Health Effects of Climate Destabilization: Understanding the Problem

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ABSTRACT

Climate change is a public health emergency. Evidence that a mass extinction is underway, that global ecosystem productivity is deteriorating, and that the biosphere is damaged by human actions continues to accumulate. This review aims to provide a summary of the health consequences of climate destabilization, which include heat-related illness and death, wildfires with air pollution, floods, droughts, water scarcity, increased frequency of intense storms, reduction in agricultural and seafood harvests, spread of infectious diseases, and higher rates of mental illness.

INTRODUCTION

Climate change is a public health emergency. The American College of Physicians Health and Public Policy Committee and the Lancet Commission on Health and Climate Change warn that climate change will harm human health by causing heat-related illness and death, wildfires with air pollution, floods, droughts, water scarcity, increased frequency of intense storms, reduction in agricultural and seafood harvests, spread of infectious diseases, and higher rates of mental illness.[1,2]

This review aims to provide a synopsis of the health consequences of climate destabilization and is intended for those who do not follow climate studies and seek a current summary.

GREENHOUSE GASES: ATMOSPHERIC INSULATION, LOWER PH IN BODIES OF WATER

Combustion of fossil fuels and deforestation are changing the climate by adding greenhouse gases (carbon dioxide, methane, nitrous oxide) to the atmosphere and carbon dioxide to bodies of water. In the United States, sources of greenhouse gas emissions are transportation (29%), electricity (28%), industry (22%), residential and commercial (12%), and agriculture (9%).[3] Adding greenhouse gases warms the Earth and alters precipitation, glaciers, ocean temperature and pH, and sea level. See Table 1, Box, and Figure for information about the basic science of greenhouse gases in Earth's atmosphere.

EXTREME HEAT, HYPERTHERMIA, WILDFIRES, AND POSSIBLY KIDNEY DISEASE

Global warming makes extended extreme heat more likely, leading to several potential health issues. Using mathematical models based on past climate changes, a doubling of atmospheric carbon dioxide (CO_2) concentration from 280 parts per million (PPM) to 560 PPM is predicted to cause an increase in the average global mean surface temperature of 2.2°C to 3.4°C.[4] Evaporation is the principal method of heat loss in a hot environment, but it becomes ineffective above 75% relative humidity.[5]

At an external temperature of 40°C, healthy adults may develop hyperthermia (see Table 2) after several hours. However, when humidity is high, they may develop hyperthermia at an external temperature of 35°C.[6] Global warming raises hyperthermia risk by increasing both temperature and humidity, and in the United States, premature heat-related deaths could increase by thousands to tens of thousands by the year 2100.[7]

Southwest Asia already has a hot climate. Near the coasts of the Arabian and Red Seas and Persian Gulf, temperatures are accompanied by high humidity. Assuming that greenhouse gas concentrations continue to rise, coastal Southwest Asia will experience extreme heat exceeding conditions for hyperthermia.[6] A regional climate simulator program was used to predict Middle

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Table 1. Summary of Health Effects of Greenhouse Gas (GHG) Emissions From Combustion of Fossil Fuels and Deforestation

Direct Effects	Indirect Effects	Social Effects
Raised global land and water temperatures[11] Maximum temperature rise is determined by net cumulative GHG emissions[12,13] Acidification of water[14,15] Deoxygenation of water	Increased evaporation causing heavy rainfall, floods, soil erosion[15,16] More powerful hurricanes with more rainfall[17] Reduced seafood and agricultural harvests[14,16] Less crop nutrient quality Toxic blooms of microorganisms in water More vector-borne human disease[15,18] Drought and wildfires Ground water depletion Loss of marine and terrestrial biodiversity = 6th extinction Floods cause soil erosion and microorganism contamination of water[7] Melting of cryosphere, sea level rise[19,20]	Loss of habitat and forced migrations due to heat, desertification, and sea level rise More people impoverished due to weather/climate disasters Grief and mourning due to personal, social, and natural losses More mental illness[15] Food scarcity and undernutrition[18,21] Disruptions to fresh water resources, exhaustion of aquifers[15]

Adapted from Figure 1 of reference 22.

Eastern temperatures if there is no climate change mitigation (Intergovernmental Panel on Climate Change Representative Concentration Pathway 8.5, IPCC RCP 8.5). Later in this century, temperatures above 35° C with high humidity would be common in summer, possibly lasting for extended periods. Outdoor activities would be severely limited, even for healthy, younger adults.[6] In contrast, temperatures predicted using a climate model with reduced greenhouse gas emissions (IPCC RCP 4.5) are more tolerable.

Hyperthermia may cause acute kidney injury, and as world temperatures rise, outdoor laborers may be at risk for a new form of chronic kidney disease that does not appear to be associated with diabetes, hypertension, or other kidney diseases. Since 1990, cases of this disease have been reported among workers exposed to extreme heat in Central America, the Pacific Coast of South America, Sri Lanka, and central India.[8] Approximately 20,000 persons have died from the disease. Patients are often poor, work long hours in sun and heat, and may suffer from dehydration. They are usually previously healthy men who develop severe renal disease over 1 or 2 years of outdoor labor. So far, neither a toxin nor an infectious agent has been consistently identified, and a hot outdoor work environment seems to be present in every case.

Extended periods of warmer temperatures with longer summers and shorter winters, coupled with little rainfall, are also associated with larger and longer duration forest fires.[9] This is apparent in the western United States, where there has been a 5-fold increase in forest fires in states west of the Rocky Mountains in the last 50 years.[9] Wildfires not only cause human deaths, as well as damage to forests and homes, but they also dramatically increase air pollution near the fire.[10] Wildfire smoke includes carbon monoxide, nitrogen oxides, and small particles that can be inhaled into the pulmonary alveoli.[9] During the Sonoma-Napa, California wildfire in October 2017, the particulate air quality (PM2.5) in San Francisco was the worst ever recorded.[9] Inhalation of small particles is associated with exacerbations of acute myocardial infarction, cardiac arrhythmia, stroke, asthma, and chronic obstructive pulmonary disease. Carbon monoxide may kill persons close to the fire, so is a particular threat to firefighters.[9]

Box. Glossary

Climate change/climate destabilization: Includes all aspects of climate over a long time period, including precipitation, temperature, winds, storm intensity.[19,23]

Global warming: Rapid warming of the global mean surface temperature (GMST) of Earth caused by GHG emissions.[19,23]

Climate adaptation: Actions taken to manage the impacts of climate destabilization as distinguished from directly reducing atmospheric [CO_2] [14]

Greenhouse effect: Visible light travels through the windows of a greenhouse warming the interior, but infrared light cannot leave the greenhouse. This traps infrared light (heat) inside the greenhouse.[17,19]

Greenhouse gases: Greenhouse gases slow the movement of infrared light through the atmosphere warming the Earth; they insulate Earth.[3]

Hyperthermia: Elevation of core body temperature above the normal diurnal range of 36° C to 37.5° C due to failure of thermoregulation. Hyperthermia is not synonymous with the more common sign of fever, which is induced by cytokine activation during inflammation and regulated at the level of the hypothalamus.[5]

Saffir Simpson hurricane wind scale: Classifies hurricane severity by wind speed, with category 5 having the highest wind speeds. Each category is a range of wind speed. Wind speed multiplied by time is an estimate of hurricane power.[24]

Water scarcity: Less than 1,000 m^3 per person of available, renewable freshwater per year.[25]

WATER SCARCITY, FLOODS, AND DROUGHT

Presently, about 17% of the global population (1.1 billion persons) experiences some degree of water scarcity as defined in the Box.[25,26] In North Africa, the Middle East, and South and East Asia, water scarcity is caused primarily by population pressure.[26] Climate change intensifies water shortages and threatens fresh

Figure. Diagram Depicting the Potential Effects of Climate Change on Human Health

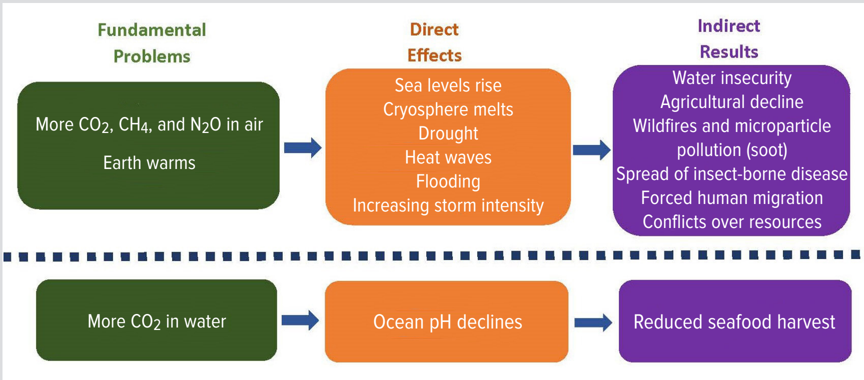

Table 2. Effects of Higher Ambient CO2 Levels on Nutrients of Crop Plants[7,33]

Photosynthesis Type	Crop	Genus	High [CO_2] Effect
C3: Photosynthesis begins with 3-carbon molecule; photorespiration	Wheat Rice Pea Soybeans Barley	Triticum Oryza Pisum Glycine Hordeum	6%-15% less protein per calorie Zinc, iron, calcium, copper, magnesium reduced per calorie
C4: Photosynthesis begins with 4-carbon molecule; no photorespiration	Maize Sorghum	Zea Sorghum	No change in protein or mineral concentrations per calorie

Plants were grown in fields surrounded by open top chambers with CO_2 enrichment (free air CO_2 enrichment [FACE]), allowing modification of ambient air for experiements. There is an unusual third type of photosynthesis called Crassulacean acid metabolism that is not found in crop plants.

water sources that, in turn, reduce water available for drinking or irrigation. For example, floods and heavy precipitation can cause water-borne infections by contaminating fresh water sources with microorganisms from animal and human waste and by breaching infrastructure barriers between drinking water, wastewater, and storm water.[7] As fresh or marine waters warm, bacterial concentrations rise.

In the United States, the most common organisms associated with water-borne diarrheal illness are enteric viruses (norovirus, rotavirus, and adenovirus), bacteria (*Campylobacter jejuni*, *Escherichia coli* O157:H7, and *Salmonella enterica*), and protozoa (Cryptosporidium and Giardia).[7] Exposure occurs through ingestion, inhalation, or direct contact with contaminated drinking or recreational water. From 1948 to 1964, 68% of outbreaks of diarrheal illness were preceded by heavy precipitation or flooding.[7] More recently, during flooding in North and South Carolina in 2018 caused by Hurricane Florence, drinking water became contaminated with animal waste and coal ash toxins when flood water flowed into wastewater pits and coal ash deposits.

Rising temperatures also make drought more likely, although locations subject to drought are difficult to predict and may occur in unanticipated places.[26] Eastern Mediterranean countries experienced a severe drought from 2007 to 2010. Observations and modeling suggest that the Mediterranean basin (Southern Europe, Middle East, and North Africa) is dryer now than in the past and, unless there is additional rainfall, has an increased probability of drought in the future due to higher temperatures.[26] Modeling also suggests that southern Africa may become dryer.[26] China, India, and Pakistan depend on fresh water from snowmelt in the Himalayan mountains. If this snowmelt declines, water scarcity could affect these populous nations as well.[27]

In the United States, the Southwest is experiencing a "hot drought," meaning that drought is caused by higher temperatures without a proportional rainfall increase.[28] In the Midwest, hotter temperatures, rainfall with spring flooding, soil erosion, and shorter, milder winters are expected. As temperatures rise, more water evaporates from the Gulf of Mexico, causing more rainfall in the Midwest and Northeast.[16] Heavier precipitation and floods cause leaching and runoff into lakes and streams, delayed spring planting, and loss of soil nutrients.

AGRICULTURAL IMPACT

Persistent heat, floods, droughts, and sea level rise are expected to reduce agricultural harvests and have a significant impact on the global food supply.[1,2]

Although some high latitude farms will benefit from warmer temperatures, higher ambient CO_2 concentrations, and longer growing seasons, average harvests worldwide are expected to decline.[29] In fact, in 2017, worldwide yields of some cereal crops declined because of climate-related disasters, and the number of hungry persons rose.[14,30]

Warming of 1.5° C will lead to reduced harvests of maize, rice, and wheat in sub-Saharan Africa, Southeast Asia, and Central and South America.[14,29] In parts of the American West, Midwest, and South, increased heat and evaporation during longer summers without a compensatory increase in rainfall will likely make agriculture more difficult. Climate change may also alter the distribution and incidence of pests, creating new sets of challenges.[31] And increasing storm intensity and greater flooding are likely to disrupt food production, storage, and transportation.[29] Food spoilage and foodborne illness are also associated with hotter temperatures.

What's more, higher atmospheric CO_2 concentrations diminish the nutrient concentration in important plants. If efforts are not made to reduce CO_2 emissions, ambient CO_2 could reach 550 PPM by 2050–2060 (Representative Concentration Pathway, RCP 8.5). Some crops grown in CO_2 concentrations of 546 PPM to 584 PPM have less protein, iron, and zinc per calorie compared to crops grown at CO_2 concentrations of 363 PPM to 386 PPM (Table 2).[32,33] In addition, some crops grown in high CO_2 concentration of 689 PPM have less iron, phosphorous, calcium, magnesium, copper, zinc, and sulfur compared to crops grown when ambient CO_2 concentration is <400 PPM.[7] A modeling study suggests that more than 100 million persons could become zinc or protein deficient and hundreds of millions of people—particularly women and children—could become iron deficient as a result of CO_2-induced nutrient deficiencies.[32]

OCEANS AND LAKES, RISING SEA LEVELS, ACIDIFICATION, DEOXYGENATION

The Earth's cryosphere—glaciers and polar ice—is melting. In fact, since 1970, the arctic ice cap has lost about 40% of its volume and, by 2040, may be completely gone during summer.[20] As water warms, its volume expands because the average distance between water molecules increases.[19] This thermal expansion, together with melting cryosphere, cause sea levels to rise.

Since 1901, the Earth's sea level has risen about 20 cm, including 7 cm since 1993.[20] Currently, the world's oceans are rising 3 mm to 4 mm per year, and the Intergovernmental Panel on Climate Change (IPCC) reports that a 1.5° C temperature increase will cause the sea level to rise 0.26 meters to 0.77 meters by 2100, compared to sea levels during 1986 to 2005.[14]

As coastal waters rise, forced migrations from affected areas will occur. Indeed, a rise of 0.9 meters could displace 100 million people.[17] Approximately 10% of the world's population (approximately 600 million people in 2007) lives in low-lying coastal regions within 10 meters elevation of sea level.[34] Much of this population resides in 17 of the world's 30 largest cities, including New York and London as well as Mumbai, India; Shanghai, China; Jakarta, Indonesia; and Bangkok, Thailand. Asia is most vulnerable to rising seas because large areas of Bangladesh, Viet Nam, Indonesia, the Philippines, and China are only slightly above sea level.[26] As many as 136 coastal cities, each with a population of 1 million persons or more, may be at risk of flooding by 2100.[26] In the US, tidal flooding affects 25 Atlantic and Gulf Coast cities.[11,35]

Climate change is also harmful to plants and animals. For example, in recent years, coral reefs throughout the world have experienced bleaching, including about 29% of the Great Barrier Reef.[36] Bleaching is caused by heat and acidification and is often followed by death. Initially, corals (phylum Cnidaria) lose the ability to perform photosynthesis because of loss of symbiotic photosynthetic algae.[37] Because numerous species inhabit reefs, which also protect immature fish from predators, the loss of corals to bleaching may cause unanticipated declines in ocean fish populations and marine biodiversity.

As water warms, less oxygen is dissolved in the water. This, in turn, can lead to "dead zones"—relatively anoxic areas in lakes, rivers, or the ocean that no longer support life. When molecular oxygen dissolves in water, heat is released; the reaction is exothermic. This is why molecular oxygen dissolves more into colder water.[38]Thus, reduced oxygen concentrations caused by warmer water may lead to loss of organisms in freshwater lakes and streams, as well as the ocean, causing reduced fish and shellfish harvests.

Blooms of "toxic algae" occur when unusually warm water receives a large influx of nutrients (eg, nitrogen and phosphorous).[7] These nutrients come from sewage, manure, or chemical fertilizers. In freshwater lakes and rivers, "toxic algae" are usually cyanobacteria, whereas in the ocean it is often the alga Karenia brevis. Rapid growth or "bloom" consumes oxygen and kills other organisms living in the affected water. Blooming microorganisms sometimes release metabolites that are toxic to other organisms and to humans. North America's Lake Erie experienced cyanobacteria blooms in 2019, while coastal blooms of Karenia brevis or "red tides" occurred in Florida in 2018.[39] Warmer waters due to climate change are partly responsible.[40] Toxic algal blooms most commonly harm children swimming in an affected freshwater lake. Toxins may cause fever, headache, rash, vomiting, diarrhea, wheezing, confusion, or paresthesia after skin exposure.[41] Drinking contaminated water produces vomiting and diarrhea. In salt water, toxins from Karenia brevis may contaminate shellfish and, if eaten, may produce diarrhea or neurologic symptoms of confusion, paralysis, or amnesia.[41]

Global warming and ocean acidification are different processes, but both occur as a result of anthropogenic CO_2 emissions. As CO_2 concentrations increase in air, more CO_2 dissolves into water. Some of this aqueous CO_2 reacts with water to form carbonic acid (H_2CO_3), which ionizes to form hydrogen ion and bicarbonate. The extent of ocean acidification is determined by tropospheric CO_2 concentration. So far, ocean pH has declined by 0.1 pH units since the beginning of the industrial revolution.[42] Ocean acidification harms not only corals, but starfish (phylum Echinodermata), squid and octopus (phylum Mollusca), and sea snails (Pteropods, class Gastropoda) as well.[26,43,44] Pteropods—pelagic molluscs abundant in polar and temperate waters—are a food source for fish, whales, and birds, and, thus, are critical to the ocean ecosystem. Acidification, warming of water, toxic blooms, and deoxygenation combine to harm fresh water and ocean organisms, reducing their biodiversity and causing seafood harvests to decline.[14]

TROPICAL STORMS: EXTRA POWER AND ADDITIONAL RAINFALL

Recently, there have been unusually large and powerful hurricanes. In August, 2017, Hurricane Harvey produced the largest rainfall (132 cm) ever recorded in the city of Houston, Texas.[45] In nearby Nederland, Texas, 153.87 cm of rain fell—the largest rainfall ever recorded in the United States.[46] Hurricane Irma (Florida and Caribbean Islands) and Hurricane Maria (Puerto

Table 3. Hotter Climate Impact on Ranges of Insect/Arachnid Vectors of Disease

Human Disease	Agent	Vectors	Climate Change Effect
Lyme[51,52]	Genus *Borrelia*	*Ixodes scapularis* (black-legged tick) (Arachnida)	Migration from US to Canada, northerly migration in Europe, more Lyme borreliosis in Canada and northern Sweden
Dengue[53]	Genus *Flavivirus*	*Aedes* mosquito (Insecta)	Migration from tropics toward poles
Malaria[53]	Genus *Plasmodium*	*Anopheles* mosquito (Insecta)	Migration to higher altitudes in Africa
West Nile Encephalitis[52]	Genus *Flavivirus*	*Culex* mosquito (Insecta)	Migration from US to Canada

Rico)—both category 5 tropical cyclones—also occurred in September, 2017.

A hurricane (eg, tropical cyclone) extracts heat from warm ocean water at least 27.8° C,[47] converts some of this heat into wind energy, and returns cooler water as rain. Extracting heat to do work is a concept in thermodynamics called a Carnot heat engine.[48] Like a Carnot heat engine, a hurricane extracts heat to perform mechanical work (ie, wind).[49] This theoretical understanding of the relationship between water temperature and energy available to a cyclone suggests that as ocean waters warm due to climate change, hurricanes will become more powerful. Modeling studies support this theory.[17,26,49] This does not mean there will be more cyclones, but that the percentage of Saffir-Simpson category 4 and 5 cyclones (defined in Box) is likely to increase, as well as the volume of rainfall per cyclone.

Hurricane-related deaths are usually caused by drowning, injuries such as lacerations or fractures, and exposure to floodwaters containing sewage and industrial chemicals.[45] In New Orleans in 2005, Hurricane Katrina claimed 1200 lives, and 63 people died as a result of Hurricane Harvey in 2017.[17,45] Problems may be further exacerbated following a hurricane, if services such as clean water and sewer, medical care, garbage removal, and schools are lost for an indefinite time.[50] For example, following Hurricane Katrina, some municipal services took 5 years to repair and 196,000 children were required to change schools.[50]

INFECTIOUS DISEASE, MIGRATIONS OF TICKS AND MOSQUITOES

Because insect and arachnid vectors are sensitive to temperature, a warmer climate may alter and expand the geographic ranges of vector-borne human diseases (Table 3). Consider, for example, Lyme borreliosis, which is caused by infection with the spirochete Borrelia and is transmitted to humans by black-legged ticks (genus *Ixodes*).

The geographic distribution of Lyme disease has increased from endemic to adjacent areas (Table 3).[51] In the United States, the number of reported cases of Lyme disease increased from 2007 to 2013 and was stable from 2013 to 2016.[51] In Canada, new cases of Lyme borreliosis have increased 10-fold since 2004.[52]

At the same time, the black-legged tick has migrated from Maine to southeastern Canada and from Minnesota to Ontario and Manitoba.[52] The mouse (ie, genus *Peromyscus*) that is the reservoir for *Borrelia* in the United States and the primary blood source for black-legged ticks also has migrated to Canada. It is possible that this expansion is due in part to global warming, though the life cycle of ticks and transmission of *Borrelia* to humans is complex and is influenced by many variables.[10] Meanwhile, in Europe, another species of tick–*Ixodes ricinus*–has migrated North during the past 30 years and caused emergence of Lyme borreliosis in northern Sweden.[52]

Human infections usually occur in the late spring and summer when ticks are active in the woods. Thus, a warming climate, longer warm season activity, and geographic expansion of ticks increase human exposure.[7,52]

As Earth becomes warmer, areas affected by mosquito-borne diseases also may expand.[7] The *Aedes* mosquito transmits dengue fever, zika virus, and yellow fever virus.[22,53,54] These are RNA viruses, genus *Flavivirus*. There are about 390 million cases of dengue fever each year. Since 1950, the vectorial capacity of *Aedes* mosquitoes has steadily increased[22] and could, in part, be caused by climate change.[53] Vectorial capacity is a measure of how many humans are susceptible to a vector-borne infectious disease. Geographic range and the size of the susceptible human population are included in this measure.

Culex mosquitoes transmit West Nile encephalitis, another *Flavivirus* disease, to humans and birds in the United States. Birds carrying West Nile virus had not been found in Canada prior to 2002.[52] Outbreaks there of West Nile encephalitis in 2007 and 2012 may have been related to unusually high rainfall and warm temperatures, respectively.[52]

The *Anopheles* mosquito transmits malaria (genus *Plasmodium*), and there are about 200 million new cases, 90% occurring in Africa.[55] Due to warmer average temperatures, this mosquito has migrated to higher altitudes in Africa, but a similar migration has not been detected in South America or Asia.[22] Still, the IPCC anticipates that global warming of 1.5° C or 2° C will cause the geographic ranges of malaria and dengue to continue to increase.[14]

MENTAL HEALTH

People not directly affected by a climate disaster may fear the upheaval and uncertainty of climate change. A study of patients seen in a family practice clinic suggests a correlation between concern about climate change and emotional distress or inner tension.[56] It seems reasonable that people would mourn or feel grief ("ecological grief") when they learn about extinction of species, forests burning, or consider how their children will inherit a diminished and more dangerous Earth.[57]

Climate destabilization increases the number of individuals exposed to disasters and, therefore, to subsequent psychological problems. People who experience extreme weather may become more susceptible to depression, anxiety, posttraumatic stress disorder, and suicidal thoughts.[10] For example, people whose homes flooded in the United Kingdom in 2013-2014 experienced depression (20%), anxiety (28%), or posttraumatic stress disorder (36%) when interviewed 1 year after the flood.[58] One month after Hurricane Katrina, 31% of persons interviewed who were directly affected by flooding had symptoms suggestive of an anxiety-mood disorder.[45] Persistent heat and resulting crop failures have been related to farmer suicides in India.[58] Violence and crime in individuals, social groups and nations may increase as resources diminish.[10,50] Migration forced by disaster may reduce mental health.[50,58] However, steps can be taken to mitigate some of the effects of disasters related to climate change. The United Nations' "Building Back Better" program has emphasized the importance of restoring housing, public services, and jobs to avoid prolonged mental effects after a disaster.[45] Repairing a damaged community improves community mental health.

CONCLUSION

A United Nations report calls climate change "the greatest threat to global health in the 21st century."[59] This crisis increases the risks of famine, drought, flooding, infectious disease, contamination of fresh water, and forced migration of human populations. And as the century continues, more people will be affected, either directly or indirectly by one or more climate destabilization events.

Individual health care workers may help to address this problem by talking with others about climate change, reducing their personal carbon footprint, and participating in an organization that works to mitigate climate destabilization.

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