to the early 1640s the summers were very cold and drought widespread. The 1638–1641 drought was probably China's most severe for half a millennium. Eventually the drought encompassed the populous rice-growing Yangtze valley region in central-southern China; as yields fell, famines and hunger followed (47).

The food shortages during those decades coincided with the further disruptive effects of the in-migration of the increasingly populous Han Chinese from the western region. The Han began displacing the ethnic Bai Chinese, who had long farmed in the central Yangtze region but who now retreated to higher altitudes. Meanwhile, several weather disasters occurred, including Yellow River flooding that caused several hundred thousand deaths. The combination of food shortages, displacements, and weather disasters caused social unrest and violence, along with smallpox epidemics (48). The mounting social turbulence, predominantly due to starvation, culminated in an uprising in 1644 that overthrew the Ming Dynasty (49, 50).

Short-Term Climatic Changes (Multiyear)

Plague of Justinian. In 542 CE a dreadful epidemic broke out in the capital of the Eastern Roman Empire, Constantinople. This was the beginning of the first pandemic of bubonic plague. Within 3 mo ≈100,000 deaths occurred in Constantinople's population of (estimated) 500,000. The pandemic subsequently spread widely in southeastern Europe and the eastern Mediterranean region, recurring widely until the mid-8th century and killing tens of millions.

Historical accounts indicate that the initial epidemic in Constantinople was introduced by infected black rats and fleas on ships carrying grain from the Egyptian staging port of Pelusium, at the mouth of Nile Delta, and subsequently exported via Alexandria. A local plague epidemic had broken out in Pelusium in 541 CE (51). Its apparent source was the plague reportedly then endemic in "Ethiopia" (the kingdom of Aksum) (52, 53), whose northern slopes were the major source of grain for export downstream on Nile river boats or via the coastal Red Sea route.

Phylogenetic evidence points to an East African origin of the "antiqua" biovar of the Justinian plague bacterium (54), perhaps deriving from its established sylvatic source in Central Africa (55). Infected black rats from Aksum would have traveled with grain shipments destined for Pelusium, via river boats or Red Sea ports (53, 56). Archaeological evidence shows that black rats had colonized northeastern and northern Africa many centuries earlier, presumably migrating from their homeland in India via the longstanding sea trade (57, 58).

Upstream conditions on the River Nile during postharvest season, passing through the Nubian Desert, would usually have been too hot (33–40 °C) and dry for rat survival and for flea reproduction, survival, and regurgitation of the plague bacteria. Similarly, the Red Sea coastal temperatures are some of the hottest in the world, typically approximately 41 °C in July and 32 °C in January. The tolerable temperature range for the several critical aspects of flea biology, especially reproduction, is ≈20–30 °C (59), well reflected in the fact that most outbreaks have occurred in places with mean annual temperature of 24–27 °C (44).

Research into the geographic origins of this pandemic has largely overlooked its striking coincidence in time with an abrupt global cooling event. In 535 CE, a massive volcanic eruption (perhaps in Rabaul) and its consequent atmospheric shroud caused a rapid global cooling of approximately 3 °C that lasted for a decade (60). Weather patterns were disrupted, with flooding in Arabia and heavy snowfalls in Mesopotamia. Dramatic crop failures, hunger, and unrest occurred at that same time in central Sweden, Ireland, northern China, and Central Asia's grassland steppes.

In Europe this "536 Event" coincided with a background cooling trend (21). The especially cooler conditions during the late 530s, along with apparent wetter weather, would have created an unusual and brief opportunity for plague-infected rats and fleas to travel north to Pelusium, where grain storage facilities doubtless sustained a thriving rat population. Although infected rats are unlikely to have survived the full journey, infected fleas can survive for long periods in protective materials (53). It was an easy next step for rats, fleas and bacteria to cross the Mediterranean and infect the citizens of Constantinople.

Great Famine, Europe. In the early 14th century northern Europe experienced the worst prolonged famine in its recorded history, the "Great Famine" (61). During the most severe 7-y period (1315–1322), dire weather prevailed, with incessant and often torrential rain, floods, mud, and cold. The horrors of this time left long-lasting memories of widespread starvation, epidemic disease, deaths, class conflicts, rain-drenched warfare, and widespread violence and theft. In 1316 the relentless rains caused such misery and starvation that horses and dogs were eaten.

The best estimate of the famine's overall mortality toll in northern Europe is that up to one-tenth of the population perished. Death rates were higher in towns and cities than in the countryside. Such statistics overlook the misery and bodily debilitation of the many thousands who starved. In such conditions of social disorder and impoverishment, infectious disease epidemics are likely. Indeed, a mysterious "grim pestilence" reportedly spread in Europe—perhaps a mix of several infectious diseases. In the most afflicted localities in The Netherlands, France, England, and Scandinavia this pestilence killed one in three persons (18).

The Great Famine was almost certainly due to a mix of social, climatic, and environmental changes, including economic disruptions from recent changes in land availability and agricultural practices (61). In such bleak settings, a change in climate can impose a critical extra stress on a vulnerable population.

Post-Tambora Cooling in Europe, 1816–1818. The heavy atmospheric sulfate aerosol pall from the "supercolossal" Tambora volcanic eruption, in Indonesia in April 1815, caused several years of global cooling—a drop of 2 to 3 °C—and erratic weather patterns. That eruption (the most extreme for more than 1,000 years), followed an unusual sequence of four other major volcanic eruptions during 1812–1814 that had already initiated global cooling. As global temperatures fell, serious harvest failures occurred in North America, China, and in Europe (62, 63). In subtropical East Africa the cooling caused an unusually severe drought.

In Europe starvation and death rates rose as food prices spiked. The price of rye increased 2.5-fold in Germany during 1816–1817 (23). Food riots occurred in England, France, Belgium, Germany, and elsewhere. The combined miseries of hunger, starvation, and outbreaks of typhus and relapsing fever caused many groups to migrate, notably out of grain-starved northeast United States (21, 63). Typhus outbreaks occurred in London, tens of thousands died in Ireland from starvation and typhus infection, and in Glasgow much of the population succumbed to these infections, including 3,500 deaths.

Fertility in northeast China, where the cooling and famine were severe, declined by half (64), whereas in Europe hungry and hostile crowds overthrew several minor monarchies.

Late Victorian Droughts (1870s, 1890s): 30–50 Million Deaths (China, India, Southeast Asia, Brazil). During the 1870s and 1890s extreme droughts and hotter temperatures occurred in China, South Asia, Australia, Brazil, and elsewhere. The droughts were associated with unusually strong El Niño events, causing a westward arc of desiccation through Asia, Africa, and northeastern South America. They caused an estimated 30–50 million deaths, particularly in India, Brazil, and China (65, 66).

Climate did not act alone. In British India the famines of 1876–1878 resulted from a combination of El Niño-driven droughts and colonially enforced integration of local food markets with the emerging global market—into which India continued to export wheat. As a marginal concession, starving laborers assigned to make-work public projects received meager rations. Millions of deaths ensued from starvation and infectious diseases.

In China, after prolonged drought, the Great North China Famine of 1878–1879 caused approximately 10 million deaths, from starvation and epidemic outbreaks. In northeast Brazil, where severe droughts occurred in 1877–1878, half a million

Table 3. Main conclusions from historical review

- Long-term climate changes have often contributed to the decline of civilizations, typically via aridity, food shortage, famine, and unrest.
- Medium-term climatic adversity, causing hunger, infectious disease outbreaks, poverty, and unrest, has often led to political overthrow.
- Infectious disease epidemics have often accompanied or followed short-term and acute episodes of temperature shifts, food shortages, and social disruption.
- Societies can build resilience and learn to cope with recurring shorter-term (decadal to multiyear) climatic cycles (e.g., El Niño Southern Oscillation, North Atlantic Oscillation) other than when extreme phases occur.
- Weather disasters afflict both rich and (especially) poor populations. Recovery, sometimes with social reorganization, usually occurs.
- The nexus of drought, famine, and starvation has been the major serious adverse climatic impact on health over the past 12,000 y.
- Cold periods, more frequent and often occurring more abruptly than warm periods, have caused more apparent stress to health, survival, and social stability than has warming.
- Historical experience shows that temperature changes of 1 to 2 °C (whether up or, more frequently, down) can impair food yields and influence infectious disease risks. Hence, the health risks in a future world forecast to undergo human-induced warming of both unprecedented rapidity and magnitude (perhaps well above 2 °C) are likely to be great.

farmers and families died from starvation and epidemics. In 1878 one-third of the population of the region's capital, Fortaleza, died from smallpox (66).

Acute Climatic/Weather Events

Countless such acute events have occurred over the centuries. Two examples are illustrative.

Yellow Fever in Philadelphia, Summer 1793. The severe El Niño event of 1789–1792 culminated in unusually hot conditions in North America. In July–August 1793 an epidemic of mosquito-borne yellow fever broke out in sweltering Philadelphia, well beyond the normal northern limit of this tropical disease.

One month earlier, more than 1,000 refugees had fled north to Philadelphia from the sugar cane-growing French colony Saint Domingue (now Haiti), where a slave rebellion and a fever epidemic had broken out (67). Unusually warm and humid conditions prevailed in Philadelphia at that time, enabling proliferation of the *Aedes* mosquito population. During the 3 mo before the unusually vast mosquito population was culled by severe early winter frosts, yellow fever caused tens of thousands of painful and ghastly deaths in Philadelphia.

Storms and Coastal Communities (Injuries, Deaths). The fluctuation of climatic conditions during the Little Ice Age was accompanied by several periods of more frequent extreme weather events. Many severe storms and floods along Europe's North Sea coast have occurred over the past millennium, often causing great destruction and mortality, both directly and by starvation from crop losses (68).

In January 1362, for example, the "Great Drowning" occurred during an extreme storm along the coasts of Denmark, The Netherlands, and Germany, causing an estimated 100,000 deaths. More than 70 coastal villages were washed away. In 1588 another great North Sea storm destroyed much of the mighty Spanish Armada, while also causing deaths and coastal devastation in The Netherlands (68).

Health Impacts: Relationship to "Climate Change" Duration and Coping Capacity

Human societies, typically conservative, either do not clearly perceive emerging external (e.g., climatic) stress, or respond too late (30). However, sustained long-term climate change necessarily endangers previously well-adapted culture and practice, especially agriculture. Much evidence over the past 7 to 8 millennia indicates that multicentury climatic changes, as impinged on the Sumerians, the Classic Mayans, the Norse Vikings in Greenland, and (in a complex sense) the Western Roman Empire, can undermine, disperse, or perhaps terminate a society. If food yields fall, often accompanied by water shortages, then nutrition and health suffer, work capacity decreases, epidemics occur more readily, social cohesion declines, and conflicts emerge. deMenocal (20) observes, "What differentiates these ancient cultures from our own is that they alone have witnessed the onset and persistence of unprecedented drought that continued for many decades to centuries." We moderns, he implies, have not yet been tested.

Multidecadal climatic changes have often imposed great suffering and increased mortality—especially in most vulnerable segments of society. However, recovery, often with social and political reorganization, usually occurs. Examples include the several occasions when sustained falls in annual Nile flows in ancient Egypt caused hunger and hardship (prompting upgraded water-risk management by pharaonic officials), and the Great Famine in Europe in the early 14th century. The latter disruption was compounded by the ensuing Black Death, both "shocks" contributing to the ongoing weakening of Europe's feudal system.

That Second Pandemic of bubonic plague, beginning in the 14th century, entailed a complex multidecadal sequence of influences on ecological and then demographic determinants of the initial outbreak (in China) and its subsequent Eurasian spread. A further complex example, from China, is the loss of the imperial rulers' *Mandate of Heaven* by four of the six last dynasties at times of sustained climatic adversity (particularly drought), food shortages, and social uprising (7, 69).

Briefer multiyear climatic fluctuations have sometimes been disastrous for health and survival, although without necessarily causing systemic damage to major social institutions—as with the great droughts of late 19th century in India and China. Other such events have destabilized societies, as occurred in the Eastern Roman Empire when stricken by the Plague of Justinian (occurring after a half-decade of abrupt marked cooling).

Short-lived, acute, climatic shocks, including extreme weather events such as floods and storms, have repeatedly wreaked great damage, injury, death, and disease. The impacts have usually been greatest in the most vulnerable populations, reflecting location, housing patterns, resources, and governance. However, although often tragic, these are transient shocks in the historical record, usually remediable by rebuilding.

Conclusion

Historical experience provides useful insight into the types and magnitudes of adverse health impacts caused or contributed to by changes in climate. Less explicit in the historical record are the benefits to health, fertility, and longevity during times of stable benign climate. Historical information makes clear that sustained or abrupt changes in climate have frequently affected food yields, nutrition and survival, epidemic outbreaks, and conflict leading to deaths, injuries, and diseases. In contrast, before the mid-20th century there is little information about health impacts of heatwaves, the mental health consequences of climatic adversity, and lower-profile infections such as dysentery.

The greatest recurring health risk has been from impaired food yields, mostly due to drying and drought. The fact that drought has been the dominant historical cause of hunger, starvation, and consequent death (70) casts an ominous shadow over this coming century, for which climate modeling consistently projects an increase in the range, frequency, and intensity of droughts (71). As evidenced by the very recent extreme-summer experiences in Russia and Western Europe, excessive heat is equally damaging to crops and livestock.

The historical evidence of climatic influences on infectious disease epidemics is less strong than for hunger and under-nutrition. In a warmer future world, the range, rates, and seasonal duration of many infectious diseases is likely to increase, because bacteria at higher temperatures and vector organisms (mosquitoes, fleas, etc.) multiply faster—up to a temperature limit that threatens survival (44). Infections and infestations will also pose increased risks to agriculture.

The main inferences drawn from this historical analysis are summarized in Table 3.

An earlier analysis of climate impacts on (mostly European) societies since the decline of Rome noted the "ominous implications for the twenty-first century, no matter how great its technical virtuosity or its global awareness" (72). Recent trends in climate change-related indicators, along with continuing international political procrastination, are making more likely a 3 to 4 °C average surface warming this century—and perhaps beyond (73–75). Compared with the historical record this would be an extreme and rapidly evolving long-term change in climate, without precedent during the Holocene. Such a change will surely pose serious risks to human health and survival, impinging unevenly, but sparing no population.

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