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Climate Change and Mortality: Time for Actuaries to Pay Attention!

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Climate Change and Mortality:

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Climate Change and Mortality

Time for Actuaries to Pay Attention!

Executive Summary

The World Health Organization (2018) pronounced climate change to be the most important health challenge of the century. The purpose of this paper is to raise awareness of the extent that this health, mortality and longevity risk is becoming an increasingly important component of climate change costs and human health.

Climate change, as evidenced by changes in various climatic factors including temperature, precipitation, humidity and wind and their consequences, poses substantial threats to human life and health. These threats involve diverse health concerns including communicable and noncommunicable diseases, injuries, hazardous exposures and vulnerabilities, and mental health as well as deaths. These health risks include those that are immediate (e.g., due to extreme weather events such as tropical cyclones, heatwaves and floods) and more gradual (e.g., due to droughts and rising sea levels).

We as a society will confront more record-breaking heat around the world (Europe and China in 2022), more frequent floods (as in India, Germany, China and Australia), more frequent droughts (as in western North America), more severe wildfires and storms (as in Russia, the United States and Australia) and rising sea levels that will threaten coastal cities (such as Miami and Jakarta)—to name a few. Actuarial employers, households, communities and society as a whole will face escalating costs and damages.

These will increasingly affect the mortality assessed in a wide range of actuarial applications. Climate change represents a health emergency, the largest health threat threatening humanity (WHO 2021B). In sum, it is an issue that deserves attention and consideration in actuarial practice now and in the future.

1. Introduction

The objective of this paper is to raise awareness and encourage discussion of the mortality and longevity implications of climate change, especially as they relate to the life insurance and annuity industries. Although most attention by these industries to date has been on the effects of climate change on their invested assets, the focus of this paper is on mortality-related risks that affect product or program financial performance and their customers.

This important, but complex, issue involves a waterfront of risks on a global basis, including those in higher-income countries, that now and will increasingly affect actuarial practice.

This paper does not address mitigation issues related to the underlying drivers of climate change, such as greenhouse gas emissions or decarbonization, as it deals with information that can enhance the understanding of the implications of climate change on human health and longevity, that is, some of its key consequences. Although it was earlier thought of as only constituting a long-term concern, this is no longer the case, as its effects are already beginning to be felt worldwide.

In a NEJM Catalyst Innovations in Care Delivery survey (Salas 2022) of nearly 800 global health care leaders, 70% of U.S. respondents indicated that climate change is already affecting the quality of health care service delivery. Yet fewer than a quarter of respondents reported that their organizations had assessed their climate-related hazards. It is time that the biological ramifications of climate change be both considered and acted on.

Several myths have emerged about this important global issue of concern over the last several years. It is the hope that this paper will, at least to some extent, dispel these myths and encourage further discussion.

The remainder of this paper is organized as follows:

- Section 2 describes some of the major climate change risks that are relevant to human mortality and health.
- After a brief overview of some of the attribution data problems associated with the analysis of this issue in section 3, relevant mortality risks are discussed in section 4, which includes key topics relating to temperature, especially related to incremental hot- and cold-related mortality, precipitation extremes, extreme events, food and water insecurity, air quality and pollution, and slow-onset conditions. Specific diseases are then addressed, including infectious, cardiovascular and respiratory diseases. Also, other related issues are addressed, including regional and local variations, urbanization, the vulnerable, especially those of extreme ages, and poverty and inequality. Also included is a discussion of possible favorable impacts of climate change.
- Section 5 addresses indirect effects and other-than-mortality impacts, including mental health.
- Section 6 discusses the effects on insurance and pension programs as well as some of the leading myths related to this topic, especially from the perspective of insurers, especially those involved in life or health insurance or annuities.
- Chapter 7 discusses data, modeling, and measurement concerns, chapter 8 uncertainties, and chapter 8 available lines of defense involved.
- Section 10 outlines areas for further research.
- These chapters are followed by a conclusion, an appendix with eight case studies included in IPCC (2022), and a list of sources referred to in this paper.

2. Climate Change

Climate and weather changes have occurred since the beginning of time. However, current concerns have arisen because of the influence of mankind's actions, their unanticipated adverse effects, and the exacerbation of other environmental and climatic risks. The current scientific consensus is that noticeable impacts have occurred since the beginning of the Industrial Revolution, especially evident over the last several decades. They are expected to have escalating impacts on the atmosphere, land and water at least through the end of this century.

This consensus strongly indicates that these changes have been primarily due to an increase in greenhouse gas emissions that in turn have increased their concentration in the atmosphere, on land and in water. Future actions to support international mitigation and adaptation[1] reflected in national commitments based upon the agreement reached at the 2015 United Nations' Climate Change Conference held in Paris (the Paris Agreement at COP21) may reduce what would otherwise have become an even greater amount of accumulated greenhouse gases. Nevertheless, climatologists indicate that, because of the accumulation of these gases, consequential climate changes will further develop over time. "Climate change will affect, in profoundly adverse ways, some of the most fundamental determinants of health: food, air and water."[2]

This paper asserts that the scope and severity of the consequences of climate change, present in today's world, will increase over time. Although it is well recognized that climate change represents a long-term peril to many components of our planet and our life on it, it is already manifesting itself today. The study of climate change should not be restricted to the study of warming temperature with respect to its intensity, volatility and duration, although its effects are wide-ranging. It also affects all other climatic factors, which include the following:

1. **Temperature extremes and volatility.** The most talked-about effect of climate change ("global warming") is an increase in average and extreme global temperatures (usually measured from the average temperature level experienced immediately prior to the inception of the Industrial Revolution, between 1850 and 1900). In the years immediately preceding 2023, the world is between 1.1 and 1.2 degrees Celsius warmer than in the pre-industrial period, with the past eight years being the hottest eight years recorded,[3] with 2023 expected to be the warmest year globally on record.

   Temperature, in turn, can influence other climatic factors that affect air, land and water in ways that can affect human health. In particular, these can take the form of heatwaves[4] and warm nighttime temperatures. In a study of 43 countries and regions, Wu et al. (2022) examined short-term temperature volatility (measuring it as the standard deviation of the average of the same and prior days' minimum and maximum temperatures). They found between 2000 and 2019 a gradually

[1] Mitigation, discussed briefly in section 9.1, refers to a reduction in the sources of climate change, principally those that are the result of the accumulation of greenhouse gases in the Earth's atmosphere. One hundred percent adaptation refers to adjustment(s) made in ecological, social or economic systems in response to actual or expected climatic stimuli and their adverse effects or impacts to a point that minimal or no damage is anticipated from an adverse climatic scenario. Zero percent adaptation means that no effective adaptation actions have been taken, and 50% adaptation is the midpoint.
[2] https://cdn.who.int/media/docs/default-source/climate-change/report-by-the-secretariat-on-climate-change-and-health.pdf
[3] World Meteorological Organization. January 12, 2023. https://public.wmo.int/en/media/press-release/past-eight-years-confirmed-be-eight-warmest-record.
[4] Heatwaves are usually defined as being a period at least two (or three) days in length that exceeds a certain temperature, e.g., 35 degrees Celsius that can differ by geographic area. The mortality effect has been found to decrease over the 10 days subsequent to the heat event.

increasing trend in global temperature variability (a 4.2% increase from January 2000 to January 2019).

Heatwaves in the U.S. are happening more frequently (an increase of about 175% between the 1960s and 2010s), with longer duration and greater intensity. During a longer hot season, some cities are experiencing increasing trends in the duration and intensity of heatwaves.[5]

For example, the number of heatwaves in the 50 largest cities in the U.S. tripled from an average of two a year in the 1960s to more than six during the 2010s, according to the U.S. Global Change Research Program (USGCRP 2018). In addition, the annual time frame in which those heatwaves occurred was 47 days longer.

2. **Extreme precipitation.** Variations in precipitation can lead to either more intense individual downpours or drought conditions. Excessive precipitation can result in flooding, landslides, soil erosion and more intense tropical[6] cyclones. Droughts in already arid regions may continue, spread and increase in duration and severity. Water scarcity ultimately can adversely affect human health and through food and water insecurity the mortality of especially vulnerable populations. These contrasting climatic patterns will differ by geographic area, humidity,[7] barometric pressure and ultraviolet radiation—all of which may reach extreme and damaging levels, especially when they occur over a long period. For example, although droughts have often occurred in parts of the western U.S., multiyear drought conditions can turn into a megadrought, which has now gone on for more than two decades and has reduced water levels in key reservoirs and rivers to record lows, the worst in at least 1,200 years (Williams et. al., 2022). Worldwide, severe drought has resulted in many cases of malnutrition and stunting.

3. **Other climatic factors.** Although not as much discussed as temperature and precipitation, other climatic factors, such as humidity, wind and barometric pressure, particularly on a combined basis, can also adversely affect mortality. For example, wet-bulb temperature,[8] which may be a better risk metric than temperature in some areas and under some conditions, measures heat stress in direct sunlight, reflecting temperature, humidity, wind speed, sun angle and cloud cover; it is also expected to increase throughout this century. Climate change has roughly tripled the exposure of the human population that experiences dangerous humid heat, already approaching the limits of human tolerance in a few locations such as the Middle East and parts of India. When temperatures rise, people can become severely ill when their bodies are unable to sweat effectively and cool off. High humidity exacerbates this risk because sweat cannot evaporate quickly. This then increases internal body temperature, which in turn can cause muscles, hormones, and enzymes to stop working and organs to shut down. Humidity also increases the overall energy requirements of cooling systems, which accounts for a large fraction of power consumption in humid climates where air conditioning has become widespread. Wind can be a risk multiplier after drought and heat conditions ignite a wildfire.

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[5] https://www.epa.gov/climate-indicators/climate-change-indicators-heat-waves.
[6] A strong tropical cyclone in the North Atlantic, central North Pacific, and eastern North Pacific is often referred to as hurricanes and a tropical cyclone in many other parts of the world are called a typhoon.
[7] Humidity is the amount of water vapor in the air.
[8] Wet-bulb temperature (wet-bulb globe temperature) contrasts with the heat index, takes into consideration both temperature and humidity and is determined for shaded areas. It measures the temperature read by a thermometer covered in a wet cloth. As water evaporates from the cloth, evaporation cools the thermometer, which mirrors how the human body cools itself with sweat.

4. **Extreme events.** Both the frequency and intensification of extreme climatic-related events may increase and will result in a great deal of physical and financial damage, which will increase as populations increase in size, age and urbanization. Examples include tropical cyclones (although the frequency of those making landfall in North America—called hurricanes—may not increase, they will likely increase in precipitation severity because of warmer air and sea), floods, windstorms, landslides and other life-threatening consequences.

5. **Slow-onset conditions** include sea-level rise, ocean acidification, biodiversity loss, glacial retreat, drought and desertification. Slowly developing or reoccurring conditions can have a cumulative debilitating effect, such as desertification in areas such as Central Asia. They can also result in sudden adverse consequences. For example, climate-induced changes will likely result in rates of sea-level rise three to four times higher than previous estimates, which can adversely affect water quality, as well as cause increases in coastal flooding and vector-spread diseases. Many areas of the world have already been affected, with East Asia and Middle East/North Africa expected to exhibit the greatest relative impacts (Dasgupta et al., 2007).

Extreme values of one or more of these factors, especially when combined with other factors, can turn a bearable situation into an unbearable one. These factors can interact, especially when several events or conditions occur in close spatial and temporal proximity. The resulting cascading or compounding risks can increase the risk of severe adverse climate-related events and conditions more than the individual factors acting independently. For example, a lengthy period of drought and excessive heat, combined with strong winds, can contribute to the spread, and thus duration and severity, of wildfires.[9]

In addition, a wide range of indirect and secondary consequences of climate change acting through these climatic factors is likely. Examples include deteriorated air quality due to unsafe amounts of ozone and particulate matter, and food and water insecurity[10] from droughts or famines, conflicts, storms, wildfires and slow-onset conditions. Secondary impacts can also arise, for example, from forced mass climate emigration of those exposed and vulnerable, which can lead to health risks associated with areas with high population densities and increases in the geographical reach and quantity of insects and other disease vectors.

Economic damage and decreased quality of life can also ensue, including from excess stress and mental illness that in turn might result in a deterioration in human longevity. These can also result in infrastructure, property and ecosystem damage to human, animal and plant health, along with adverse productivity, standards of living and other economic consequences.

Flood risk is a good example of the complexity and interconnectedness of the wide range of circumstances and consequences. For example, interacting with weak urban infrastructures and changing land use and soil sealing[11] can expose urban areas to river (fluvial) floods, flash floods, precipitation-driven (pluvial) floods, sanitary and sewage system overflows, floods due to inadequate drainage, coastal floods and glacial

[9] The frequency of wildfires, according to the United Nations Environmental Programme (2022), is expected to increase by 50% by 2100.
[10] Defined by the U.S. Department of Agriculture as "economic and social condition of limited or uncertain access to adequate food." Diet-related conditions such as cardiovascular disease and diabetes are linked to food insecurity. https://www.ers.usda.gov/topics/food-nutrition-assistance/food-security-in-the-u-s/definitions-of-food-security
[11] The destruction or covering of the ground by an impermeable material such as asphalt or concrete.

lake outburst floods. Sea-level rise, tropical cyclone storm surge and rainfall intensity all increase the probability of coastal city flooding, especially where cities are located in low-elevation coastal zones.

Coastal flooding associated with sea-level rise may be exacerbated by the significant number of people living in surrounding areas, especially those in areas that are subsiding. Kaspersen et al. (2017) noted that flooding in European cities could increase by up to 10% for every 1% increase in impervious surface area. This is especially the case where there has been limited investment in drainage solutions and flooding regularly disrupts livelihoods and undermines local food safety and security for the urban poor. In addition, flooding of agricultural land can adversely affect food production and distribution, which in turn increases food insecurity of those living in urban areas. Overall, the increase in flood risk and damage from urban development can be considerable: a function of where we build, what we build and how we build.

The intensity of flooding and damage from it can also differ dramatically across regions and locales, depending on geography and the preparedness of those in the exposed area for a particular type of risk. These events and conditions can batter public health systems, regardless of the quality of their health care and emergency response infrastructure, although these can help reduce damage.

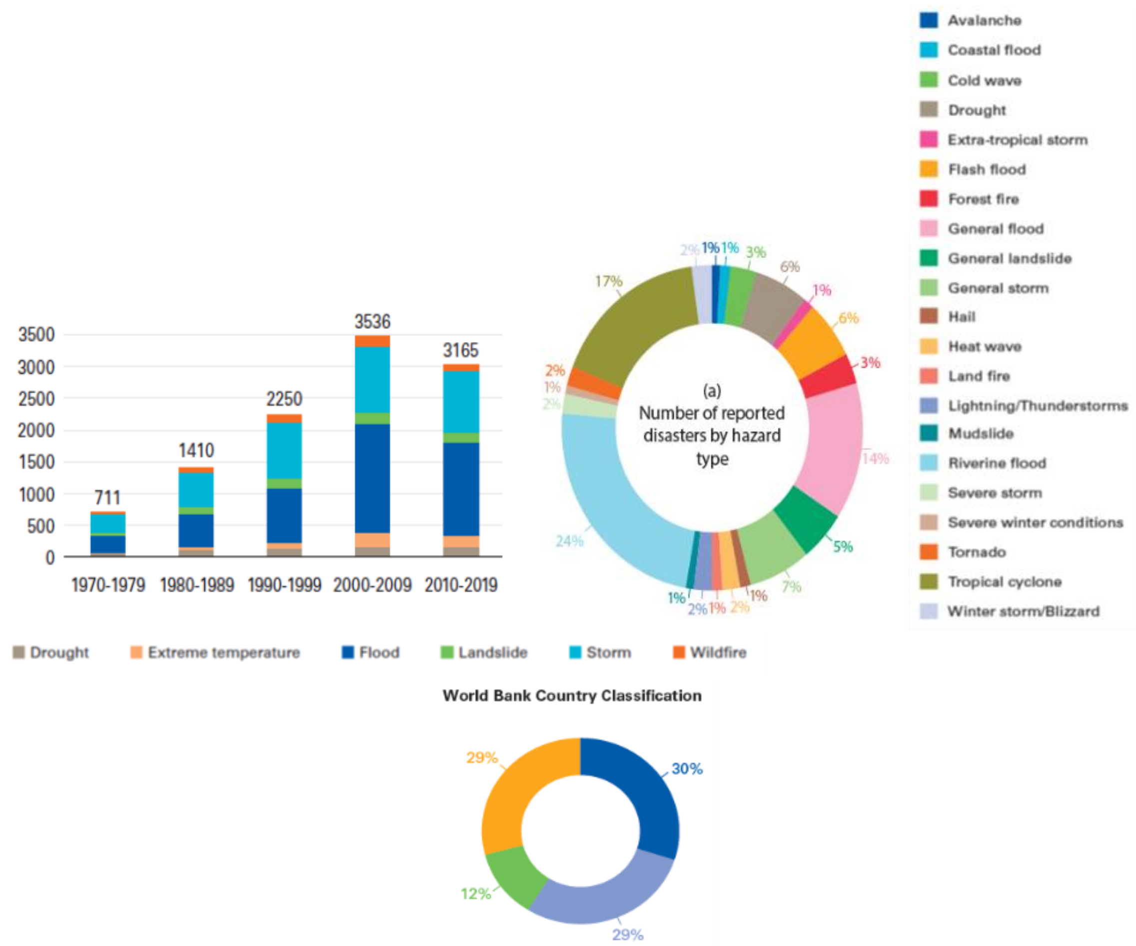
Although climate change has often been associated with its adverse effects, in some cases it can bring benefits and opportunities (further discussed in section 4.10). These effects can arise both as a result of climate change itself (e.g., changing crop patterns that might reduce food insecurity and decreased mosquito populations than would otherwise be the case) and from opportunities presented by mitigation and adaptation actions (e.g., increased use of air conditioning may reduce deaths resulting from extreme heat conditions and contribute to more effective development and applied technology, further discussed in section 9.2). Opportunities can arise as society adapts to the new realities and can piggy-back with adaptation action.

Figure 1 shows the global trend over the past 50 years of the number of weather-related disasters[12] by type and by the income level of the applicable country. During that period, about 650,000 deaths were due to droughts, 575,000 were due to storms, 59,000 were due to floods and 56,000 were due to extreme temperatures. The general trend over the 50-year period has been an increase, although the number of disasters declined in the 2010s. The mix of types can differ significantly by country, region and timeframe; in the U.S., for example, in most years heatwaves now kill more Americans than hurricanes, tornadoes and floods combined (Adams-Fuller 2023).

[12] A disaster in this context is defined as a "serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources." https://disasterdisplacement.org/the-platform/key-definitions/. It is especially dangerous when interacting with high levels of exposure and vulnerability.

Figure 1

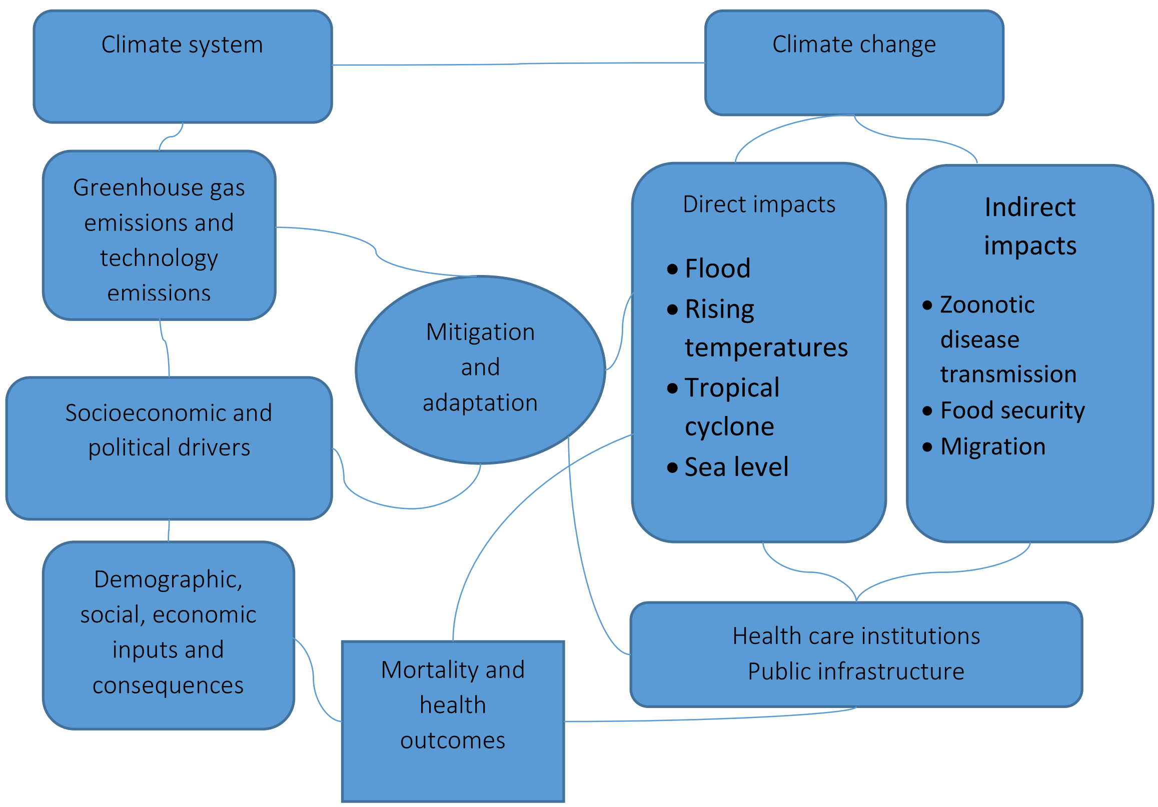
NUMBER OF WEATHER-RELATED DISASTERS (11,072 IN TOTAL) BY TYPE AND INCOME CATEGORY OF COUNTRY



Source: World Meteorological Organization (2021).

Figure 2 is a simplified diagram of the complex relationship between contributing factors driving climate change risks and health and longevity. At the local and regional levels, the direct and indirect health and mortality impacts of climate risks can be reduced by effective adaptation actions. Although the subsequent discussion in this paper relies on these elements and the characteristics of these relationships, some of them will not be discussed in detail, as they have been extensively covered in many other sources (see, for example, Gutterman 2020).

Figure 2
A SYSTEM REPRESENTATION BETWEEN CLIMATE RISKS AND HEALTH AND LONGEVITY: INPUTS AND IMPACTS



3. Attribution

Attribution issues affect the findings of a climate change and mortality analysis in two ways: (1) the distinction between "normal" weather or climate and climate change-related factors, conditions and events and (2) the identification of reported deaths due to climate change. Attribution attempts to provide answers to both of these questions. Both are affected by the complexity of the processes involved, including the climatic change process described in section 2 and the multiple biological and environmental factors that can contribute to death.

Attribution analysis is a developing area that addresses these processes, distinguishing the contributing factors involved. In some cases attribution cannot be done accurately because of the multiple factors and mortality drivers involved. In addition, climate change can in some cases be viewed as a mortality risk multiplier, exacerbating other adverse health conditions, not necessarily reported as being the primary cause of death. For this paper, it can be assumed that climate change has amplified—and will continue to amplify—the impact of many extreme weather events and conditions.

This can often be made more difficult because of the lengthy time lags involved in some cases; the longer the lag between the event and death, the less likely the attribution relates to the event. For example, 64 deaths in hospitals were reported in Puerto Rico due to Hurricane Maria in 2017; this contrasts sharply with the official estimate of about 3,000 over the succeeding weeks and months, which was possibly over 5,000 using a door-to-door canvas of deaths to reflect all relevant excess deaths (Kishore et al. 2018).

This topic is important because climate change perils, such as excess heat, are not commonly indicated as being the primary cause of death, even when it is a contributor cause. The Centers for Disease and Prevention (CDC's Wonder Data Base) has indicated that they increased from a low of 297 deaths in 2004 to 1,714 in 2022, reflecting a significant increase in recent years (ICD codes P81.0, T67, and X30). It can be presumed that the number of climate-related risks has been and will be underestimated.

Although the attribution of climate change as the primary driver of adverse mortality events or conditions is difficult at the best of times, some drivers are fairly clear. For example, various attribution studies have shown that a heatwave as severe as that seen in India in the first half of 2022 would be highly improbable were it not for global warming.[13] In contrast, the precise percentage attribution of climate change to the 2021 autumn floods that stopped many Chinese farmers from planting their wheat at the best time and under the best conditions cannot be definitively determined. As extremes of temperature, precipitation and other climatic factors are becoming more common, so is the likelihood that multiple adverse events might arise in the same growing season, with potentially devastating consequences.

Conclusions may differ depending on the circumstances involved and the metrics used. For example, heat extremes have increased in frequency and intensity, and tropical cyclone rainfall and storm surge height have increased worldwide, with tens of thousands of deaths being directly attributable to climate change (Clarke et al. 2022). Meanwhile, some droughts may not be attributable to climate change at all.

An attribution study, using 28 different definitions of a heatwave (e.g., daily maximum, mean average daily and minimum daily temperature, each over a specific threshold temperature and a minimum number of days) that can differ by location found, using a threshold of 35 degrees Celsius daily maximum over at least two days in two regions of North Carolina, that between 25% and 27% of the cost related to emergency room visits could be attributed to climate change (Bell, Puvvula and Abadi 2021).

A 43-country study associated with additional heat exposure to warming during the period between 1991 and 2018 found that, on average, 37% (range 20.5–76.3%) of heat-related deaths could be attributed to climate change and that increased mortality is evident in every inhabited continent—about 9,700 annually in the 732 locations studied (Vicedo-Cabrera, Scovronick and Gasparrini 2021). Across all locations, heat-related mortality amounted to an average of 1.56% of all warm-season deaths, which differed widely by region: for example, 0.87% in the United States, 1.06% in Canada, 1.78% in Australia and more than 5% in southern Europe.[14] In many locations, dozens or hundreds of deaths each year are attributed to heat due to climate change.

Indirect mortality consequences include, for example, many air pollution-caused deaths. Although climate change may result in an exacerbation of poor air quality in the form of particulate matter ($PM_{2.5}$) from wildfire smoke, air pollution also has other contributing causes, and climate change shares common drivers for some. Thus, the adverse impacts of air pollution are often associated with and can be included as a co-cost of greenhouse gas accumulation. In addition, some of the actions aimed at managing the adverse

[13] https://www.worldweatherattribution.org/extreme-humid-heat-in-south-asia-in-april-2023-largely-driven-by-climate-change-detrimental-to-vulnerable-and-disadvantaged-communities/
[14] Vicedo-Cabrera, Scovronick and Gasparrini Supplementary Data. https://doi.org/10.1038/s41558-021-01058-x

impacts of climate change, that is, mitigation of and adaptation to its many elements, carry with them additional costs and benefits.

Although this paper focuses on deaths that (in whole or in large part) are attributable to climate change, it may be more useful for some purposes to focus on all significant climate and weather-related risks, as the extent of deaths attributable to climate change can be contentious. However, if the purpose of the assessment is to determine how much it is worth to help mitigate the drivers of human-induced climate change, attribution can be important.

See the Committee on Extreme Weather Events and Climate Change Attribution et al. (2016) for further discussion of this topic.

4. Mortality Risks

This paper describes the effects on mortality as a result of multifaceted climate changes. The global number and sources of weather-related deaths over the period 1970 to 2019 are shown in Figure 3. Climate change can be a mortality risk multiplier, that is, it can exacerbate existing biological, environmental, climate and weather-related mortality risks.

Prüss-Üstün et al. (2016) estimated that in 2012 about 12.6 million deaths globally were attributable to the environment (not restricted to those due to climate change). This represents about 23% of all deaths and 22% of disease burdens expressed in terms of Disability-Adjusted Life Years (DALYs).[15]

From 1970 to 2019, according to CRED (2020), weather, climate and water hazards accounted for about half of all disasters (including technological hazards), 45% of all reported deaths (2.06 million) and 74% of all reported economic losses (US$3.6 trillion). Thus, on average, a disaster related to either a weather, climate or water hazard event occurred every day over the 50-year period, killing 115 people and causing US$202 million in economic losses daily.

In 2022, 29,061 deaths were directly attributable to 355 global climate or weather-related catastrophic events, slightly greater than the average number of deaths from such events between 2002 and 2021 (see Table 1). Of those in 2022, about 16,805 were from the European heatwave (some estimates were more than 20,000), 2,465 were from the drought in Uganda, India suffered 2,035 deaths from floods, and Pakistan saw 1,739 deaths from floods.

[15] DALYs are a common measure used to assess the effect of a factor affecting healthy life expectancy.

Table 1

DIRECT DEATHS FROM CLIMATE OR WEATHER-RELATED DISASTERS

Type of Disaster	2022	Average 2002–2021
Extreme temperature	16,416	8,538
Flood	7,954	5,195
Drought	2,601	1,057
Storm	1,611	10,006
Landslide	403	838
Wildfire	76	82
Total	29,061	25,716

UCLouvin, CRED, USAID (2023).

The WHO (2021B) estimated that projected climate change between 2030 and 2050 could result in 250,000 deaths per year under a mid-emission scenario. This is expected to be dominated by increases in deaths due to heat (94,000, mainly in Asia and high-income countries), childhood undernutrition (85,000, mainly in Africa but also in Asia), malaria (33,000, mainly in Africa) and diarrheal diseases (33,000, mainly in Africa and Asia). Overall, more than half of this mortality is expected to occur in Africa. Climate change–related deaths in 2030 are estimated to be predominantly due to childhood undernutrition (95,200 out of 241,000 deaths).

Science writer Gaia Vince[16] has identified extreme heat, drought, flooding and fire as being the four horsemen of the Anthropocene era. Together with other climate-related factors such as extreme events, unhealthy air quality and sea-level rise, they will render more of our planet uninhabitable by 2100.

Climate change has already exacerbated normal weather volatility to more extreme levels,[17] which will warrant increasing concern over time. The metrics used should be carefully selected and interpreted; for example, the average nighttime temperature may in some cases be more important than the maximum daily temperature, as human bodies need time to cool off. Typically, that would happen during sleep when the body's temperature dips. Particularly after a hot day, people must have an opportunity to bring their core body temperature down; otherwise, relief will not be achieved, placing more physiological strain during hot summer nights, increasing the likelihood of illnesses and deaths. According to USGCRP (2018), nights on average are warming faster than days across most of the U.S.

[16]Vince, Gaia. 2022. Nomad Century: How Climate Migration Will Reshape Our World. Flatiron Books. August 23, 2022

[17] Various indices have been developed to identify the frequency and trend of extreme climate factors; see, for example, the Actuaries Climate Index for Canada and the U.S. at https://actuariesclimateindex.org/home/.

In some cases, it is the duration of exposure that poses the greatest danger to human life rather than a single shock, such as through temperature or precipitation. For example, mortality from excessive heat exposure depends on both the temperature and the duration of exposure, which is why the length in days of exposure to excessive heat or weeks or months to drought is important.

Some of the mortality risks resulting from climate change are lumpy, that is, individual risks are not randomly distributed globally. Rather, they may be concentrated, for example, by geographic location, season and socioeconomic group. Thus, in many applications, concentration and tail risks are important risk characteristics to consider.

An example of concentration risk can be seen in the left bar chart in Figure 3. It is true that, overall, the number of weather-related deaths has decreased over the last several decades. However, 1,238,000 deaths were the result of seven events[18] (with at least 100,000 deaths each): four severe droughts in East Asia in the 1970s and 1980s and three severe storms in South Asia in the 1970s, 1990s and 2000s. Excluding these events and based on World Meteorological Organization (2021), 156,000 deaths occurred in the 1970s, 117,000 in the 1980s, 189,000 in the 1990s, 189,000 in the 2000s, and 185,000 in the 2010s. Because there has been an increase in global adaptation, such as increasing use of air conditioning, the author believes that the number of deaths over the 50-year period reflecting current adaptation conditions may have been an increase.

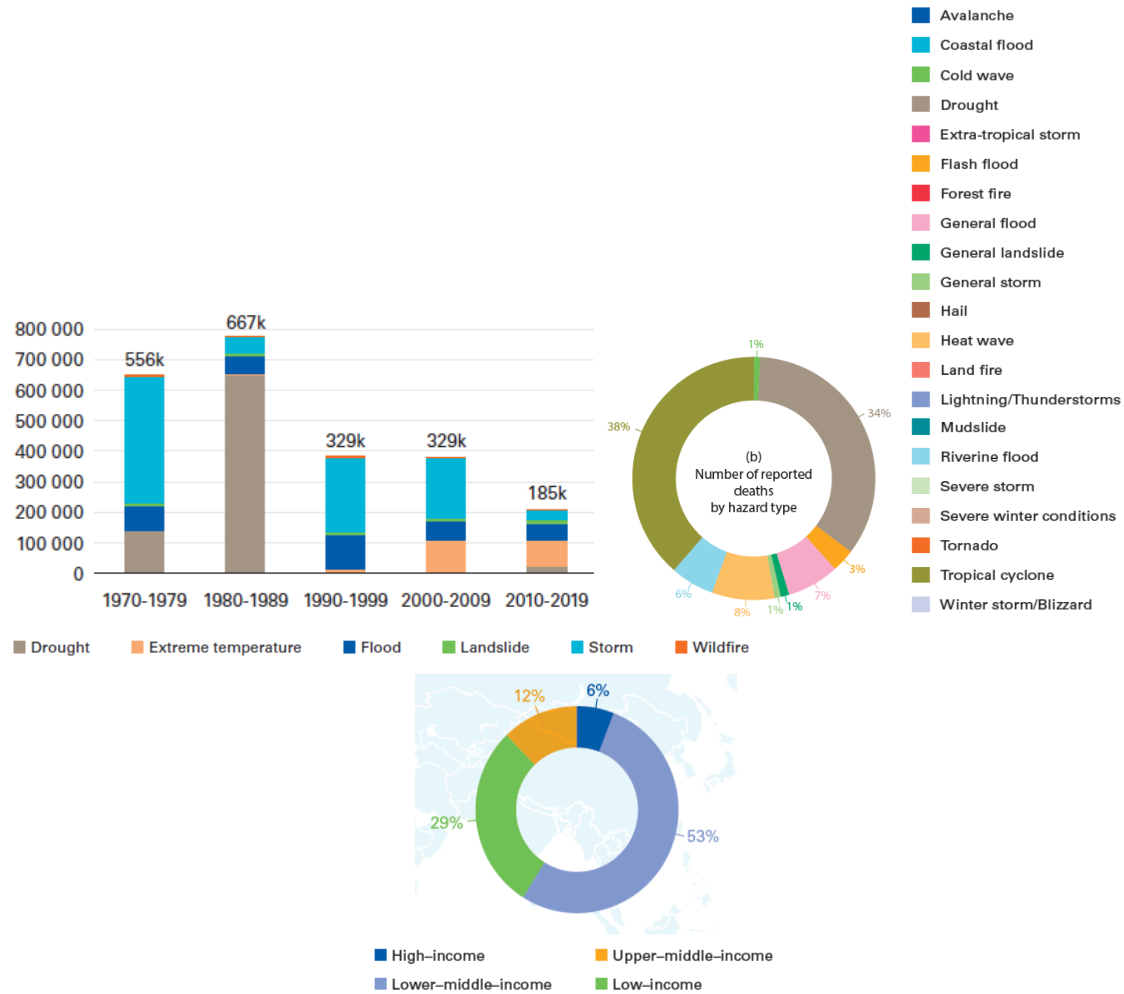
Although some climate change-related hazards are either of a sudden or slowly developing hazard nature, others can take the form of both. For instance, flooding might occur suddenly, but the resulting low-quality food and water supplies can be the result of organisms that cause food poisoning and microbial contamination of drinking water for years afterward.

To provide a current overview of weather-related mortality hazards, the data shown in Figure 3 were developed from the same database as that used in Figure 1. These data show the number of reported deaths by the type of reported number of weather-related disasters over the last five decades; because of the severe droughts and storms indicated above, they constituted a large percentage of these total deaths. Deaths in high-income countries have had significantly fewer deaths, although (not shown here) they had a significantly higher average economic loss.

[18] Droughts resulted in 300,000 deaths in Ethiopia in 1983, 150,000 in Sudan in 1983, 100,000 in Ethiopia in 1973, and 100,000 in Mozambique in 1981. Severe storms resulted in 300,000 in Bangladesh in 1970, 139,000 in Bangladesh in 1991, and 139,000 in Myanmar in 2008. (World Meteorological Organization 2021)

Figure 3

NUMBER OF REPORTED WEATHER-RELATED DEATHS (2,064,929 IN TOTAL) BY TYPE AND INCOME CATEGORY OF COUNTRY



Source: World Meteorological Organization (2021).

The following section discusses several major categories of climate change risks: temperature extremes and volatility, heavy or limited precipitation, extreme events, food and water insecurity, air quality and pollution, and slow-onset conditions. It also addresses consequential causes of death, including infectious diseases, cardiovascular and respiratory diseases, cancers and conflicts of violence; key aspects of these mortality risks including regional and local variations, urbanization and the vulnerable; and possible favorable effects of climate change.

4.1. TEMPERATURE EXTREMES AND VOLATILITY

Heatwaves have been referred to as the silent killers of climate change, as they may not be the sole or direct contributors to death. This is partly because excessive heat can aggravate existing conditions, such as respiratory and cardiovascular diseases, making attribution difficult. The increase in multimorbidities makes this an even greater concern, especially for those older than age 65. Heatwaves also do not damage property as floods and hurricanes do, except when they are linked to drought, wildfires, wind or other climate risks. Many people seek shelter when there are tornado warnings and leave coastal areas before a cyclone hits, yet many ignore extreme-heat advice.

According to the UN Development Programme and the Climate Impact Lab (2022), climate change is driving Earth's overall temperatures higher and amplifying the frequency of higher-intensity extreme events.

Extreme temperatures directly or indirectly caused 27% of all deaths attributed to weather-related disasters between 1995 and 2015 (UNDRR 2016), with a large majority (148,000 out of 164,000 lives lost or 90%) being the result of too much heat rather than too much cold. Further, Vicedo-Cabrera et al. (2021) estimated that 37% of heat-related deaths can be attributed to climate change.

An annual average of 25 major heatwaves resulted in an annual death toll of 7,232 between 2005 and 2014 (UNDRR 2016). In 2015, the hottest year on record (until subsequent years), there were 3,275 reported deaths from heatwaves in France, 2,248 in India and 1,229 in Pakistan. Watts et al. (2021) indicated that for those over age 65, heat-related mortality (not restricted to major heatwaves) had increased by 53.7% between the 2000–2004 and 2014–2018 periods (to about 300,000 deaths in 2018), with the majority being in Japan, eastern China, northern India and central Europe. Some have estimated that in 2022 Western Europe alone experienced more than 20,000 extreme heat-related deaths.

Many adverse consequences result from excessive heat. As the body struggles to cool itself by sweating, it can dehydrate. That puts the kidneys under stress, possibly resulting in kidney stones or kidney disease. Pressure also builds up in the heart, as it works to pump more blood and carry excess heat out of the body. This means there is less blood reaching the brain, which can cause dizziness, thus, among other things, increasing the likelihood of accidents. Under extreme heat conditions, increases in emergency room visits and hospitalizations have resulted from fluid disorders, dehydration, hyperthermia, renal failure and disease, urinary tract infections, septicemia, general heat stroke and stress, respiratory disorders and injuries.

Extreme temperatures can also contribute to diminished work capacity, sleep quality, behavioral and learning habits and academic performance, impaired concentration and cognition in both adults and children due to dehydration, electrolyte imbalances and fevers. Less severe outcomes are also possible, such as lethargy, headaches, fevers, rashes, cramps and exhaustion that can negatively affect children in school and play environments.

During extremely hot days, it can be difficult to thermoregulate. When the wet-bulb temperature exceeds skin temperature (about 35 Celsius), human bodies are no longer able to effectively dissipate heat into the environment, and in the extreme will result in greater mortality risk. Heat risk increases with exposure, the size and aging of the human population, and mounting vulnerability.

In 2019 an additional 475 million vulnerable people were exposed to heatwaves (Watts et al. 2021); the IPCC (2022) suggested that by 2040, even at 1.5 degrees Celsius above preindustrial levels, nearly one billion people could face life-threatening heatwaves at least once every five years.

By 2100, extreme heat events may make cities, where currently up to 600 million people live in parts of Asia and Africa, uninhabitable (United Nations Office for the Coordination of Humanitarian Affairs et al. 2022). Densely populated urban centers in South Asia, the Middle East and North Africa will suffer from recurring life-threatening heat events. The present exposure to heatwave events is estimated to be 14.8 billion person-days per year, with the largest cumulative exposures occurring in southern Asia (7.19 billion), sub-Saharan Africa (1.43 billion) and North Africa and the Middle East (1.33 billion). By the end of this century, one-third of the global population could be living in areas with average temperatures above 28.9 degrees Celsius.

This United Nations report also indicates that if global temperatures rise in excess of 2 degrees Celsius above preindustrial levels, by 2070 extreme heatwaves will make parts of the U.S., including Alabama, California, Georgia and Louisiana, less suitable for human habitation. In 2021 extreme heat killed more Americans than any other weather-related disaster. Many regions are already experiencing increasingly hot and frequent heat events. Heatwaves will become deadlier with every further increment of climate change. In July 2022, for example, more than 150 million Americans (nearly one in two Americans) lived in areas that had at least one extreme heat alert issued.

Not everyone is sensitive to heat in the same way. Some are at risk immediately as the temperature exceeds their comfort zone. Thermoregulation works inefficiently in some people, making their health more sensitive than others at a given temperature level, particularly the elderly and young children. Trends in heat sensitivity are likely to be scale- and situation-dependent, as considerable variation exists across population groups and geographic areas.

A global threshold beyond which daily mean surface temperature and relative humidity become lethal has been determined (Mora et al. 2017, in a review of 783 cases of excess mortality in 164 cities in 36 countries). About 30% of the world's population is currently exposed to conditions in excess of this threshold. Mora et al. projected this percentage will be between 48% and 74% by 2100 (Mora et al. 2018), depending on the level of warming and population distribution.

Wu et al. (2022) found a substantial mortality burden associated with temperature variability (both hot and cold), with a great deal of geographic heterogeneity. Globally, Wu et al. found that 1,753,392 deaths annually were associated with temperature variability (excess deaths associated with temperature variability, defined as the standard deviation of the average of the same and previous days' minimum and maximum temperatures) during the period 2000 to 2019, accounting for 3.4% of all deaths. Asia experienced the highest percentage of excess mortality (4.5%), with Europe the lowest (1.7%). Globally, the percentage of excess mortality increased by about 4.6% per decade.

Heatwaves across Europe (2003), Russia (2010), India (2015) Japan (2018) and India and Europe (2022) resulted in significant deaths and hospitalizations. In 2003 more than 70,000 deaths were attributed to the European heatwave out of about five million total deaths; in 2010 there were more than 55,000 heat-related deaths in Russia out of about two million total deaths (Klingelhöfer et al. 2023). The far lower number of deaths in Paris associated with a comparable heatwave in 2019 has been attributed to better preparedness of the public, health care infrastructure and emergency procedures, all of which should be implemented everywhere.

Shi et al. (2015) found that, across U.S. ZIP codes, increased mortality rates in warmer summers in New England in the United States were entirely due to temperature anomalies, while increased mortality risk was more related to the standard deviation in long-term average differences in summer temperature. They found that the health effects of both summer and winter mean temperature and temperature variability can differ greatly across climate zones. Adverse health effects of climate change can stem from an increase in year-to-year temperature fluctuations from which people have been acclimatized or an increase in daily variability within a season rather than to the warmer temperature itself. These authors thus found that both long-term and within-season volatility impact health risk.

Heat-related deaths are projected to increase in North America as a result of a combination of climate change and aging populations, poverty, chronic diseases and inadequate public health systems. From 2008 to 2017 in the contiguous U.S., Khatana et al. (2022) found that extreme heat was associated with greater all-cause mortality. In addition, greater increases in mortality rates were found for older than younger adults (0.19 deaths per 100,000 individuals), male compared with female adults (0.12 deaths per 100,000), and non-Hispanic Black compared to non-Hispanic white adults (0.11 deaths per 100,000). Without further mitigation, Khatana et al. projected that the increase in extreme heat due to climate change will widen health disparities between these population groups: "each additional extreme heat day in a month was associated with 0.07 additional deaths per 100,000 adults."

In the U.S., in contrast to an expected 8,500 deaths in a typical year under current baseline climate and demographic conditions, an additional 59,000 deaths per year are expected by 2050; this projection by the Atlantic Council (2021) assumes no further adaptation, no increase in power outages and no exceptionally hot years, but does reflect the effects of population growth and aging. Many of these excess deaths are expected to occur in southwest Arizona, southern California and southwestern Texas. Barreca (2012) estimated that in the U.S. each additional day of extreme heat (greater than 32.2 degrees Celsius) increased mortality by about 0.2 deaths per thousand or about 0.02%.

As average temperatures in India have increased, Mazdiyasni et al. (2017) found that, based on data from the India Meteorological Department between 1960 and 2009, there has been a substantial increase in mass heat-related deaths (periods with more than 100 deaths). Their results, including a recent period with more frequent and lengthier heatwaves, suggest that, after a certain point, acclimatization does not help much and that even moderate increases in mean temperature can result in a large increase in heat-related mortality. These heatwaves can result in unsustainable living conditions.

Mazdiyasni et al. (2017) found that an additional day in India with mean temperatures exceeding 36 degrees Celsius increases annual mortality rates by about 0.75% (relative to a day in the 22 to 24 degrees Celsius range). This is about seven times larger than currently the case in the U.S. (Deschênes and Greenstone 2011), but about the same as in the U.S. in the 1920s and 1930s before the introduction of air conditioning.

Thus, climate change-boosted heatwaves can increase the burden on societies like India, where many people live amid crowded conditions and in poverty, and where health care services are often strained. The probability of these mortality events can increase by a factor of 2.5% to 32% with an increase in summer mean temperature of 0.5% (to 27.5 degrees Celsius; Mazdiyasni et al. 2017). Such conditions were especially evident in the spring of 2022 when hundreds of millions of people in India and Pakistan experienced a massive heatwave, leading to threatening damage to entire ecosystems and key economic sectors such as agriculture, wreaking havoc on water and energy supplies.

Human-induced climate change is increasing the frequency and intensity of heatwaves that have already impacted human health in areas such as Europe (Vicedo-Cabrera et al. 2021). For example, the 2010 heatwave in Eastern Europe resulted in 55,000 heat-related deaths and at least 16,000 in 2022 in Western Europe, while the 2018 heatwave in Northern Europe and the 2019 heatwave in Western, Central and Northern Europe also had significant health impacts. About 35% of heat deaths in the U.S. can be attributed to climate change, with more than 1,100 deaths a year in about 200 U.S. cities. Vicedo-Cabrera et al. reported that Honolulu had the highest portion (82%) of heat deaths attributable to climate change.

Kovats et al. (2011), under a medium-to-high or balanced greenhouse emission (A1B) scenario as outlined by the IPCC in 2000 that did not anticipate further climate change, mitigation or adaptation, estimated an additional 26,000 deaths per year from the heat in the 2020s, rising to 89,000 per year by the 2050s, and 127,000 per year by the 2080s. Although each region of Europe is projected to experience an increase in heat-related mortality, this is expected to be particularly acute in Southern Europe.

To further illustrate the effect of alternative climate scenarios, Chen et al. (2022) projected about 20,000 heatwave-related deaths in China under Representative Concentration Pathway[19] (RSP)2.6, 35,000 deaths under RSP4.5, and 72,000 deaths under RSP8.5 (a high warming scenario), reflecting expected population size and aging.

Based on its central set of assumptions, the WHO (2014) projected 38,000 extra annual global deaths of those over age 65 by 2030 due to excessive heat. This projection assumes a relatively high level (50%) of adaptation; with no further adaptation, there would be 92,000 extra annual deaths. The central projection increases to about 100,000 extra deaths per year by 2050 and more than 250,000 with no further adaptation. The projected increase between 2030 and 2050 is expected to be greatest in South, East and Southeast Asia.

Despite increases in temperature and general population aging, heat-attributable mortality fractions (ratios of these deaths to total deaths) have declined in many countries due to general improvements in health care systems, increased prevalence of air conditioning and behavioral changes. These factors can significantly affect the susceptibility of a vulnerable population to higher temperatures. In any case changes in the possible level of climate change, adaptation and population composition should be considered in any projection.

4.1.2 HOT AND COLD

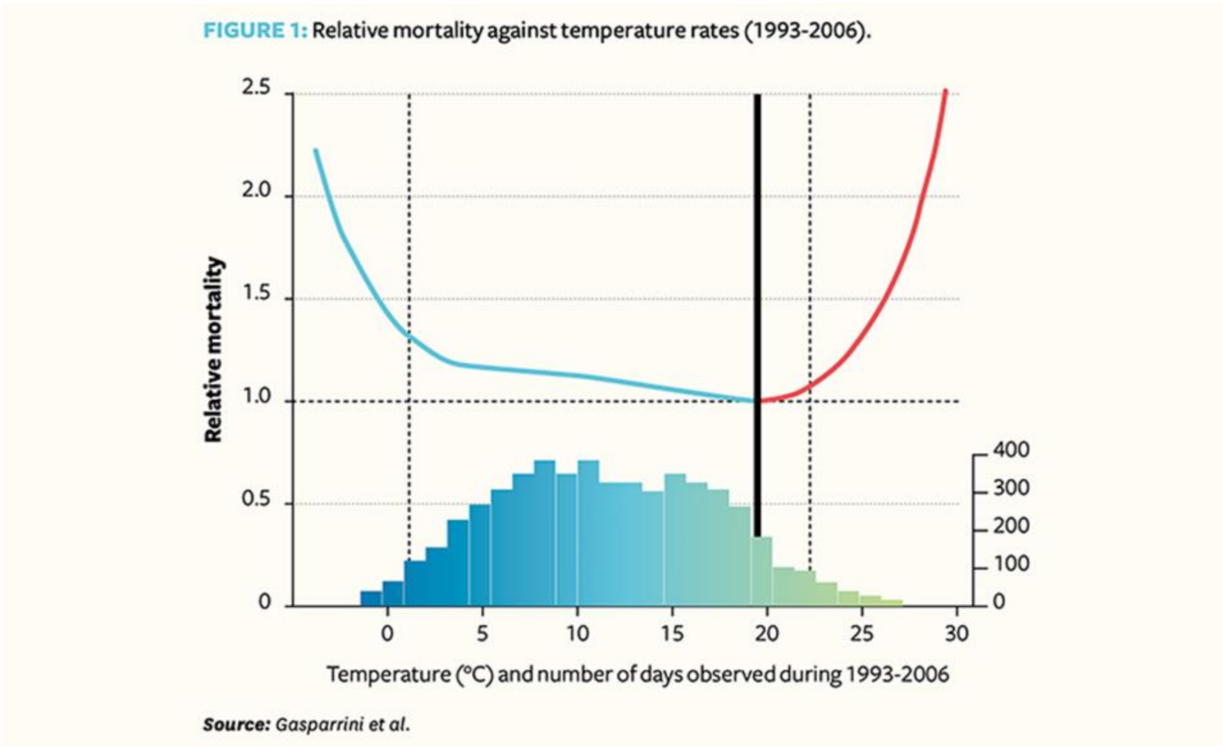
Increasing average global temperatures will likely increase the frequency and severity of extreme heat events and conditions, but at the same time may moderate the frequency of cold weather incidences. The relative importance to overall mortality of these two factors, including their volatility, is an important part of this discussion. The IPCC (2022) indicates that, with high confidence, future increases in heat-related deaths are expected to outweigh those related to cold.

In many countries in the aggregate, more deaths have occurred in the winter than in the summer. This is somewhat in contrast to the broadly U-shaped relationship between temperature and mortality shown in Figure 5: both extreme heat and extreme cold can lead to greater mortality risk. As overall temperature increases, the offsetting effects on mortality of these patterns depend on several factors, depending on the exposure to these temperature ranges and the vulnerability and sensitivity of applicable population segments: factors such as location, population mix and aging, socioeconomic mix and the effectiveness of adaptation measures taken (e.g., those with robust and affordable heating systems for cold temperatures and cooling systems for hot temperatures; Carleton et al. 2022).

[19] Representative Concentration Pathways are developed from Integrated Assessment Models were selected from the published literature as used in the Fifth IPCC Assessment as a basis for the climate predictions and projections presented in its Working Group II report AR5, labelled after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m^2, respectively). Higher values mean higher greenhouse gas emissions and therefore higher global temperatures and more pronounced effects.

Figure 5

A GLOBAL MORTALITY/TEMPERATURE CURVE OVER 14 YEARS



Source: Gasparrini et al. (2015)

In an extreme baseline case, if there were no heat-related deaths and a considerable number of cold-related deaths, an increase in temperature would most likely result in fewer deaths in total. In a study of 13 countries, more temperature-attributable deaths were caused by cold (7.29%) than by heat (0.42%), extreme cold and hot temperatures being responsible for 0.86% of total mortality (Gasparrini et al. 2015). However, because this study did not consider the effect of changes in future conditions, it may be inappropriate to conclude that global warming will necessarily benefit global mortality.

Extremely hot days can have a damaging nonlinear effect on mortality (Bressler 2021) because the frequency of extremely hot days is expected to increase exponentially as global average temperatures increase. Those in locations that have had naturally hotter climates are expected to be affected more than others because of the greater frequency of extremely hot days. In contrast, places with colder climates may see some mortality benefits from climate change because of the lower frequency of extremely cold days.

Between 2000 and 2019, although heat-related deaths[20] made up about 1% of global deaths (about 0.5 million deaths annually, increasing from 0.91% to 1.04% in the 2016–2019 period), cold-related deaths affected about nine times as many people (decreasing from about 10 times in 2000–2003 to about eight times in 2016–2019). There were about five million cold-related deaths annually: 8.52% of total deaths over the entire period, reduced to 8.19% during 2016–2019. As temperatures have risen since 2000, heat-related deaths have increased by 0.21% (116,000 deaths) while cold-related deaths have declined by 0.51%

[20] Using average daily temperatures, with cold and hot temperatures taken at suboptimal levels. The cold and hot temperatures were defined as temperatures either lower or higher than the minimum mortality temperature.

(283,000) (Zhao et al, 2021). Note that there is substantial variation geographically, with more than half of these total excess deaths occurring in Asia.

Mortality has been associated with both seasonal mean values and standard deviations of temperature. For example, among the U.S. Medicare population (those aged 65 and older) in New England during 2000–2008 (Shi et al. 2015), an increase in mean summer temperatures of 1 degree Celsius was associated with 1.0% greater mortality, and an increase in mean winter temperatures corresponded to 0.6% lower mortality. This suggests that people may be somewhat more sensitive to the effects of changes in hot temperature than corresponding changes in cold temperatures. It was also found that greater temperature volatility (standard deviations) in both summer and winter represented a health risk.

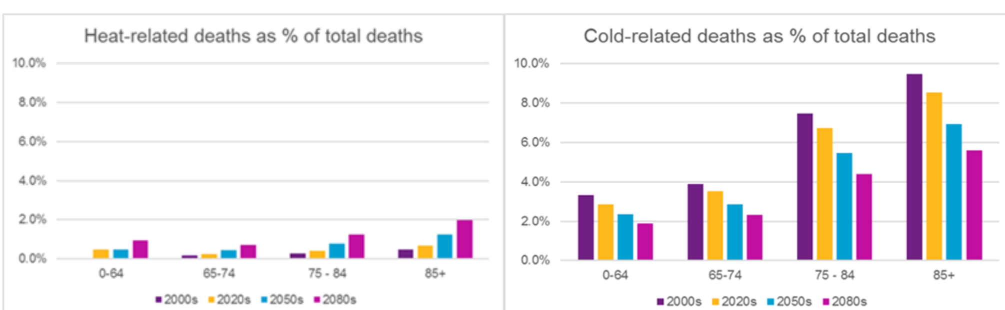
Cold spells are projected to decrease across Europe, particularly in Southern Europe. But in many cases, this decrease will not totally offset the projected additional heat-related deaths (Martínez-Solanas et al. 2021). In addition, climate change may exacerbate and extend cold spells at certain times and locations (e.g., Cohen et al. 2021) because of more erratic jet stream behavior, even if winters are on the whole warmer. However, the relative importance of these factors remains under discussion in the scientific community.

Hajat et al. (2014) estimated hot- and cold-related deaths in the United Kingdom during the 2000s, 2020s, 2050s and 2080s, split between 12 regions, using a medium emissions scenario (A1B) and nine climate sensitivities. Figure 6 shows the resulting estimates and projections of U.K.-wide temperature-related deaths as a percentage of all-cause mortality rates by age group. The results show that, for the United Kingdom,

- Cold-related deaths are currently far more frequent than heat-related deaths;
- Cold-related deaths are expected to decrease because of climate change and more than offset the increase in heat-related deaths (for a constant population);
- Temperature-related deaths as a proportion of total deaths increase with age; and
- More than half of temperature-related deaths currently occur at age 85 and above, an age group that will increase as the population ages.

Figure 6

PROJECTED U.K. TEMPERATURE-RELATED ANNUAL DEATH RATES BY AGE GROUP AS A PERCENTAGE OF ALL-CAUSE DEATH RATES, ASSUMING NO CHANGE IN MORTALITY FROM OTHER CAUSES (MEAN OF NINE CLIMATE SCENARIOS)



Source: Hajat et al. (2014). Temperature-related death rates derived from 1993–2006 baseline; Office for National Statistics, National Records of Scotland and Northern Ireland Statistics and Research Agency (population and all-cause death data for 1993–2006).

Countries with temperate climates similar to the United Kingdom have had proportionately more cold-related deaths than naturally colder countries like Sweden. Among the reasons for this disparity include (1) many U.K. houses are not suited to colder temperatures because many are poorly insulated, being both difficult and expensive to heat, and (2) individuals may not be as well prepared for and may inappropriately dress in cold weather as a result of underestimating temperature-related risks (Baker et al. 2022, Hanna and Tait 2015. In addition, efforts to make homes warmer in winter by making them more airtight may unintentionally make them hotter in summer. The United Kingdom also has a relatively large number of heat-related deaths; for example, air conditioning is not common in homes or London, and overheating can occur on public transport.

U.K. public health officials have reported excess winter deaths in England and Wales using the month of death (Hajat and Gasparrini 2016) rather than following an attribution process to cold-weather–related causes. The definition of excess winter deaths used by the U.K. Office for National Statistics is the number of deaths in the period of December to March, minus the average of deaths in the previous and subsequent four months—this measure can be distorted by changes in seasonal weather patterns. For example, there were 23,000 excess deaths during the winter of 2018–2019, whereas in 2017–2018 there were about 50,000.[21] An alternative denominator is the excess over an average of the prior years, although these may not include years with unusually high mortality, such as during the COVID-19 pandemic.

Acute temperature extremes can affect the risk of mortality across a wide range of causes of death, including those of an external nature (Burkart et al. 2021; for further discussion see section 4.7). Excess winter deaths have been more frequent for females than males, partly because there are more females than males in the oldest age category who are the most vulnerable to winter deaths. The main causes of these deaths have usually been respiratory and circulatory diseases and dementia, including Alzheimer's, although influenza[22] can also be a major source.

The Netherlands is also currently experiencing excess cold-related mortality (Botzen et al. 2020), with the impact on mortality of extreme heat and cold differing by age group, with people at least 80 years of age being more vulnerable and sensitive to hot days (4.6%/degree Celsius) than to cold days (2.1%/degree Celsius). Long time lags can occur between exposure under extreme temperatures and consequential deaths, especially under cold conditions. Botzen et al. expect climate change to decrease total net mortality in the Netherlands in the immediate future because of the dominant effect of reduced cold-related mortality; however, they expect that this relationship will reverse over time under high emission scenarios unless additional adaptation measures are taken.

Similarly, in a study of 16 European countries assuming three different climate scenarios in four climate models, Martínez-Solanas et al. (2021) projected that the heat-attributable fraction of mortality will begin to exceed the reduction of the cold-attributable fraction in the second half of the 21st century, especially in the Mediterranean area and under higher emission scenarios. They found that 7.17% of deaths reported between 1998 and 2012 were attributable to extreme temperatures, with cold being more harmful than heat by a factor of 10: 6.51% versus 0.65%, with large differences across countries.

[21] https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/bulletins/excesswintermortalityinenglandandwales/2018to2019provisionaland2017to2018final
[22] The number of deaths due to influenza, usually heavily concentrated in the winter, may be more because of the effectiveness of that year's flu vaccinations, living more indoors or in proximity to others, and the timing of COVID-19 waves, than to the specific winter temperatures.

Nevertheless, Martínez-Solanas et al. (2021) asserted that there is no longer a strong association between the extent of cold temperatures and excess winter deaths. They suggested that this might be because of improvements in housing and health care, higher incomes and increased awareness of cold weather risks.

The assertion that cold-related mortality will decrease in the next two decades in countries such as the United Kingdom has been contested by the results of several studies (e.g., Ebi and Mills 2013; Staddon, Montgomery and Depledge 2014; Ballester et al. 2016). This disagreement has been based on the distinction between deaths caused by cold and excess winter deaths. If true, climate change may not significantly decrease the number of cold-related deaths. Supporting this disagreement are the following:

- Kinney et al. (2015), using daily temperature and deaths, studied the extent that cold temperatures are associated with excess winter mortality across and within 36 U.S. cities (1985–2006) and three French cities (1971–2007). Across cities, they found that excess winter mortality did not depend on the corresponding seasonal temperatures. Variability in daily mortality within a city was not strongly influenced by winter temperatures. Although seasonality may be a significant factor, this suggests that the winter temperature may not be a key driver of such excess mortality.
- U.S. and Canadian cities that are generally warmer experience worse mortality from extreme cold events and cold temperatures than do corresponding colder cities. Although deaths directly linked to cold exposure (e.g., hypothermia, falls and fractures) are generally limited, the relatively greater mortality during somewhat milder temperatures is thought to be largely due to respiratory infections and cardiovascular impacts (Lee 2014; Gasparrini et al. 2015). Although positively correlated with temperature, they may not be directly caused[23] by cold temperatures, nor are they the primary mortality driver in these excess deaths.

Despite global warning trends, mortality during winters may not significantly decrease, partly because of the importance of the range of other medical and nonmedical factors that also contribute to excess winter mortality. For example, in south central Canada, the intra-annual distribution of freezing rain events later in the 21st century may become more frequent from December to February, but less frequent in other months (Cheng et al. 2007). The net result will depend on location, socioeconomic, occupational and other nonclimatic determinants of individual health and socioeconomic vulnerability, as well as other climatic factors, such as low humidity, which has been found (Barreca 2012) to be at least as important as the temperature.

It is important to avoid simple aggregate extrapolations when considering changes in the temperature-mortality relationship over time. For example, heat- and heatwave-related mortality has generally diminished over time, although it appears to have stabilized lately (Arbuthnott et al. 2016 in a literature review primarily covering the U.S. and Europe). This pattern may have partly been due to more effective adaptation measures and increased population density, offset to some extent by population aging. No clear trend was apparent regarding the impact of cold weather, although that may have been because of a dearth of studies on this topic. Results differed significantly by location, possibly affected by acclimatization.

[23] Correlation in this case does not necessarily indicate causation. The U-shaped relationship between temperature and mortality should not be taken to mean that temperature itself is always responsible for changing mortality. In the United Kingdom, for instance, deaths in winter are generally driven by other factors, including the variability of seasonal rates of influenza-caused deaths, rather than cold weather itself. Although temperature and mortality are clearly linked, simply modeling that relationship may not fully incorporate all of its important underlying drivers. Thus, an increase in average winter temperature does not necessarily imply that winter deaths will correspondingly decrease.

Between 1985 and 2012, mortality attributed to cold temperatures has increased in the U.S. and has been stable in Canada, despite increasing winter temperatures (Vicedo-Cabrera et al. 2018). Some reductions in cold-related mortality in Mexico and the southern United States are projected under climate change, but less so in colder climates in the northeastern United States and Canada.

A common mistake is to think that temperature-related deaths occur only at extreme temperatures. One example where this was not the case arose in India in 2015, when the mortality risk and the number of cold-related deaths at moderately cold temperatures (defined as less than 13.8 degrees Celsius to cause-specific minimum mortality temperatures) were far greater than the corresponding mortality at the extremes of current climate conditions (Fu et al. 2018 on a nationally representative basis) by an aggregate factor of more than five to one. Fu et al. also found that excess mortality was greater for all medical causes (6.3%), stroke (27.7%) and respiratory diseases (6.5%) in moderately cold temperature conditions than at extreme temperatures. The authors noted that this finding, can differ by geographical area.

In general, deaths are more frequent when people are not prepared or acclimatized to a temperature extreme. Thus, a greater mortality effect may be common during cold days in generally warmer regions, as are hot days in generally colder regions. In the case of Mexico, Cohen and Dechezleprêtre (2022) estimated that 26,000 deaths each year are triggered by temperatures from which people with low income are inadequately protected; that is, those in the top half of the income distribution were twice as likely to die from extreme temperatures as those in the bottom half. In Mexico, 92% of weather-related deaths are experienced during cold or mildly cold days, with only 2% on extremely hot days.

Whether or the extent that mortality related to cold waves will decrease in the coming decades in Europe or the U.S. is currently unclear (IPCC 2022). Although projected global cold extremes are expected to decrease in frequency and intensity, greater regional climate volatility means that cold waves will remain locally important threats in many areas, including in generally milder regions with larger temperature differences between “normal” winter days and periods with extremely cold conditions, especially where there is less ability or willingness to adapt. Many countries in the global north will likely experience minimal to moderate decreases in cold-related mortality, whereas warm-climate countries in the global south are projected to experience increases in heat-attributable deaths by the end of the current century. This will be accentuated in many cities, particularly in Europe and East Asia, by their aging populations, who are vulnerable to cold wave health risks, and who have failed to take adequate adaptation protection action.

Regarding weather volatility, according to the National Oceanic and Atmospheric Administration (U.S.), scientific opinion is divided between whether there will be a decreasing or even an increasing trend in polar or arctic vortices.[24] (Lindsey 2021) However, in some areas, they will continue to occur, especially in spurts, no matter how hot global average temperatures will be. It is unlikely that cold temperature-driven weather will disappear with global warming.

In summary, although some countries will experience reduced mortality, at least in the short term, experience suggests that this may not continue, because (1) there can be stronger sensitivity to hotter than colder temperatures, especially among those who are most vulnerable, (2) temperature variability may not significantly reduce cold-related deaths, (3) adaptation and population composition by age can make a

[24] A polar vortex is a band of strong winds that forms in the stratosphere between about 10 and 30 miles above the poles every winter that can result in extremely cold weather as they move farther south.

difference among populations, (4) the concentration has increased of those who are urbanized, especially among those who are most vulnerable and (5) outcomes can differ by location and socioeconomic group.

Changes in exposures, vulnerability and possible causes of death can drive changes in mortality risk over time. In any case, analysis of both hot- and cold-related mortality should be incorporated if the objective is to assess the net effect of climate change.

The relative importance of these factors remains under discussion in the scientific community. In any case, analysis of both hot- and cold-related mortality should be incorporated when assessing the net effect of climate change. It has to be remembered that the impact of a warmer climate is greater than the direct impact of temperature itself. For example, hotter temperatures also contribute to other climate change mortality risks, including those associated with more intense storms, worse air quality including from smoke from wildfires, increased flooding from more intense rainfall, and additional infectious diseases from expanded scope of vectors such as mosquitoes, desertification, and sea level rise. In contrast, there are comparatively few indirect cold-related deaths.

4.2. EXTREME PRECIPITATION

Both too little and too much precipitation can present material public health risks. Extreme precipitation, evidenced by both droughts and floods, is affecting an increasing number of vulnerable communities (located in the wrong areas and that are under-resourced) and will get worse. It is not that these have not happened before, but their frequency may increase in severity and in some cases frequency.

They can affect agricultural yields and delivery of food to those most in need because of, for example, high staple food prices and availability, in some cases due to inadequate or fragile food supply chains. In many areas of the world these in turn heighten the risk of childhood malnutrition, hunger and premature death.

Droughts and floods have resulted in mass emigration, malnutrition, poor living conditions and increased deaths in areas such as eastern Africa. The threat from multiyear drought conditions arises for both food and water insecurities. Zaveri et al. (2020) found that cumulative water deficits result in five times as much migration as water excess. Between 1970 and 2019, 7% of all disaster events worldwide were drought-related; yet they contributed to 34% of disaster-related deaths, mostly in Africa (IPCC WG2 2022).

Somalia provides a prime example of the effect of droughts. The year 2022 marked a fifth consecutive failed rainfall season, with many climate-related catastrophes since 1990, including 12 droughts and 18 floods. 2.3 million people are suffering serious water, food and pasture shortages there, with more than 70% living below the poverty line for whom starvation is possible. The country saw 43,000 excess deaths in 2022, although conflict and terrorism also certainly played a role; the United Nations’ Office for the Coordination of Humanitarian Affairs estimated that 1.1 million people were driven from their homes in 2022 by drought. The lack of access to safe water and sanitation has heightened the risk of waterborne diseases. In 2022 there was an estimated increase in the number who need assistance and protection by 30%, to about 7.7 million, almost half the total population. Life and health concerns particularly involve children, the elderly, women and the disabled.

There are also many examples of too much precipitation (sometimes as a result of an extreme event, discussed in section 4.3), with consequences including flooding, landslides and mudslides, and the spread of infectious diseases.

In the spring of 2022, for example, Pakistan (and India) was hit by a heatwave that saw temperatures above 49 degrees Celsius, followed in August and September by floods that inundated a third of the country,[25] both of which appear to have been made more likely by climate change. Flooding was primarily caused by heavier-than-usual monsoon rains[26] and melting glaciers (resulting unstable mountain lakes can burst; Taylor et al. 2023 reported that 15 million lives are estimated to be threatened in Asia, more than half of whom live in India, Pakistan, Peru and China). Major health risks ensued, in addition to the more than 1,700 people who died at the time of the floods, about a third of whom were children, with more than 12,000 injured.

In addition, the UN News (2022) reported further spread of malaria, dengue fever and other water- and vector-borne diseases ensued. Because nearly 900 health facilities across the country were damaged, of which 180 were destroyed, millions have been left without access to health care and medical treatment, with longer-term adverse health effects.

4.3 EXTREME EVENTS

Extreme events attributable to climate change can result in deaths either directly or indirectly. A significant increase in severe natural disasters has already been observed, in both their number and intensity. Examples of sudden extreme events include heatwaves, floods, storms, tropical cyclones (e.g., North American hurricanes) and wildfires, and one can lead to another, referred to as cascading risks. For instance, extremely dry, hot and windy conditions are resulting in increased wildfires in every inhabited continent. Also, floods have led to increases in vector- and waterborne diseases and challenges to the delivery of public health services.

Proactive adaptation action is necessary to enhance disaster risk management, to both reduce damages and recover after the event happens (discussed further in sections 9.2 and 9.3). For example, it is often assumed that health care systems and services will be available on an uninterrupted basis. However, the shocks and stresses associated with climate change can affect the resilience and capacity of health care systems, infrastructure and staff. The inability to respond to such emergencies can exacerbate morbidity and mortality. Special attention to the protection of these facilities and resources is needed to minimize ill health and deaths.

Another proactive approach is the use of effective early warning systems to reduce loss, which can differ by type of risk and location. They can provide sufficient time, sometimes measured in terms of hours or days, to seek shelter and reduce damage and deaths. Avoidance, prevention or damage reduction is almost always better than recovery after an event, especially with respect to ill health or death.

For example, an early warning system can add significant value. Bangladesh has more than 5,000 permanent cyclone shelters but limited community cooling facilities (Kazi and Urrutia 2022). The time needed to effectively anticipate an extreme weather-related event differs by the source of the problem:

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[25] Six months after these floods struck Pakistan, more than 10 million people still lacked access to safe drinking water (UNICEF https://www.unicef.org/press-releases/more-10-million-people-including-children-living-pakistans-flood-affected-areas) leaving families with no choice but to use potentially contaminated water. Direct injuries, kidney diseases and personal cascading risks have led to socioeconomic status degradation, as well as increasing physical and mental health issues.

[26] Average annual rainfall in monsoons in India has decreased since 1950; however, more rain is falling in extreme bursts, leading to more dangerous flooding.

living in a flood plain or the path of a likely tropical cyclone or wildfire and sea level risks all have their own timelines. This necessitates accurate and timely information delivered effectively, especially to those who are vulnerable and may need more time to respond. Underlying this process is trust in and acceptance of the accuracy and effectiveness of the safety services provided; if this is lacking, warnings may not be successful.

Those with chronic illness or disability are at particular indirect risk both during and after the event, because of such factors as treatment interruptions, lack of access to medication, transportation disruption, weakened health systems due to lack of available resources and staff, drug supply chain breakdowns, loss of power and population evacuations. Stone et al. (2021) indicated that during a heatwave, heavy air conditioning systems usage can lead to a power outage, failures of which have increased by 60% since 2015 in the U.S., reducing the value of air conditioning when most needed. Although only an inconvenience to many, such power outages can have a disastrous effect on the most vulnerable who have no alternative, such as having an alternative power generator or convenient access to community cooling areas.

While El Niño and its counterpart La Niña occur cyclically, mainly because of the effects of global climate patterns, extreme weather events associated with these phenomena—such as droughts and floods—according to U.N. agencies have increased in frequency and severity. The El Niño of 2014–2016 was arguably the most intense on record; the deaths caused by this warming of the Pacific Ocean have been partially attributed to climate change, although a consensus regarding attribution has not been reached. Although the extent of “blame” has been debated, adverse extreme outcomes keep occurring more frequently in many areas.

These events do not always follow regular patterns, such as El Niños and La Niñas usually do. For example, writing about powerful thunderstorms over the Sahel region of Africa, Taylor et al. (2017) indicated that, between 1982 and 2016, the frequency of extreme Sahelian storms has tripled.

Tropical cyclones are among the most damaging forms of extreme weather-related risks, the economic costs of which are rising. As the number of people, homes and businesses in a vulnerable area grows, the potential for extreme events to cause costly damage increases. Globally, there have been nearly 8,000 climate, water and weather disasters, killing 563,735 in the 29 years since 1992, according to the Emergency Events Database (EM-DAT) disaster database (CRED 2020). According to the World Meteorological Organization (2021), by 2050 1.6 billion people will be at risk of floods (up from 1.2 billion currently), and 3.2 billion may live in water-scarce areas (up from 1.9 billion in 2010).

If health care facilities and resources are destroyed or have no accessible backups, inadequate health care services will result, which consequentially will increase mortality. In extreme situations, the effects of a storm or water-related event could result in the relocation of masses of people, with significant adverse consequential health issues.

The U.S. has had 265 weather disasters since 1992 (roughly double that of the 1980s) that each caused at least US$1 billion in damage (in 2021 dollars). From 1980 to 1992, the U.S. averaged three US$1 billion weather disasters a year; since 1993 the country has averaged nine a year. These disasters caused 11,991 deaths and cost US$1.8 trillion, an 11-fold increase. Ongoing property development in areas most at risk of hurricanes, flooding or wildfire damage in turn can create additional risks. In some cases natural barriers are destroyed that would otherwise help protect at-risk areas. For example, in Florida, “hardened” waterfront properties have replaced “spongelike” wetlands and mangroves that were better able to absorb storm surges and rainfall.

4.4 FOOD AND WATER INSECURITY

The agricultural sector is crucial to food security and nutrition, not only because it supplies food to eat, but also because of its fundamental role in the livelihood, income, health and longevity of a considerable number of those who are vulnerable.[27]

Though the world currently produces more than enough food to feed itself, for many, its distribution is currently inaccessible or unaffordable. In addition, rising temperatures and extreme weather events and conditions can affect both the total amount of food produced and its distribution, particularly among vulnerable groups.[28] There have been "a few studies that demonstrate a strengthening relationship between observed climate variables and crop yields that indicate future expected warming will have severe impacts on crop production" (IPCC 2019), with warmer temperatures and either too little or too much rainfall affecting others. Particularly in low and middle-income countries, food insecurity, malnutrition and undernutrition, micronutrient deficiencies, obesity and diet-related mortality can be driven or exacerbated by one or more climatic factors.

Between 702 million and 828 million people in the world faced hunger in 2021, an increase since 2019 of about 150 million people, or likely more than 20% (Food and Agriculture Organization of the United Nations 2022). Almost 3.1 billion people could not afford a healthy diet in 2020. Although some of this increase was due to COVID-19, the data provide an early indication of the possible size of climate change risks. The FAO stressed that, in addition to the impact of conflict, economic shocks, and growing inequalities, climate extremes have also played a part in this intensified adverse trend.

Famine[29] can result from several causes, including overpopulation, bad government policies and conflicts, as well as or in conjunction with climate change. The likelihood of famine increases when more than one of these factors is present.

Although the number of people who have died of starvation globally has decreased over the last several decades, if appropriate agricultural practices and governmental actions are not adopted and health care infrastructure is not established or maintained, famine can still take hold in certain areas. Climate change is often thought of as an immediate mortality risk; however, undernutrition and malnutrition at an early age can have long-lasting effects, including increased risk of illness, delayed mental development and premature death, as well as possibly passing health risks onto the next generation.

A severe lack of water availability can also contribute to severe loss or spoilage of food and drinkable liquids. The direct result is a significant increase in malnutrition and undernutrition, which in children can lead to stunting. Both immediate deaths and long-term increases in mortality can result. The WHO (2014), using a model of national food availability developed by the International Food Policy Research Institute, estimated the number of deaths due to malnutrition and stunting of children under the age of five to be

[27] According to the Food and Agriculture Organization of the United Nations (2023) https://www.fao.org/hunger/en/, a person is food insecure when they lack regular access to enough safe and nutritious food for normal growth and development and an active and healthy life. Water insecurity is usually defined as the lack of adequate and safe drinking water for a healthy and productive life. This may be because of physical scarcity, when there is a shortage of food or water because of local ecological conditions or economic scarcity, or when there is inadequate food or water infrastructure or lack of resources to obtain food or water.

[28] In a manner similar to the effect of the significant reduction of Ukrainian wheat and seeds from global markets in 2022, according to an article in the *Wall Street Journal* (Steinhauser 2022) in the second quarter of 2022, about 47 million people globally became acutely food insecure (to 345 million who are no longer able to consume enough calories to sustain life and livelihood).

[29] Famine is defined by the Integrated Food Security Phase Classification scale as an area in which 20% of households face an extreme lack of food, 30% of children experience severe acute malnutrition, and 1 in 5,000 people die daily from starvation or disease related to food deprivation. https://www.ipcinfo.org/ipcinfo-website/resources/resources-details/en/c/1152968. Recent UN-declared famines occurred in Somalia in 2011, when 260,000 people died, and South Sudan in 2017.

about 95,000 deaths per year in 2030, with a range of –120,000 to 310,000. By 2050, the corresponding estimate is about 85,000 deaths per year.

Exposure to extreme weather and climate events may result in the consumption of inadequate or unhealthy food, as well as an increase in the risk of disease, either over a short period during a sudden event, a long period in its aftermath or over a long exposure period. Children, pregnant women and the elderly will experience disproportionately greater adverse nutrition and health impacts. As is true with other hazards, climatic impacts on nutrition are strongly mediated by socioeconomic and other vulnerability factors.

Food insecurity is a worldwide issue, for example, increasing from about 193 million to 258 million people from 2021 to 2022 (World Food Programme 2022). In the Horn of Africa, for example, the primary reasons for the recent food catastrophe are rising temperatures and unpredictable weather patterns. This region has not had sufficient rainfall for planting crops, experiencing in 2023 an unprecedented fifth consecutive drought season since late 2020, the last one the worst in the last 40 years. There has been worsening food insecurity in the entire area, including parts of Ethiopia and Kenya. According to the World Food Programme, more than 15 million people (about half of Somalia's population) are facing acute food insecurity, and 1.4 million children face acute malnutrition, with more than one million people being displaced. More than a million livestock perished in Ethiopia's 2016–2017 drought, which among other things increased food insecurity.

The risk of hunger will increase by midcentury, concentrated in sub-Saharan Africa, South Asia and Central America. The IPCC (2022) indicated that this risk would affect between eight million, under its SSP1-6.0[30] scenario, and 80 million people under SSP3-6.0. The IPCC observed that this will partly be due to an increase of up to 29% in cereal prices by 2050 resulting from climate change, with low-income consumers facing the highest risk of hunger. Climate change will increase the loss of years of full health by 10% in 2050 under RCP8.5.

Springmann et al. (2016) projected that by 2050 climate change will be associated with 529,000 annual climate-related deaths worldwide, representing a 28% reduction in the number of deaths that could be avoided by changes in dietary and weight-related risk factors (including changes in fruit and vegetable consumption, red meat consumption and the prevalence of being underweight or overweight and obesity) between 2010 and 2050. Springmann et al. said that the composition of future diets may have twice the impact on mortality than the climatic-related increase in underweight considered by the WHO.

Most of the expected additional deaths in Asia will be due to changes in temperature and precipitation. These are expected to reduce global crop productivity, cause changes in food production and consumption, and affect global population health by changing the composition of diets, the profile of dietary and weight-related risk factors and consequential mortality. Even a modest reduction in per-capita food availability could lead to changes in the energy content and composition of diets that can lead to adverse health implications. Based on an average of four emission pathways, Springmann et al. (2016) found that although food availability and consumption are projected to be greater in 2050 than in 2010, climate change could lead to per capita reductions of 3.2% by 2050 in global food availability, 4.0% in fruit and vegetable consumption and 0.7% in red meat consumption compared with an environment without climate change.

[30] A Shared Socioeconomic Pathway (SSP) describes a future. SSP-1 is the most favorable of IPCC's scenarios, with global warming maintained around 1.5 degrees Celsius above preindustrial temperatures. Higher numbered SSPs represent scenarios with a greater extent of global warming.

Climate change is expected to affect agriculture in Southeast Asia in several ways. According to the Asian Development Bank (2009), reflecting the experience of the Philippines, "during El Niñas, excessive water causes intense runoff and soil erosion, massive floodings, damage to riverbanks and many irrigation systems. During El Niños, water is scarce, causing water shortages for irrigation of water crops." This in turn adversely affects water quality and supply—too much water but too little usable water. Loss of agricultural land can also exacerbate food insecurity.

4.5 AIR QUALITY AND POLLUTION

Poor air quality and pollution cause more than short-term irritation. It can damage almost every organ in the body. Immediate causes of death that result from air pollution include chronic obstructive pulmonary disease (COPD), acute lower respiratory disease, cardiovascular, stroke, cerebrovascular and neurological diseases, lung cancer and premature births. Apte et al. (2018) estimated that in 2016, PM2.5 exposure reduced average global life expectancy at birth by about one year with reductions of between 1.2−1.9 years in heavily polluted countries of Asia and Africa. It contributes to morbidity, whereby people live with disease and incur significant health care costs. Mental health can also be affected, including cognitive decline and depression.

The relative importance of causes of poor air quality (measured by $PM_{2.5}$ differs significantly by country, region and age. According to Khomenko et al. (2023), the top six sources of death in European cities in 2015 from air pollution were residential (22.7%), agricultural (18.0%), industry (13.8%), land transportation (13.5%), energy (10.0%) and shipping (5.5%). According to the IHME (2019), premature deaths from outdoor air pollution are concentrated in Asia, with China (1.42 million) and India (0.98 million), followed by Pakistan and Indonesia (0.11 million), Egypt (0,09 million), Russia and Nigeria (0.7 million) and the U.S. (0.5 million). Whereas in much of the United States and in several other high-income countries, pollution from traffic and power generation is important, pollution from agricultural processes is the largest contributor in Europe, Russia and East Asia.

Pollution is the largest environmental cause of disease and death in the world today, responsible for an estimated nine million premature deaths annually (Fuller et al. 2022), about one in six total deaths. The International Energy Agency (IEA 2016) indicates that poor air quality and pollution are now the world's fourth overall leading cause of premature death (after high blood pressure, smoking and poor nutrition). In addition, air pollution deaths are expected to increase 15% on a global basis, to 7.5 million annually by 2040 (from 6.5 million currently, with an increasing share being from outdoors), unless countries act decisively to reduce soot and fumes from vehicles, industry, and household stoves and heaters.[31]

Based on an updated University of Chicago Air Quality Life Index in June 2022,[32] 97.3% of the global population is breathing toxins (the corresponding U.S. percent is 93% and in Western Europe is 95.5%, with harm being most intense in low-income, still-industrializing locations).[33]

In 2020 exposure to concentrations of $PM_{2.5}$ matter above the 2021 World Health Organization guideline level resulted in 238,000 premature deaths in the EU-27 (European Environment Agency 2022). The Economist Intelligence Unit (2021) indicated that in 2018, 417,000 premature deaths were a result of

[31] Indoor pollution, which may contribute to about 3 million of these deaths, is not a result of climate change but can contribute greenhouse gas emissions.
[32] In 2021 the WHO decreased its global air quality standard from 10 micrograms per cubic meter of $PM_{2.5}$ to 5 micrograms per cubic meter.
[33] https://aqli.epic.uchicago.edu/news/air-pollution-kills-10-million-people-a-year-why-do-we-accept-that-as-normal/

$PM_{2.5}$, 55,000 were due to nitrogen dioxide, and 20,600 were due to ozone. No country currently meets the WHO air quality standard. Air pollution is the largest environmental health hazard in Europe. Between 2005 and 2020, emissions of particulate matter, PM_{10} and $PM_{2.5}$, fell by 30% and 32%, respectively, with 2020 benefiting from the COVID-19 lockdown.[34]

Smoke contributions to daily $PM_{2.5}$ concentrations increased between 2006 and 2020 by up to 5 micrograms per cubic meter in the western U.S. (double or triple over the last decade), reversing decades of policy-driven improvements in overall air quality,[35] with concentrations growing fastest for higher-income and Hispanic populations (Childs et al. 2022). The number of people in locations with at least one day of smoke $PM_{2.5}$ above 100 micrograms per cubic meter per year has increased 27-fold over the last decade, including nearly 25 million people in 2020. In contrast to the 2006–2010 period when there were relatively few extreme smoke days, between 2016 and 2020 more than 1.5 million people, particularly in the western U.S., were routinely exposed to levels that carried immediate risks. Although other sources of air pollution are being reduced, that success has been more than offset lately, especially in the West, partly because of wildfire smoke (Burke et al. 2023). As climate change intensifies fire risk across the country and smoke plumes travel thousands of miles from their source, no one is safe from their effects.

Unlike other forms of air pollution, smoke can kill quickly if inhaled. Although rare overall, death from smoke inhalation is common among wildland firefighters, who also suffer significantly higher mortality from lung cancer and cardiovascular disease. Even short-term exposure to wildfire smoke can worsen bronchitis, asthma and COPD, as well as trigger heart attacks, heart failure and strokes. Although some pollutants return to normal concentrations shortly after a fire has stopped burning, other chemicals might persist in the environment for long periods of time, including heavy metals and hydrocarbons.

In a global study of 749 cities in 43 countries and regions during 2000–2016, Chen et al. (2021) found that mortality due to wildfire-related $PM_{2.5}$ exposure resulted in 0.62% of all-cause deaths, 0.55% of cardiovascular disease deaths and 0.64% of respiratory deaths.

Changing weather patterns, including warmer temperatures and increased incidence of wildfire smoke, are projected to increase exposure with significant premature mortality and adverse effects on health across large swaths of the U.S. (Garcia-Menendez et al., 2015), as well as increased incidence of nonfatal respiratory and cardiovascular diseases. Silva et al. (2017) found that global premature mortality attributable to climate change (other than from urbanization) from $PM_{2.5}$ and ozone will increase by about 260,000 deaths per year in 2100 under RCP8.5, with substantially different results depending upon the extent of warming.

In the United States, Abel et al. (2018) estimated that the impact of climate change on annual $PM_{2.5}$ and ozone-related deaths will be 13,000 and 3,000 deaths, respectively in 2069, with heat-driven increased use of air conditioning accounting for 645 and 315 of the $PM_{2.5}$ and ozone-related annual excess deaths (a 4.8% and 8.7% increase above climate change impacts alone), respectively.

[34] https://www.eea.europa.eu/publications/air-quality-in-europe-2022/sources-and-emissions-of-air
[35] Wildfire pollution is enough to threaten the gains of the U.S. Clean Air Act, which, though passed five decades ago, is still saving an estimated 370,000 lives each year. Already about 30% percent of the air quality gains of that law has been undone by the effects of wildfire smoke. In 2020, such smoke accounted for roughly half of the air pollution in the western U.S. David Wallace-Wells. August 24, 2022. The American West's Haunting, Smoke-Filled Future. The New York Times. https://www.nytimes.com/2022/08/24/opinion/environment/wildfire-smoke-health-pollution.html

Concentrations of certain air pollutants such as $PM_{2.5}$ in several higher-income cities have recently decreased as a result of clean air regulations that have controlled emissions, bringing substantial improvements in public health. This improvement in air quality contrasts with the situation in certain areas in South Asia, Southeast Asia and Africa, with their continued increases in urbanization and economic growth that may not peak until midcentury. In many cities in North Africa and the Middle East, these effects are due mainly to windblown dust, whereas in many African cities, it can arise from growing populations, energy demand and urbanization. In contrast, in South Asia and East Asia it is mainly anthropogenic in origin.

In 2019 about 1.67 million deaths (17.8% of total deaths) were attributable to air pollution in India. The majority of these deaths were from ambient $PM_{2.5}$ (0.98 million deaths, an increase of 115.3% from 1990) and household air pollution (0.61 million, a decrease of 64.2% from 1990) (India State-Level Disease Burden Initiative Air Pollution Collaborators 2021).

Mailloux et al. (2022) estimated that the health benefits of elimination of large air pollution emissions ($PM_{2.5}$, sulfur dioxide and nitrogen oxides) from the electric power, transportation, building and industrial sectors in the contiguous U.S. could prevent 53,200 premature deaths each year and provide US$608 billion in benefits from avoided $PM_{2.5}$-related illness and death. Although the total elimination of these emissions may not be practical in the near future, this provides a context for such mitigation efforts. Although these sources are not a direct result of climate change, reductions in these emissions can help to reduce climate change and its adverse health effects.

To express this loss of life in economic terms, a joint study with the World Bank and the Institute for Health Metrics and Evaluation (2016) found that premature deaths due to air pollution in 2013 cost the global economy about US$225 billion in lost labor income or about US$5,110 billion in welfare losses.

Many air pollutants harmful to human health also contribute to climate change by affecting the amount of incoming sunlight reflected or absorbed by the atmosphere, with some pollutants warming and others cooling the Earth. These include methane, black carbon, ground-level ozone and sulfate aerosols, all of which significantly affect the climate. Methane and black carbon emissions are also among the top contributors to global warming after carbon dioxide.[36]

4.6 SLOW-ONSET CONDITIONS

A slow-onset condition can be thought of as a set of circumstances from which there is usually plenty of time to prepare, with minimal health and mortality consequences. However, this may not be the case.

Sea-level rise, a prime example of a slow-onset climate-related condition, evolves over decades and centuries. However, it has been accelerating over the last few decades. Gradually increasing desertification caused by ongoing droughts is another slow-onset condition. These conditions may affect the lives of hundreds of millions of people.

Water-related deaths arise in two principal ways: from sudden disasters, such as flash (fluvial) flooding, and slow-onset conditions, such as the indirect consequence of rising ocean levels, acidification or salinization. In reality, they can interact: the more the sea level rises, the greater the likelihood of sudden flood damage.

[36] https://scied.ucar.edu/learning-zone/air-quality/air-quality-and-climate-change

Despite the seemingly small sea level rise (on average currently measured in inches or centimeters rather than feet or meters), together with an increase in long-term warming of the seas, the water level from hurricanes such as Michael and Ian, two of the strongest storms ever to hit the U.S., as well as the extensive 2022 Pakistan floods was made worse in part from additional sea level rise. High-tide flooding has at least doubled throughout the U.S. Gulf regions in this century. Although not yet a direct mortality risk, it can degrade infrastructure and increase flood damage, ultimately leading to increased mortality risk.

If recognized far enough in advance and if economically feasible, emigration away from high-risk exposed areas (such as low-lying areas, a city close to an ever-expanding area of drought or encroaching desert, or inadequately constructed or protected buildings), located too close to the ocean, low-lying small island developing states, or land, such as that in the Louisiana delta, will save lives. More than 250 million people now live on land less than two meters above sea level, and this population may increase to more than 400 million by 2100.

Assuming sufficient warning has been provided, immediate deaths may be minimal. However, in many cases, people do not pay sufficient attention to the warnings or simply do not believe in or trust those who provide warning to take appropriate action. Severe economic and health consequences can ensue over a long period, especially if emigration is required. For example, crowded emigration areas can lead to waterborne and infectious diseases and violence, with those of lower income more likely to suffer because of inferior temporary living conditions.

Catastrophic damage due to high tides or a storm is more likely as ocean levels rise. For example, the occupants of the tremendous build-up of high-rise apartments and condominiums in southern Florida may ignore an early warning or may not wish to believe that they need to relocate and abandon their property. Builders may not have considered worst-case scenarios. In any case, structural damage or flooding may make their homes uninhabitable or not be capable of being remediated promptly or affordably.

Sea-level rise, de-glacierization and chronic flooding (the results of which have been seen in Pakistan in 2022) can compromise paddy fields, adding to the problems of displacement and food availability. In addition, salt water, agricultural nutrients and other chemicals can spread through rising sea levels and floods affecting wells and other sources of drinking water.

4.7 CONSEQUENTIAL CAUSES OF DEATH

Both the incidence and severity of both noncommunicable and communicable diseases can be affected by climate change. In numerous regions, especially in large urban areas in Asia and Africa, substantial increases in morbidity and mortality due to respiratory, cardiovascular and infectious illnesses, including their effects on the immune system, are appearing. Climatic factors such as temperature can interact with sensitive physiological mechanisms via multiple pathways to adversely affect health. Future climate change can be expected to magnify health risks both now and over the long term.

Several diseases are of special interest in a discussion of climate change and mortality, a discussion of which follows.

4.7.1 INFECTIOUS DISEASES

Infectious diseases are important adverse consequences of climate change. These diseases are spread by several methods. The communicable diseases primarily affected by climate change are spread by insect vectors and by water, although other means of transmission may also be affected.

4.7.1.1 Vector Spread

Climate change is expanding the boundaries of several vectors. For example, in high-altitude Nepal, more people are falling ill due to mosquito-borne diseases. The country suffered from an outbreak of dengue fever in 2022, spreading as a result of warming temperatures linked to climate change. More than 52,000 cases and some 60 deaths have been reported, though that may be an underestimate.[37] Malaria spread by *Anopheles stephensi* in Djibouti has spread rapidly, with 27 cases in 2012, 1,228 between February and May 2013, and 73,000 in 2021 (Zayed et al. 2023).

Around 277 human pathogenic diseases can be aggravated by the broad array of climate change risks. As noted by Mora et al. (2020), "58% (that is, 218 out of 375) of infectious diseases confronted by humanity worldwide have been at some point aggravated by climatic hazards; 16% were at times diminished." For example, the transmission of pathogens that result in diseases spread by mosquitoes sensitive to higher temperatures and greater precipitation has increased the risk of vector-borne, waterborne and foodborne diseases.

Pathogens include protozoa (malaria and human sleeping sickness), viruses (COVID-19, dengue, Zika, Nipah, Hendra and West Nile virus), bacteria (Lyme disease and plague) and nematodes (river blindness). Warming temperature affects the behavior and physiological characteristics of vectors, pathogens and reservoir hosts. Climate change can also increase the risks of human-to-human disease spread and zoonotic spillover. Habitat loss has pushed bats into areas occupied by people and livestock that may lead to a greater spread of pathogens and disease (Eby et al. 2023).

IPCC (2022) indicates that milder winters have reduced the mortality of many vectors and reservoir hosts for viruses and bacteria and have enabled an expansion in their habitats, and therefore the scope for spreading infectious diseases. These include malaria, dengue fever, Lyme disease, West Nile virus, diarrheal diseases such as cholera, Zika, chikungunya and yellow fever. The IPCC indicates that at least the first four are expected to increase over the next 80 years. Changes in vector ecology brought about by floods and damage to environmental hygiene have led to increases in diseases across sub-Saharan Africa, with increases in malaria, dengue fever, Lassa fever, Rift Valley fever, Lyme disease, Ebola virus and West Nile virus.

For example, the malaria parasite is usually spread by invective female *Anopheles* mosquitoes that are cold-blooded and depend on ambient air temperature to set their metabolism. Malaria risk then tends to increase with warmer temperatures, peaking at an average of about 25 degrees Celsius. As the temperature rises further, mosquitoes become less able to function, and at about 34 degrees Celsius, they start "dropping out of the air." Albeit based on a worst-case emission scenario, an estimated 8.4 billion people could be at risk from malaria and dengue by the end of the century if emissions keep rising at current levels, according to WHO (2003), the number at risk of contracting malaria may increase by some 5% (150 million people) if temperatures rise 2 to 3 degrees Celsius higher than pre-industrial levels. Although malaria incidence has declined globally because of non-climatic socioeconomic factors and health care system responses, a shift to higher altitudes and expansion of the range of mosquitoes has been observed as the global climate warms.

Most of those who currently die from malaria live in Africa and are under age five. The WHO (2014) estimated that, compared with a future without climate change, by 2030 an additional 60,000 deaths per

[37] https://www.hrw.org/news/2022/11/28/nepal-dengue-surge-exposes-climate-risk

year will be due to malaria, more than 95% of which are expected to be in sub-Saharan Africa. Although not contagious, it can be spread through blood transfusions and the shared use of needles.

The warmer the weather, the more frequently mosquitoes bite humans and animals. Thus, the longer the summer season, the wider the spread of mosquito-related diseases. These diseases are gradually spreading to higher-income areas such as parts of the U.S., including Florida and Texas. UNICEF has indicated that these infectious diseases have also been facilitated by El Niños in Central and South America. Also, floods can increase exposure and broaden the dispersal of hosts.

Infectious diseases carried by ticks and other vectors also increase with a warming climate, resulting in their poleward expansion where they have no natural predators. Climate variability and population mobility, accompanied by even small increases in temperature, relative humidity and precipitation, are positively associated with increases in various vector diseases. These include dengue (compared to 2015, an additional one to five billion people are projected globally to be at risk of dengue exposure by 2080, depending on the warming scenario), chikungunya virus in Asia, Latin America, North America and Europe, Lyme disease in North America, and Lyme disease and tick-borne encephalitis in Europe. Infectious diseases also include Rocky Mountain spotted fever, West Nile fever and malaria.

Climate change may result in thousands of currently unknown viruses spreading among animal species over the long term, which may increase the risk of emerging infectious diseases and viruses jumping from animals to humans. As we have seen by experience associated with COVID-19, many pathogens involved in infectious diseases and pandemics can be initially spread in a zoonotic manner; these risks can be accompanied by enormous consequences.

According to Thomson and Stanberry (2022), effective adaptation measures differ by disease, method of transmission and pathogen. For example, common measures for those diseases transmitted by mosquito bites such as malaria, dengue and West Nile fever are community-level mosquito-control programs and household action such as the use of bed nets. Avoidance of vector habitats and use of proper clothing can be effective against ticks that spread Lyme disease, resulting from public communication and education. Vaccines and drugs can be effective in reducing the spread or the adverse health effects of diseases such as yellow fever and encephalitis. Early warning systems and up-to-date training of health care professionals can be of importance for all infectious diseases.

4.7.1.2 Waterborne

Causal linkages between climate change and its volatility and the incidence of waterborne diseases are complex, with indirect outcomes even greater than that from the direct hazard. Heavy rainfall can result in a cascading set of hazards and disease events, especially where there are critical infrastructure weaknesses and vulnerable populations. Heavy rain and flooding can lead to storm runoff, landslides or mudslides, damaged water and sanitation infrastructure, overwhelmed containment systems and untreated wastewater. For example, the USGCRP (2018) indicated that extreme rainfall could overwhelm the nation’s ailing water and sewer systems, contributing to shortages of drinkable water and increasing exposure to gastrointestinal disease. In a period of increases in water temperature, gastrointestinal illnesses and infections can spread.

Diarrhea is associated with heavy rainfall, flooding events and higher-than-normal temperatures. It is currently causing more than one million deaths each year, especially of children. Future diarrhea risk will be highly dependent on development trajectories, given that waterborne disease transmission is exacerbated by a lack of clean drinking water and effective sanitation systems, inadequate food safety and hygienic conditions, and lack of flood and drought protection.

About 48,000 deaths each year from diarrheal disease are expected to be attributable to climate change by 2030 and about 33,000 in 2050 (WHO 2014), especially affecting children younger than 15, the elderly and the immunocompromised. About 60% of these deaths are expected to be in sub-Saharan Africa and 25% in South Asia. Climate change threatens the progress that has been made toward reducing the burden of diarrhea, especially in areas of significant inequality.

Interactions of diarrheal disease can arise with other risks such as food insecurity and infrastructure damage. Diarrheal disease is affected by both temperature and rainfall, although the WHO study was restricted to temperature effects. Cholera, which is predictable and preventable, is an acute diarrheal infection caused by eating or drinking food or water contaminated by the bacterium *Vibrio cholerae*.

The worst cholera outbreaks in years have affected 28 million people in 11 eastern and southern African countries.[38] These outbreaks are exacerbated by poverty, disasters, conflict and climate change consequences, like extreme storms and flooding, as well as a lack of access to safe water and sanitation. In Malawi and Mozambique, for instance, cholera spread from flooding following cyclone Freddy. Between mid-2021 and March 2023,[39] Africa experienced the seventh deadliest cholera pandemic in recorded history, with high mortality rates (WHO); in 2021 Africa experienced more than 4,000 deaths in 19 countries. Ali et al. (2015) indicated a wide range of estimates, from 1.3 to 4.0 million cholera cases and 21,000 to 143,000 deaths worldwide per year in endemic countries. UNICEF estimated in February 2023 that one billion people in at least 43 countries are at risk.[40]

The WHO's projection of continued declines in childhood mortality assumes further economic development and improved water quality and sanitation. This progress may be undermined if environmental changes damage urban infrastructure or reduce the availability of water. Extreme flooding and tropical cyclones can also spawn epidemics of leptospirosis. Just walking through floodwaters can increase the risk of this bacterial blood infection by a significant amount.[41]

Drought can also lead to both decreased water availability and quality, resulting from increased travel distance to alternate or uncontaminated sources, decreased health of livestock, poor hygiene, and exposure to human and animal excrements, as well as industrial chemicals dumped from what was expected to be a safe containment facility. There can also be contamination of seafood by chemicals, biotoxins and pathogenic microbes.

4.7.1.3 Other Infectious Spreads

Other means of infections can arise. For example, UNICEF has expressed a concern that southern Africa could see increased transmission of HIV as a result of climate variability such as a result of an El Niño, due to a lack of food that can affect access to antiretroviral therapy.[42] This is partly due to patients who do not take their treatment on an empty stomach, and with many people using their limited resources for food rather than on transport to a health facility in another village or town.

In northern Europe, recent anthrax outbreaks among humans and mass mortality events among reindeer have been linked to abnormally hot summer temperatures that caused permafrost to melt, causing

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[38] https://www.unicef.org/esa/reports/cholera-outbreak-eastern-and-southern-africa#download
[39] https://reliefweb.int/report/mozambique/mozambique-severe-tropical-storm-freddy-floods-and-cholera-flash-update-no-11-20-march-2023
[40] https://news.un.org/en/story/2023/05/1136822
[41] https://www.cdc.gov/leptospirosis/exposure/hurricanes-leptospirosis.html
[42] https://reliefweb.int/report/lesotho/el-nino-la-nina-could-lead-spike-new-hiv-infections-africa-unicef

exposure to diseased animal carcasses that have led to the release of highly infectious anthrax spores (Ezhova et al. 2021).

4.7.2 CARDIOVASCULAR AND RESPIRATORY DISEASES

Some types of cardiovascular disease (CVD) morbidity, such as myocardial infarctions and strokes, are temperature sensitive. In addition, certain medications used to treat CVD diseases, such as diuretics and beta blockers, may impair resilience to heat stress. Based on their review of published research, the IPCC (2022) concluded that climate change will increase heat-related CVD mortality by the end of the 21st century, particularly under higher emission scenarios.

Climate change is projected to result in or exacerbate several cardiovascular morbidity and mortality risks, including the following:

- *High temperature.* Extreme weather and high humidity, whether through heatwaves or other high-temperature conditions, can result in reductions in physical activity, increased sleep disturbance, dehydration and increased exposure to air pollutants. Although older adults have inherent sensitivities to temperature-related health impacts, children can also be affected by extreme heat.
- *Air quality.* Smoke from increases in the number and severity of wildfires can lead to an increase in exposure to air pollution, including $PM_{2.5}$, ozone, black carbon, oxides of nitrogen and sulfur, hydrocarbons and metals, which can result in pro-inflammatory and prothrombotic states, endothelial dysfunction and hypertensive responses.
- *Vector-borne disease*. The dissemination of zoonotic vectors can cause infectious diseases.
- *Sea-level rise*. Related saline intrusion of groundwater may increase salt intake, a risk factor for hypertension.

The extent of the increase in CVD deaths will depend on the extent of climate change. For example, temperature-related myocardial infarctions in Germany are projected by Limaye et al. (2018) to increase under high emissions scenarios; with an additional 11,562 annual deaths of those age 65 and older by 2050 from cardiovascular stress in the eastern U.S. CVD mortality in Brazil is projected to increase up to 8.6% by the end of the century under a relatively warm scenario (RCP8.5), compared with an increase of 0.7% under a more moderate one (Silveira et al. 2021).

Although a higher occurrence of CVD mortality has often been associated with prolonged periods of low temperatures, evidence is growing that CVD deaths are more related to heat events than to cold spells (IPCC 2022).

The following studies projected increased rates of heat-related CVD mortality in China throughout the remainder of this century, the significance of which is illustrated by the 64-day record-breaking heatwave in 2022 that was accompanied by very dry weather; heatwave-related mortality rose by a factor of four from 1990 to 2019, reaching 26,800 all-cause deaths in 2019 (Cai et al. 2021). Further, in a meta-analysis of heatwaves and mortality in China, a hazard ratio of 1.25 for cardiovascular mortality (for nonaccidental mortality a hazard ratio of 1.19, respiratory of 1.18, stroke and circulatory of 1.11), with a significantly greater effect on those with fewer years of education (Pan et al. 2023). The following forecasts have been made for the country:

- In Beijing, CVD deaths could increase (from a 1980s baseline) by an average of 18.4%, 47.8% and 69.0% in the 2020s, 2050s and 2080s, respectively, under RCP4.5 and by 16.6%, 73.8% and 134.0%, respectively, under RCP8.5. Respiratory mortality was projected to experience similar patterns. These percentages are affected by population size and aging (Li et al. 2015).
- In Beijing, temperature-related mortality due to CVD under alternative climate change, population and adaptation scenarios (from a 2007–2009 baseline) were projected to increase by 3.5% and 10.2% under alternative climate change scenarios. When population change was considered, the annual rate of increase in temperature-related CVD deaths was up to five times greater than those under corresponding no-population-change scenarios because of an increase in susceptible population segments, such as the elderly and those with existing illnesses. The decrease in the number of cold-related deaths did not totally offset the increase in heat-related deaths. In addition, adaptation action may increase cold-related CVD mortality greater than decrease heat-related CVD mortality (Zhang et al. 2018).
- According to Yang et al. (2021), in China heat-related excess CVD mortality (from a 2010 baseline of 1.9%) is expected to gradually increase to about 5.5% by the end of the century under RCP8.5 and to over 3.0% under RCP4.5. Yang et al. also expect that population aging will amplify future heat-related excess deaths 2.3 to 5.8 times under alternative climate scenarios.

Substantially elevated mortality risks for the elderly have been found to exist for temperature-induced cerebrovascular, cardiovascular and respiratory outcomes (an international meta-analysis by Bunker et al. 2016). Excluding heatwave and cold wave studies, excess mortality at high temperatures was similar or slightly larger for cardiovascular causes than for respiratory causes. A 1 degree Celsius temperature rise increased cardiovascular (3.44%), respiratory (3.60%) and cerebrovascular (1.40%) mortality. The effect of respiratory causes on morbidity was found to be more sensitive than that of cardiovascular causes under both high and low temperatures. Each cause-specific mortality in the groups studied was greater under higher temperatures.

Several climate change hazards, including poor air quality, wildfires, dust storms and heavy rainfall, can contribute to increased respiratory risks, both making preexisting respiratory diseases more severe and initiating respiratory conditions in previously healthy individuals. Those most at risk include those older than 65, children whose lungs are developing, those in lower socioeconomic groups because they are more likely to live in areas with poor air quality, and those who work outside.

Respiratory allergies and lung diseases, evidenced by reduced lung function, coughing and wheezing, continue to become more prevalent. These are partly the consequences of climate change as a result of air pollution, increased exposure to pollen (due to altered growing seasons), molds (from extreme or more frequent precipitation), aerosolized marine toxins (due to increased temperature, coastal runoff and humidity) and dust (from megadroughts, erosion and sandstorms). Drought can be accompanied by more dust, which the 2018 U.S. National Assessment (USGCRP 2018) indicated can aggravate allergies and asthma and can also accelerate the reproduction of disease-causing fungi in soil.

Considerable premature respiratory-driven deaths are occurring as a result of related air pollution and poor air quality. See section 4.5 for a discussion of this hazard.

4.7.3 CANCER

The IPCC (2022) found that much of the literature points out that climate hazards are likely to increase the risk of several types of cancers, though the degree to which these risks will increase remains unclear. For example, climate change may alter the fate and transport of carcinogenic polyaromatic hydrocarbons and may increase the mobilization of carcinogens such as bromide and persistent organic pollutants, including polychlorinated biphenyls that can accumulate in areas contaminated by industrial runoff, as well as radioactive material.

Exposure to these carcinogens can occur through multiple environmental means exacerbated by the effects of climate change. There are several examples: (1) through increased flooding due to extreme precipitation events and from sediment where carcinogens have accumulated, (2) through exposure to ultraviolet light, which can result from shifts in precipitation and can increase the incidence of malignant melanomas, especially for outdoor workers, and (3) through air pollution, which can cause lung cancer by creating inflammation that encourages the proliferation of cells with existing cancer-driving mutations, providing a mechanism that could apply to other cancers caused by environmental exposure.

Exposure of those living within 50 kilometers of a wildfire within the prior 10 years in Canada has been associated with a slightly increased incidence of lung cancer (4.9% additional mortality) and brain tumors (10%), according to a study of more than two million people followed for a median of 20 years (Korsiak et al. 2022).

4.8 CONFLICTS AND VIOLENCE

It has been speculated that drought, especially when accompanied by an extreme increase in temperature, has and will contribute to conflicts and violence, particularly in conjunction with disputes over depleted natural resources such as water. For example, the World Bank (2016) expressed the belief that the likelihood of future conflicts may increase significantly near a 4 degree Celsius global temperature increase compared to pre-industrial climate. However, the IPCC (2022) did not find such a strong relationship.

Whether or not these conflicts and other external drivers are directly caused by such climate changes, they can contribute to mass (climate) emigration by being a risk multiplier. Even if their effects were measurable, attribution would remain problematic. For example, it is not known how many of the deaths that resulted from the internal Syrian conflict that began in 2011 or the more recent Tigray conflict in Ethiopia could be attributed to an underlying multiyear drought in those areas. Nevertheless, it appears likely that increased population pressure, whether or not caused by extreme climatic factors, can give rise to consequential increased mortality.

In addition, a growing body of research suggests that rising temperature increases some types of interpersonal violent crimes, such as intentional homicides, sex offenses and assaults (Mahendran et al. 2021).

4.9 IMPORTANT ASPECTS OF MORTALITY RISK

As indicated earlier, direct and indirect climate and weather risks are quite complicated. This is of special concern in extreme cases in parts of the world, as some cities and regions will become uninhabitable and migration patterns can be exacerbated. The following is a discussion of several important associated aspects of mortality risk.

4.9.1 REGIONAL AND LOCAL VARIATIONS

Much of the discussion of the risks associated with climate change has until recently focused on global averages (e.g., average global temperature increases). Although harmful health conditions are expected to increase in frequency and intensity over all land areas, even more dramatic changes will arise on regional and national, if not local, bases.[43] Variations in exposure and vulnerability to mortality and morbidity by location will be experienced in terms of vulnerability to the level and volatility of temperature, precipitation, storms and other climatic-related factors and their combinations.

For example, the IPCC (2022) indicates that strong regional variations in heat- and cold-related mortality trends are likely under an RCP8.5 scenario, with countries in the global north experiencing minimal to moderate decreases in cold-related mortality, whereas warm climate countries in the global south are projected to experience increases in heat-attributable deaths by the end of the century. This variation in the temperature-related burden of disease is due to a wide range of climate change, adaptation and demographic scenarios, which will differ by geographical area.

In 2022 the IPCC spent considerable space in its reports on regional variations (using Africa, Asia, Australasia, Central and South America, Europe, North America, Small Islands and the Ocean as regions). One clear message is that global averages and trends cannot be assumed to apply to a particular region or locale, although aggregate trends cannot be ignored.

In some regions, such as Western Europe, differences between extreme weather and corresponding mean values are expected to increase more rapidly than the mean, owing to greater variability in conditions, especially between the northern and southern hemispheres. Although great uncertainty is involved, heat extremes have grown disproportionately since the advent of industrialization and are expected to intensify further (Simolo and Corti 2022).

For example, Canadian warming is occurring at twice times the global average rate, or even three times in its northern portion (Warren and Lulham 2021). In addition, heatwaves are expected to become more frequent and more severe. Warming has contributed to a 58.4% increase in heat-related deaths of those over age 65 in Canada in less than two decades.[44] Polar regions have, in general, experienced more temperature change than global change.

Some of the largest increases in heat-related mortality in the U.S. are expected to occur in the northeast part of the country, where by midcentury there could be 50 to 100 excess deaths per one million people (USGCRP 2018).

Heat as a health risk factor (see section 4.1) has been overlooked until recently in many low- and middle-income countries. The country-level percentage of mortality attributable to extreme temperatures (heat and cold) has been found to range from 3.4% to 11.0%. The Global Burden of Disease Study 2019 (GBD 2019 Risk Factors Collaborators 2020) estimated the burden of DALYs attributable to low temperature was 2.2 times greater than the burden attributable to high temperature. However, these overall global outcomes can obscure important regional variations. Countries with a high sociodemographic index, mainly those with a midlatitude high-income base and temperate-to-cool climate, were found to have a cold-related burden 15.4 times greater than their heat-related burden, whereas warmer lower-income regions, such as those in South Asia and sub-Saharan Africa, the heat-related burden was estimated to be 1.7 times and 3.6 times greater, respectively.

Those hit hardest by climate change in total are those located in Africa and Asia, although the relative size of this impact is expected to change. In 2030, sub-Saharan Africa is projected by the WHO (2014) to have

[43] Important location risk characteristics can differ by hazard and condition, for example, closeness of a river, sea, or elevation for flood risk, dryness of timber in a forest for wildfire risk, extent of adaptation actions taken and concentration of vulnerable people.
[44] https://www.hrw.org/news/2021/07/09/record-canada-heat-harms-older-people-and-people-disabilities

the greatest burden of mortality attributable to climate change, due to changes in its climate, demography and relative economic conditions. However, by 2050 South Asia is projected to be the region most affected by the health effects of climate.

An important element involved is temperature sensitivity, which also differs widely by location. Country-specific estimates show a clear north-south pattern within regions (Vicedo-Cabrera et al. 2021). Although climate change-attributable deaths are currently less than 1% of total deaths for countries in northern subregions of America, Europe and East Asia, a larger percentage has been estimated in southern Europe, South and West Asia and some countries in Southeast Asia and South America. The largest climate change-induced outcomes (more than half) have been in South, Southeast, and West Asia and several countries in Central and South America, suggesting a rich-poor region divide that may indicate that hotter temperatures also may impede economic progress.

A 31 degrees Celsius day, which represents a 99th percentile temperature for a particular day in Chicago, was associated with a 36% increase in all-cause mortality, while at the same percentile, for Johannesburg, a 24 degrees Celsius day was associated with only a 9% increase, and in Berlin, a 28 degrees Celsius day was associated with an increase of 57% (Vicedo-Cabrera et al. 2021).

Temperature thresholds at which the rate of heat-related hospital admissions significantly increases also differ by region. Historically hot Arizona hits a hospitalization spike beginning at around 36 degrees Celsius, whereas cooler Oregon starts seeing a hospitalization spike at about 27 degrees Celsius (Vaidyanath et al. 2019). This differential further suggests that those areas that are used to warmer temperatures have become more acclimatized and have better adapted to higher temperatures. Speculatively, this concept of acclimatization and adaptation may also affect other consequences of climate change.

4.9.2 URBANIZATION

The global move to further urbanization has increased the aggregate importance of urban-related risks that adversely impact mortality and morbidity. In North America and Europe, as well as other parts of the world where rural depopulation is projected to continue, a dominant driver of increases in exposure to heat-related mortality is urban growth (Jones et al. 2018). For example, because of urban heat islands[45] and the high concentration of motor vehicle and industrial activity and resultant pollution, urban dwellers, particularly those in poverty, will be more exposed to extreme heat stress and air-quality-related respiratory illnesses than their rural counterparts.

Additional heat stress within American cities can be attributed to the urban heat island effect, especially affecting disadvantaged African American and Hispanic communities. U.S. National Weather Service data[46] indicate that extreme heat is now the leading weather-related killer in the U.S., while Shindell et al. (2020) projected that annual heat-related deaths in the U.S. could increase by 97,000 by the end of the century if no further emission reduction measures are taken. Assuming a continuation of recent vulnerabilities and no further adaption, Shindell et al. indicated that every area of the world would experience an increase of

[45] Urban temperatures compared are often higher than those in rural areas. This difference may be as high as 2 degrees Celsius. A corresponding heat island effect appears to affect both summer and winter temperatures in urban areas, which can reduce the number of deaths in winter, although in a study of Birmingham, England, those affected in the winter are fewer than those in the summer (Macintyre et al. 2021).

[46] https://www.weather.gov/phi/heatcond

2–10 percentage points in the proportion of deaths attributable to heat by the end of the century in the RCP8.5 (high emission) scenario.

Cities are at the epicenter of vulnerability to heatwaves. For the 150 most populated cities of the world, a 500% increase in exposure to extreme heat events occurred between 1980 and 2017, with more to come. Their heat islands are partly due to urban infrastructure such as buildings and roads that absorb and reemit the sun's heat more than natural landscapes—the surface-energy balance due to the thermal characteristics and space of the built environment, especially in megacities. Human-made surfaces and urban canyons also retain heat better into the night. Urban heat islands are further amplified during heatwaves, the extent to which differ by location, urban design and time of day.

Because of limited vegetation, incoming solar energy directly enters physical surfaces rather than through overhead canopies, with less going into evaporating water vapor. When combined with warming induced by urban growth and the energy generated, its extreme heat risks may affect half of the future urban populations.

Longer-term urban planning and design can reduce these risks by reducing concentrations of or using less pavement and asphalt that trap heat, using more heat-absorbent cement materials, enhanced infrastructure, and white walls and roofs, as well as nature-based approaches such as parks, tree-lined streets and grassy rooftops.

Although a great deal of attention has been given to urban heat islands, other climatic elements can also adversely affect human health. For example, many of the largest Asian cities are particularly exposed to future flood risks arising from these climate risks. Between 2000 and 2030, rapid urbanization in Indonesia elevates flood risks by 76–120% for river and coastal floods, while sea-level rise will further increase exposures by 19–37%.

In addition, 56% of all cities with a population greater than 300,000 in 2014 were exposed to at least one of six major physical hazards: cyclones, floods, droughts, earthquakes, landslides, and volcanic eruptions (Gu et al. 2015). Those highly exposed and vulnerable to multiple hazards were also in the urban areas that had grown rapidly in population since 1950. Among 27 cities highly exposed to multiple disasters, 13 cities had a population of one million or more. The eight megacities most vulnerable to disaster-related mortality were Jakarta, Karachi, Kolkata, Manila, Mexico City, Osaka, Tianjin and Tokyo, with 143 million people.

Some urban populations will experience indirect risks due to inadequate food and potable water systems, variations in the distribution and seasonality of infectious diseases, and a growing demand for shelter due to increased migration. Many large cities have grown because of their proximity to rivers or other bodies of water; they suffer when this water gets out of control, partly because of weak infrastructure. Climate migrants due to drought or flooding tend to move to large cities. Floods caused by heavy rainfall can churn up pollutants that are then swept into their water supply. The accumulation of these risks over time can generate accelerating declines in community resilience and health, with future vulnerability expanding in a nonlinear fashion.

Heat and other climate-related risks are associated with a range of health issues, unevenly distributed among urban residents. Less advantaged socioeconomic groups are especially affected, including their very old and young elements, resulting in greater medical costs and deaths, higher utility costs, lower productivity of caregivers and workers, and missed work and school days.

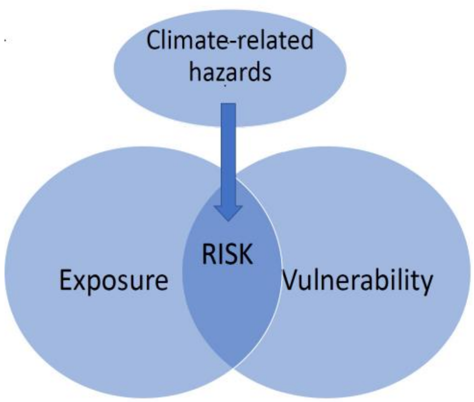
Current urban development patterns can place the existing infrastructure at risk in areas such as the Mekong Delta in Vietnam. Flooding in urban areas may be exacerbated both as a result of encroachment of higher and more volatile water flows in areas that retain water and lack adequate protective infrastructure such as embankments and flood walls. These conditions can also impact food security, with direct and indirect consequences, possibly leading to mass emigration and deaths.

4.9.3 THE VULNERABLE

Climate change risks primarily exist for those who are exposed to a particular type of climate risk hazard and especially those who are most vulnerable to harm from those hazards, whether in developed or developing countries (IAA 2019). Throughout this section, indeed, throughout this paper, various populations and communities are identified as being especially vulnerable to one or more climate-related risks. For many of these people, these risks especially exacerbate other existing mortality risks. It may be helpful to examine all of these risks to obtain a total (holistic) look at the health and mortality risks involved with them.

Those who are more often adversely affected with respect to a particular hazard are often those who live in an especially exposed geographic area. The at-risk population is those in the intersection of being exposed and who are especially vulnerable to a type of climate-related exposure, as indicated in Figure 7.

Figure 7
RISK: THE INTERSECTION OF EXPOSURE AND VULNERABILITY



An example of those who are disproportionally vulnerable are those who are disabled, who are also exposed to climate emergencies partly because of their inherent vulnerabilities, as their ability to take protective action may be impaired. In addition, they are often excluded from adaptation planning. Other demographic groups at risk include those in certain age categories, racial or ethnic minorities and indigenous peoples.

The extent of and the inability to avoid exposure to one or more ongoing climate hazards and the inability to recover from damage are key determinants of the harm process. In addition, once exposed, sensitivity to harm is crucial, for both the individual, her or his household and the communities in which they live. Highly vulnerable populations are not usually evenly distributed across regions or within countries. Yet even those fortunate enough to live in better neighborhoods with greater financial resources, higher-paying jobs and more convenient access to resources and services may experience adverse outcomes as a result of a lack of action or community-level interactions and linkages. Nevertheless, those well-off may be able to avoid or minimize their exposure and enhance their ability to withstand damage.

Those with greater exposure and vulnerability include the elderly, the fragile, young children, pregnant women; those undernourished and malnourished; those of lower socioeconomic status and those with lesser educational attainment, inadequate access to information and health care services; the socially isolated; those suffering from certain preexisting chronic medical or mental health conditions (such as CVD, kidney disease, diabetes and respiratory diseases); those with limited family and community support; those who live in poor quality housing or an otherwise degraded environment; and those who work under unsafe conditions.

According to Birkmann et al. (2022), mortality over the last decade from floods, drought and storms can be 15 times greater for countries ranked as highly vulnerable (e.g., Afghanistan, Haiti, Mozambique and Somalia) compared to less vulnerable countries (e.g., Australia, Canada and the United Kingdom). More than 3.3 billion people are now living in countries classified as very highly or highly vulnerable. Although an increase in drought has been observed in each continent to various degrees, it is especially in the most vulnerable regions where such events result in relatively high mortality.

Emigration from areas more susceptible to losses and damage, either in advance, at the time of or even immediately after an adverse event or condition occurs may be possible for some. Clement et. al. (2021) indicated that, without concerted climate mitigation, South Asia, sub-Saharan Africa and Latin America could experience climate change, being a potent driver of migration that in turn could force 216 million people to move within their countries by 2050. Further, if natural disasters occur at the same rate seen in the last few decades, the Institute for Economics & Peace (2020) expects that around 1.2 billion people could be displaced globally by 2050 due to natural disasters and climate change, most of which will move to cities.

However, many who are most vulnerable do not have the resources to move or start over. In any case, unless forced to, convincing anyone to relocate may be a tough sell, although the higher cost of insurance or a lack of insurance availability can provide a meaningful incentive. In addition, they may lose much of their wealth such as their home upon evacuation or migration. In some cases, an exposed area might otherwise be viewed as being highly desirable, such as living on a river or ocean front, or at the edge of a forest.

These climatic events and conditions can overwhelm the functionality of even the best health care system and related factors, such as a result of compounding or cascading power outages. They can adversely affect anyone, but especially the most vulnerable.

4.9.4 AGE AND GENERATION-RELATED EFFECTS

Current and future age structures have a considerable influence on vulnerability to weather and climate-related mortality risks. The very young and very old tend to be more vulnerable than those of middle age, although both groups may be less affected in high-income countries than those in low-income countries. The oldest will likely be most affected in the case of weather extremes (particularly hot weather). Many of the youngest in low-income countries may experience stunting arising from malnutrition due to such a condition as a drought, which in turn can expose them to higher mortality risks from accidents or diseases such as a diarrheal disease throughout their future life.

Cumulatively, the impact of extreme climatic factors can create conditions of chronic lack of well-being, if not death. Such vulnerability is compounded by weak health care infrastructure, particularly but not exclusively in South Asia and parts of Africa. For example, socioeconomically disadvantaged populations are more likely to live in hotter parts of cities with higher-density residential structures, less effective insulation and lower quality or older construction materials.

4.9.4.1 The Elderly

Population aging, particularly an increase in the number of elderly people, is expected to increase temperature and weather-related illnesses and deaths. Among the hardest hit will be those suffering from multimorbidities, especially when they include respiratory or cardiovascular diseases (see section 4.7.2). Their greater sensitivity to various health consequences of climate change increases their vulnerability to its adverse effects.

Older people are directly and indirectly disproportionately affected by disturbances in climate and ecosystems—directly, from extreme weather events such as heatwaves, flooding and severe storms; indirectly, from altered vector-borne disease transmission and the reduced ability to produce and in turn obtain nutritious food due to drought, soil degradation and compromised water quality.

Heatwaves are especially deadly for the elderly when temperatures rise suddenly. The WHO (2014) estimates that there will be about 38,000 heat stress-related deaths of those aged 65 and older in 2030 associated with climate change (95,000 in 2050). This was based on A1b emissions, a base-case socioeconomic scenario, and a 50% adaptation scenario, compared to that of an optimum temperature scenario. About 9,200 of these deaths would be in South Asia, 8,000 in East Asia, 3,000 in North America, 2,800 in sub-Saharan Africa, 2,600 in Western Europe, 2,400 in South-East Asia, 2,000 in Eastern Europe, and 2,000 in North Africa/Middle East. Of these, WHO identified about 4,500 in high-income regions. In a study of the combined effects of warming temperatures and an aging population in South Korea, Lee and Kim (2016) projected a four- to sixfold increase in heat-related deaths by the 2090s.

Older people are less able to adapt to sudden changes in temperature. They might also take medications that result in heat intolerance and impair the body's response to heat, including the ability to thermoregulate. Living in small units or apartments can make it difficult to deal with extreme heat, especially with minimal ventilation, insufficient green space or shade around their buildings. In some cases, small window sizes or lack of windows that open can contribute to insufficient airflow where an air conditioner may not be easily installed. In addition, many cannot afford to buy or operate cooling devices; nor can everyone stay at home all day in an air-conditioned space. In the United Kingdom in 2021, about 90% of heatwave deaths were among people aged over 65.[47]

Older adults are more vulnerable than others to waterborne pathogens, due to their often inefficient thermoregulatory systems, greater sensitivity to dehydration and gastrointestinal illness, and weaker immune systems. Older adults may also be less prompt in seeking medical attention.

Older people may disproportionally suffer from adverse mental conditions, such as a reduced ability to cope with trauma, anxiety, agitation and depression from conditions such as heatwaves or other extreme conditions, as well as constantly worrying about uncertainty and insecurity over how they will survive future events. Social isolation, although not only of concern for the aged, can contribute to more deaths when living alone. Although also due to many underlying causes, nearly half of the deaths related to Hurricane Katrina in Louisiana in 2005 were persons over age 75.

In addition, evacuations from either sudden or slow-onset events and conditions can pose significant health risks to less mobile and fragile older adults, especially those who are frail, medically incapacitated, cognitively impaired or residing in nursing facilities. Evacuations may be further complicated by the need to

[47] https://www.theguardian.com/uk-news/2022/aug/23/deaths-in-englands-july-heatwave-up-7-on-rest-of-the-month

concurrently transfer medical records where not stored digitally offsite, medications and medical equipment.

4.9.4.2 Children and Pregnant Women

Children, fetuses and pregnant women can experience high rates of exposure and vulnerability to climatic hazards, extreme weather conditions and undernutrition. Heat, for example, is associated with higher rates of preterm birth, low birth weight, stillbirth and neonatal stress, along with adverse child health. Extreme heat during the first and third trimesters of pregnancy can contribute to premature births and eclampsia. Extreme weather events and climate conditions can reduce access to prenatal care, increase the chance of unattended deliveries and decrease pediatric health care access. Such adverse early-life experiences can have lifelong morbidity and mortality consequences. (Baharav et al. 2023)

Nearly half the world's young population (1 billion children) live in countries where health and safety risks due to the effects of climate change represent serious environmental hazards, including droughts (nearly 160 million children live in areas vulnerable to high or extremely high drought), floods (nearly 500 million children live in extreme flood zones exposing them to waterborne diseases), heatwaves (nearly all children), wildfires, tropical cyclones and other extreme weather events, creating food insecurity (25 million more malnourished children), threatening water supplies and forcing migration, including by unaccompanied children. In the Caribbean, for example, the number of children displaced by extreme weather events has increased sixfold in the past five years (UNICEF 2023).

Future generations will be more affected by climate change than existing ones. Under the 2021 Paris Agreement national climate commitments, children born in 2020 on average will be expected to experience a two to seven times increase in extreme events than those born in 1960 (Thiery et al. 2021), particularly heatwaves (4 ± 2 heatwaves during their lifetime compared with 30 ± 9 heatwaves for those born in 2020), and the land area annually affected will increase from around 15% in 2020 to about 22% by 2100. A six-year-old in 2020 is expected to be affected by twice as many wildfires and tropical cyclones, three times more river floods, four times more crop failures, five times more droughts and 36 times more multiple extremes compared with a reference person. Thiery et al. noted that this does not include expected increases in their intensity and slow-onset events such as coastal flooding: under a 3 degrees Celsius pathway, children under 10 in 2020 will experience a fivefold increase, while under a 1.5 degrees Celsius pathway, they will experience a fourfold increase. As expected, lower-income countries will face larger increases for these young cohorts.

The following is a summary of key health risk factors for children and pregnant women resulting from climate change (Perera and Nadeau 2022), which closely mirrors the risks of the entire population:

- *Heat stress*. Heat-related illness, increased emergency room visits and hospitalizations (e.g., for cardiovascular, respiratory and renal diseases), mental health effects, increased infections and pregnancy complications.
- *Air quality and pollution*. Toxic gases and $PM_{2.5}$ can increase the risk of pregnancy complications, asthma, lower respiratory infection and bronchitis due to underdeveloped lungs, allergen exposure, attention deficit–hyperactivity disorder, autism spectrum disorder, depression, anxiety, immune-system dysregulation, hypertension and decreased cognition.
- *Food supply and safety*. Nutritional deficits, stunting, infection, food insecurity and climate-related extreme event exposure.
- *Water quality and quantity*. Pregnancy-related risks, waterborne infection, diarrhea, allergies, immune dysfunction, increased respiratory illnesses, exposure to contaminated water, decreased lung function and decreased cognitive and motor skills due to increased toxic metals from water scarcity.

- *Extreme weather events*. Injuries, displacement or emigration, posttraumatic stress disorder and other mental health effects and immune-system dysregulation.
- *Vector distribution and ecology*. Increased susceptibility to infectious diseases, associated pregnancy complications and complications when residing where the disease is endemic or emerging (e.g., Lyme disease) or in areas that commonly experience flooding.
- *Social factor*. High risk of displacement; health inequity can be both enhanced and can result in greater mortality risk.

Experience of maternal health in lower- and middle-income countries indicates that the effects of climate change-linked heatwaves and rising temperatures on pregnant women residing in these regions will be far greater than those in more developed countries. Similarly, in the U.S., heat-related adverse pregnancy outcomes are nearly double for Black and Hispanic women, who often live in densely populated neighborhoods that heat up quickly and take longer to cool because of a lack of green space, compared with white women (León-Depass and Sakala 2021).

4.9.5 POVERTY AND INEQUALITY

Climate change especially affects the health of those with low incomes and in areas with scarce resources, limited technology use, and weak health care and related infrastructures. These factors increase health inequity that in turn threatens the well-being of many. Actions that respond to climate change risks should, where practical, reduce existing inequities. Nevertheless, even moderate future climate change and climate hazards are likely to push many people further into poverty and risk further destabilization of personal and societal security (Birkmann et al. 2022).

A country's poor may not be able to afford the adaptation tools available to others to avoid some of the most adverse effects of climate change, compelling them to rely on postdisaster recovery efforts and the largesse of others. For example, disadvantaged neighborhoods, because of socioeconomic or racial or ethnic reasons, tend to have fewer green spaces and are located closer to higher exposure areas. Those in poorer households also tend to have higher exposure to air pollution, low-quality water and sanitation, heightening their exposure to climate change–related health risks.

The poor are more likely to have more severe preexisting health conditions that can be exacerbated by climate risks. They may lack access to or are less able to pay for the additional electricity to run air conditioning or other adaptation measures. They may also be less likely to work in air-conditioned offices, needing to face a trade-off between their health and jobs.

Relative income and wealth also influence how people perceive health risks and their response to evacuation orders and other emergency warnings, for example, in response to potential flood and wildfire risks. This affects their ability and willingness to evacuate or relocate to a less risk-prone (and possibly more expensive) location.

If, for instance, a tropical cyclone, tornado or flood hits a less affluent and more congested area, there may be a greater number of deaths than if at-risk lives had not been so concentrated. This concentration risk is also of concern to insurers with extensive coverage or financial institutions that have extensive credit exposures there.

It has long been understood by actuaries that wealth and income are highly correlated to increased longevity. It is therefore not surprising that WHO (2014) noted "[Climate change] impacts are greatest under a low economic growth scenario because of higher mortality rates projected in low- and middle-income countries."

The WHO (2014) went on to say that, even under optimistic scenarios of future socioeconomic development and with reasonably effective adaptation measures, climate change is still projected to have substantial adverse impacts on future mortality—"avoiding climate-sensitive health risks is an additional reason to mitigate climate change, alongside the immediate health benefits that are expected to accrue from measures to reduce climate pollutants, for example through lower levels of particulate air pollution. It also supports the case for strengthening programs to address health risks including undernutrition, diarrhea, vector-borne disease, and heat extremes, and for including consideration of climate variability and change within program design. The strong effect of socio-economic development on the projections of future risks emphasizes the need to ensure that economic growth, climate policies and health programs particularly benefit the poorest and most vulnerable populations."

It is not just the relative lack of resources of individuals and households, but of their countries as well. However, in the case of excess heat, because higher-income countries have tended to be in more temperate zones, adverse effects on mortality are not necessarily positively correlated with this income. According to the UNDRR (2016), 92% of deaths from heatwaves were recorded in high-income countries, with Europe reporting the lion's share at 90%.

4.10 FAVORABLE IMPACTS

Despite the adverse risks discussed above, climate change will favorably impact some aspects of human health, including likely reductions in cold temperature–related mortality and morbidity in certain regions. In addition, mitigation and adaptation measures may not only reduce the adverse mortality effects due to climate change, but also may reduce non-climate-change mortality as a result of accompanying improvements, such as enhanced health care infrastructure. Nevertheless, although Smith (2014) concludes that adverse impacts on health greatly outweigh the favorable benefits, the latter should not be ignored.

Average winter temperatures will increase in many areas, with fewer cold-related deaths, as indicated in section 4.2. Although extreme cold events and volatility will continue, such as a result of polar vortices, there may be fewer cold temperature extremes. For example, Hajat et al. (2014) projected that, without any adaptation, although cold-weather-related deaths in the United Kingdom will increase by 9% in the 2020s, this will be followed by a decrease of 26% in the 2050s and by 40% in the 2080s.

Warmer weather makes it possible to grow certain crops (and more of certain other crops that are currently limited) in some regions, where it was previously difficult or impossible. An anecdotal example is increasing areas where growing grapes may be possible. On its own, this may improve some local health outcomes, but these beneficial effects may be offset somewhat by the loss of crop yields in other areas. Offsetting this, at least to some extent, will be an increase in the number of extreme events, more variable precipitation patterns, a loss of agricultural land to sea-level rise (especially in Southeast Asia) and increased drought-prone areas. Climate variation will explain about one-third of global crop yield variability (Ray et al. 2015).

Other biological benefits may arise, such as a "CO_2 fertilization effect" (Zhu 2016), which can increase carbohydrate production in plants with improved growth and yield as CO_2 levels rise. A significant increase in leaf production has been observed (data from NASA and the U.S. National Oceanic and Atmospheric Administration) for more than three decades. Green leaves produce sugars using energy from the sunlight to mix CO_2 drawn from the air with water and nutrients pumped from the ground. These sugars are then a source of food, fiber and energy. More sugars are produced when there is more CO_2 in the air. However, some studies have shown that plants acclimatize or adjust to a rising CO_2 concentration, with the fertilization effect diminishing over time. (Zhu 2016)

In the course of taking environmentally favorable mitigation, transition (e.g., decarbonization) and adaptation actions, risk management of buildings and other resources should also reduce climate change risks, but also be accompanied by cobenefits. These can include an enhancement of health care systems, which can reduce a wide variety of mortality risks, reduce air pollution from causes other than climate change, and lead to overall loss prevention.

According to Vohra et al. (2021), 350,000 premature deaths annually in the U.S. are attributed to $PM_{2.5}$ air pollution generated by fossil fuel combustion (more than 10% of total deaths). As the country attempts to move toward net-zero greenhouse gas emissions over the next several decades, this source of adverse mortality should gradually decrease, while overall climate change-related deaths should increase.

5. Indirect Effects beyond the Mortality Impacts

Much of section 4 and the rest of this paper is devoted to a discussion of mortality risks that are directly related to climate change. However, for each type of climate change risk there may be even greater impacts from indirect effects on illness and morbidity, including work productivity, economic growth and educational effectiveness.

Indirect impacts on mortality include deaths caused by what may be a spike in or a sustained surge in demand that would otherwise be within the current capacity of a health care system to cope effectively. Although such a situation is more often associated with developing countries, as discussed in section 2, these risks can also arise in developed countries, as seen in 2005 when Hurricane Katrina in the U.S. resulted in the massive displacement of people in all socioeconomic categories, accompanied by an overload of community health care services that did not have a significant amount of spare capacity to begin with. In essence, climate change hazards can highlight and exacerbate weak or inadequate health care risk management and infrastructure systems.

As with direct effects, people and countries with limited resources will tend to be most exposed and vulnerable, suggesting that areas such as South and Southeast Asia and large parts of Africa will more likely experience a significant portion of the indirect mortality consequences. Nevertheless, Hurricanes Katrina and Sandy in the United States serve as powerful reminders that these adverse effects are not limited to developing economies and vulnerable population segments. Consequential economic effects will in turn result in heightened mortality risks, particularly but not exclusively those with lower income or wealth, through various feedback loops.

As an example, in high-income countries, an increasing number of heat-related injuries have accompanied the expanding participation in sports. The highest rates of exertional heat illness are reported in endurance events (e.g., running, cycling and adventure races), football and athletics. Having been a race organizer and having called off a running event with almost 10,000 runners on a day of high temperature and humidity, the author realizes that it is not easy to take appropriate health action.

In general, high temperatures and humidity levels, for example, can aggravate existing medical problems. Respiratory illnesses tend to worsen, as heat causes the number of harmful pollutants and air quality to increase that may in turn prove fatal.

Other direct and indirect mortality and morbidity effects are numerous. For example, an increase in transportation (e.g., motor vehicle and bicycle) accident risks can also be associated with extreme precipitation and temperature. In combination with other risks, such as extreme events, sandstorms and wildfires, climate change effects can contribute to long-term health risks or be deadly.

The health, safety and productivity consequences of working in extreme heat, especially those working outdoors in the agriculture and construction industries who experience high heat-related fatality rates, are widespread. Occupational heat strain in outdoor workers can manifest as dehydration, a reduction in kidney function, fatigue, dizziness, confusion, impaired thinking and motor functions, loss of concentration and general discomfort. Occupational injuries can result from fatigue and decreased psychomotor performance. When working daytime hours in the heat, there is often a gradual, progressive deterioration in the ability to lose heat, resulting in loss of productivity and illness. Enhanced work conditions in a time of excessive heat, for example, by rescheduling work to cooler times of the day, can help to reduce injuries and deaths.

Significant economic costs will be incurred as a result of climate change, both in total and in many sectors of the economy, such as agriculture and tourism. Extreme heat or storms will also undermine agricultural and livestock systems, degrade natural resources, damage infrastructure and contribute to migration. The International Labor Organization (Urban Climate Change Research Network 2019) projects that economic losses related to heat stress will rise from US$280 billion in 1995 to $2.4 trillion in 2030, with lower-income countries seeing the biggest losses, although not necessarily the largest costs. These costs, referred to elsewhere in this paper, will be enormous.

A nonlinear relationship is found between temperature and global economic productivity, with potential global economic losses of 23% by 2100 due to climate change without sufficient mitigation and adaptation actions—in other words, short-term gains versus long-term losses. For example, heat-related reductions in urban labor productivity in Australia cost between US$3.6 and US$5.1 billion per year (Zander et al. 2015, based on self-reported performance reduction and absenteeism in 2013–2014). In 2019 India and Indonesia lost potential labor capacity equivalent to 4% to 6% of their annual GDP from heat-related mortality (Watts et al. 2021).

Some regions are already experiencing heat stress conditions approaching the upper limits of labor productivity and human survivability (IPCC 2022). By 2050, NASA predicts that South Asia, the Persian Gulf and the Red Sea will be uninhabitable; by 2070, Eastern China, Brazil and some of South East Asia will join these areas.[48] Most Indians currently have little choice but to work with limited protection against excessive heat. In addition, many children in rural areas attend schools in sheds with tin roofs, which would be unbearable in extreme heat, built in such a way that they trap heat, instead of ensuring ventilation.

5.1 MENTAL HEALTH

The IPCC (2022) found that climate change is expected to have adverse impacts on many people's well-being, including mental health. Extreme events, such as floods, droughts, wildfires and cyclones, are often followed by increased rates of mental illness and increased anxiety.

The IPCC also describes some of the mental health risks that tend to directly or indirectly be more severe for those with preexisting mental health disorders, physical injuries, and respiratory, cardiovascular and reproductive system conditions. Indirect impacts may be greatest from displacement, migration, lack of mobility, malnutrition and famine, degradation of health and social care support systems, conflict or violence, and climate-related economic and social losses. Excessive heat is associated with greater crime, anxiety, depression and suicide. As with mortality, the demographic factors involved in increasing an individual's vulnerability to adverse mental health include age, gender, the extent of disability, if any, and

[48] https://ecobnb.com/blog/2022/07/climate-change-places-uninhabitable/

low socioeconomic status, which are most significant, though their effect will differ depending on the specific source of climate change and individual conditions. (Thoma, Rohleder and Rohner 2021)

Manifestations of climate change can alter physical activity and mobility patterns, which in turn can produce alterations in mental health status. Climate change can also adversely affect physical and mental labor capacity because excessive heat can reduce the ability to effectively engage in manual labor, as well as cognitive functioning.

Climate change can also increase aggression in some people, with Burke, Hsiang and Miguel (2015) indicating that a 2.4% increase in interpersonal conflicts and an 11.3% increase in intergroup conflict for a 1 degree Celsius temperature increase (this risk may not be offset by a reduction by any corresponding reduction in cold extremes). Increased temperatures are also linked to higher hospital admissions for mood and behavioral disorders, experiences of anxiety, depression, acute stress, domestic violence and suicide rates (UNODC 2019).

A positive and increasing correlation is seen between extreme heat and emergency department visits for substance use disorders; anxiety, stress-related and somatoform disorders; mood disorders; schizophrenia, schizotypal personality and delusional disorders; self-harm; and childhood-onset behavioral disorders (Nori-Sarma et al. 2022). Nori-Sarma et al. suggest that a significant contributor to these effects may be sleep disruptions, as well as an increase in hopelessness, stress and uncertainty attributable to the anticipation of climate change and associated extreme events. The higher rates of emergency department visits in the Northwest, Northeast and Midwest regions of the U.S. suggest an increased risk of adverse mental health outcomes in regions less well adapted to heat.

Extreme weather events, such as floods, heatwaves and wildfires, can trigger posttraumatic stress disorder, anxiety and depression; the IPCC (2022) indicated that 20% of people exposed to a tropical cyclone or flood develop depression or posttraumatic stress disorder or symptoms within the first few weeks after the incident, especially when the individual or a friend or relative is directly affected. Sub-Saharan African children and adolescents may be especially vulnerable to adverse direct and indirect impacts on their mental health (Mabrouk et al. 2022).

Climate risks, especially temperature increases, have contributed to a significant number of suicides during the growing season in India, affecting some 60,000 farmers and farm workers over the past three decades. The number of suicides was sensitive to the size of temperature spikes—an estimated average increase of 1 degree Celsius was associated with 67 additional suicides and an increase of 5 degrees Celsius, with an additional 335 deaths per day. In contrast, temperature increases outside the growing season did not show this correlation. Additional rainfall of 1 centimeter in a year was linked to a 7% drop in the suicide rate, with strong rainfall reducing suicide rates for the two following years. (Carleton 2017)

Although some benefits may accrue to mental health and well-being from fewer very cold days in the winter, any favorable effect associated with reduced low-temperature days is generally expected to be outweighed by adverse effects of increased high temperatures.

6. Relevance to Insurance and Pension Programs

As described in previous sections of this paper, climate change will likely have a wide range of adverse (and some favorable) effects on future mortality, differing by geographical area and extent of population vulnerability. So far, most of the discussion has addressed mortality risks for the overall population, with an emphasis on those who are more vulnerable.

There will also likely be a wide range of effects on areas of significant concern to many private-sector financial institutions and products, public programs and society. For example, insurance products affected include those that cover life and health insurance, property damage insurance, business interruption insurance, liability insurance, agricultural damage and crop insurance, and directors' and officers' liability insurance.

The management of these risks should be part of the overall risk management and financial disclosure processes of an entity. Information regarding the mortality and morbidity aspects should be a rigorous element of the analysis of its risks. A discussion of these risks is undertaken in section 6.1.

Many actuaries provide advice to private sector insurance and retirement plans (e.g., life insurance, annuities and pension programs) in more economically developed countries. Many of these programs provide coverage to population segments that tend to be less vulnerable to climate risks than the overall population, although that is gradually changing with the growth of the middle class. As a result, mortality studies conducted by actuaries of these population segments have not been as affected by climate change as have public sector programs or the entire population.

Those covered by these programs tend to be better able to, for example, afford to buy, use and maintain air conditioning in their homes and have better access to quality health and emergency care services than an average person. Although the affluent may live in buildings with more enhanced storm protection than those who are less well-off, they may still live in densely populated or risk-prone areas. Although possibly exposed to similar risks, those with more income or resources may not be as vulnerable.

Climate change–related mortality rates will increase over time compared to what would have been experienced without climate change, because of both the increased effects of climate change itself and the aging of the global population that will increase the number of those who are vulnerable. As a result, more of the effects on mortality will be increasingly felt by insurers and pension plans over the intermediate and long-term future than in the immediate future. In any case, these effects may differ from those for the overall population.

Partly as a result, the financial impact of climate change on mortality risks of many insurers providing life insurance coverage may be less than that on their invested asset values. Its impact on their mortality experience also may not be as significant as on other private and public sectors that deal with a wider range of socioeconomic groups, but these outcomes may differ by the individual insurance and investment portfolios of the insurer.

Notwithstanding the considerable uncertainties involved, these mortality and longevity risks will tend to be more concentrated in certain population segments and geographic areas that may or may not represent a significant effect on an insurer's overall financial results. Thus, the actual risk will be affected by the particular population segments covered and the resulting concentration risk involved. Further, depending upon the trajectory, volatility, adaptive measures taken and adaptive capacity, climate change risks have the potential to affect the long-term sustainability of certain life insurance programs and entities whose mix of coverage lies in, for example, densely populated areas and population segments more exposed or vulnerable.

Exposure to these risks differs, in some cases dramatically, by insurer. For example, some life insurers have an older inforce client base. Because temperature and air quality–related deaths tend to affect elderly people (over age 65, but certainly greater for those over age 85), their life insurance portfolio may suffer more claims proportionally than the corresponding overall population. However, in countries such as the

Netherlands or the United Kingdom that may experience fewer cold days, it may prove to be the opposite in the near term.

Some insurers that offer insurance to groups may have a less affluent insured population than those that primarily sell individually underwritten insurance coverage. Although insurers with a more affluent portfolio usually experience lower mortality rates, there is limited information from which to believe that their mortality improvement rates will differ from those of the overall population.

Increased mortality, although resulting in adverse financial results for life insurance, represents an expected reduction in costs and risks for a writer of annuities and defined benefit pension programs. To the extent that direct or indirect effects of climate change impact mortality experience, they will impact reserving for annuities and life insurance, although in opposite financial directions. Thus, to the extent their participants are derived from similar geographic and risk susceptibility, mortality and longevity risks tend to offset each other, constituting a potential natural hedge.

Actuarial concerns can arise despite the relative lack of traditional pension and life insurance penetration of many who are vulnerable to climate change risk. In Africa, for example, there has been a rapid rise in mobile phone usage for day-to-day insurance transactions. This in turn has driven an explosion in the volume of microinsurance in some areas, often on a “loyalty” basis as part of a phone package. In 2022, there were 253 microinsurance providers in 43 countries covering about 223 million people, principally in Asia, Africa, Latin America and the Caribbean (Merry and Calderon 2023).

Other distribution models have also proven successful in reaching the general population, whether through “freemium” distribution[49] or other microinsurance routes. Millions of people now have coverage, including some of the poorest and most vulnerable. If a climate change event or condition has a sufficiently long lead time, an upsurge in applications for life or health insurance may occur prior to the emerging risk. At the same time, the insurer might take proactive action by encouraging or even building their own early warning system to reduce the mortality risk to their insureds.

Even in richer countries such as the U.S., more than 11% of the population in 2022 lived in poverty.[50] For this population segment, as well as others, a significant insurance and pension protection gap exists. An increasing number of deaths attributable to or exacerbated by climate change (resulting in a drag on overall mortality improvement) will have noticeable actuarial ramifications in these markets.

Just because current mortality outcomes resulting from climate change or insurance coverage of those who are vulnerable do not currently appear to be large, this does not imply that the underlying effects discussed in this paper should be ignored (see section 6.1 for further discussion). In addition, because of their concentration, these risks are often borne by global reinsurers, which is the reason actuaries at those insurance companies have paid more attention to these risks than those at direct insurers (other than those that cover a significant amount of those exposed or vulnerable). In addition, as mentioned in section 7, there are potentially other cautions; for example, if a mortality assumption regarding the future is based on experience over a period in which the reduction in cold-related deaths is greater than the increase in

[49] Freemium distribution uses a pricing strategy by which a product or service, typically a digital offering or app such as software, media, game or web service, is provided free of charge, but money (premium) is charged for proprietary features, functionality or virtual goods via a mobile app.

[50] https://www.census.gov/library/publications/2023/demo/p60-280.html

heat-related deaths, expectations may be biased if this experience is applied to a period in which the opposite relation applies.

6.1 COMMON MYTHS

Several myths have emerged that an actuary and the entities and programs to which actuaries provide advice may confront when dealing with the allocation of resources and how to consider the effect of climate change on mortality, especially in an insurance or annuity context. These myths have led some to conclude that climate change is not a significant issue that requires the immediate attention of those dealing with mortality or longevity. The following presents some of the most common myths and discusses them, consistent with the discussion in section 6 above.

Myth 1. Fewer people die now of natural disasters than in the last century, so any worry is overblown.

Based on a review of deaths due to natural disasters over the last 50 years (see Figure 3), the underlying facts involved in this myth are true.

According to CRED (2020), the average number of deaths due to weather, climate and water-related disasters decreased almost threefold from an average of over 50,000 annual deaths in the 1970s to fewer than 20,000 in the 2010s. This reduction was largely due to advances in early warning systems worldwide, for example, in Bangladesh. The largest death tolls from a single tropical cyclone were about 300,000 in Bangladesh in 1970, about 139,000 in Bangladesh in 1991, and 138,000 in Myanmar in 2008, with others during the last 50 years experiencing fewer than 15,000 deaths per event.

However, although fewer people globally have died recently from natural disasters than even 50 years ago, most of those earlier deaths were in less-developed countries in areas such as in South and Southeast Asia that, because of a lack of effective early warning systems and adaptation techniques, succumbed to death en masse.

In the U.S., for example, although a significant reduction in heat-related deaths occurred over the last half of the 20th century because of the introduction of air conditioning (Barreca et al. 2016), further progress may not continue because of a lack of affordability, and so overreliance on past trends may not be warranted. Another example can be seen in the experience of Phoenix, Arizona (and surrounding Maricopa County) in the summer of 2021: although air conditioning is common there, 339 people still died of heat-related causes, up 71% from 2019, with males constituting 81% of all deaths and 75% occurred outdoors.[51] And in many countries, more people may have died from heat stress or other conditions because of a lack of air conditioning, rather than because of worse events and conditions. Thus, a simple trend line of deaths does not represent a meaningful or useful comparison, especially where the focus is on the experience of higher-income countries.

Most higher-income countries have experienced a much lower overall all-cause level of mortality than the global average, with far smaller pricing margins (for insurance products), with more at risk. It does not take as many illnesses and deaths to constitute a financial or competitive impact. In addition, ill health and death affected by climate change or climate risk will result from more than just natural disasters.

The U.S. saw more than US$10 billion in health-related costs from 10 disasters in 2012, including wildfires, extreme heat and Hurricane Sandy (Limaye et al. 2019). This was due to about 900 deaths, 17,000

[51] https://www.maricopa.gov/ArchiveCenter/ViewFile/Item/5494

emergency room visits and 20,000 hospitalizations, including the cost of treating injuries, illnesses and mental health problems, not including the longer-term impacts of lost lives. Although this may not seem like many deaths, 2012 was still early in the current climate change process. Losses are expected to grow in a nonlinear fashion over the coming decades.

Myth 2. Even if there are increased deaths from hot weather, there will be far more deaths saved from weather that is not as cold.

It is true that, globally, more deaths occur in the winter than in the summer in most areas, and there are currently more cold-related deaths than hot-related deaths.

But the relative mix of deaths resulting directly from hotter weather and fewer from extreme cold weather is changing. In addition, this ignores the increase in weather volatility, unavailable or ineffectively used adaptation measures and non-temperature-related climate change risks. The relative risk of extreme hot versus cold-related weather deaths is discussed in section 4.2.

Even under optimistic climate scenarios, it is likely that average volatility and extreme temperature and humidity levels in many countries will continue to increase over the lifetime of current insurance purchasers. In some countries and areas, especially under pessimistic scenarios, these may increase significantly. In addition, just because usually more deaths occur during the winter than in the summer does not necessarily mean that all of these winter excess deaths are temperature-sensitive.

Even in countries where the population is well prepared, adaptive techniques such as air conditioning and community cooling areas may not be readily accessible and used. In addition, all such techniques come with some limitations, such as possible adverse consequences of power outages in periods of extreme heat and demand for electricity, as experienced in the summer of 2022 in Texas (e.g., loss of operation of air conditioning and hospital equipment, although back-up power sources can reduce this risk) or as a result of a lack of convenience by the vulnerable in all areas, for example, the elderly, frail and disabled.

In addition, this myth, although true in the relatively short term in some countries or areas regarding the direct effect of temperature change, takes an overly narrow view of climate change and its risks. Temperature is just one of the climatic factors affected by climate change, and others may not have offsetting factors; for example, there are no “negative” or opposite weather events to storms, and the opposite of a flood caused by excess rainfall is a drought that has its own adverse effects.

Myth 3. Even if a valid long-term concern, climate change will not affect the life or health insurance business for decades.

The consequences of climate change will indeed grow over time over a longer-term period as the climate change process evolves. But that does not suggest that it is not a concern now or will not be in the upcoming year.

Recently, many of the effects of climate change have become readily observable, probably understated because many related deaths are not attributed to environmental causes, with the secondary effects of these changes being difficult to identify. This problem can result in a great deal of near-term uncertainty.

Some of the adverse weather and climate weather effects to which climate change contributes are now becoming more obvious. Increasingly, serious events and conditions seem to be popping up somewhere every year, including extreme temperatures, precipitation and winds, floods, droughts, wildfires, polar and glacial ice melt, and tropical cyclones that are occurring earlier and more intensely than many experts had previously forecasted. A concern is that such events or conditions will continue to unfold in a relatively rapid adverse manner.

Increased morbidity will show up earlier than increased mortality in many cases, especially from slow-developing CVD, respiratory, cancer and infectious diseases. Examples of current risks include smoke from wildfires and other air pollutants that can become serious contributors to premature illness and death, especially people 65 years of age and older, with an increased risk of short-term respiratory events, people with preexisting cardiac or respiratory conditions, people living in low-income areas, who have an increased risk of short-term cardiopulmonary events; pregnant women, outdoor workers due to their increased exposure, and children because of their relative immature respiratory and immune systems.

In addition, indirect and secondary environmental drivers of mortality and morbidity are becoming more important factors in both physical and mental health outcomes. In some cases, additional morbidities and deaths are occurring now on a delayed basis, with situations in which the environment plays a contributing role that can be difficult to isolate and identify with certainty. A better metric than reported direct deaths can be excess deaths over a benchmark not affected by these deaths.

Myth 4. Climate change will not affect a life or health insurer's book of business because its market segment includes those with higher income and who live in a temperate climate.

Those who have higher income or wealth and live in a temperate climate will usually be less exposed than others. Nevertheless, despite the overwhelming attention that has been given to the most vulnerable, anyone can be exposed to many of these risks. Examples include wildfire and wildfire $PM_{2.5}$ risks, heat stress for those over age 65, droughts, floods, and sea-level rise. In addition, because an insurer's insurance inforce tends to have a higher percent in specific population segments or locations, it may be exposed to concentration risk, under which a single event or condition may create a greater overall risk to them compared with other insurers or the general population. Some climate risks are more affected by geographical area or luck than income or wealth.

Certainly, those who can better afford to adapt, build resilience and have increased mobility will be more successful in avoiding some of the more serious physical consequences of climate change. Nevertheless, it can be quite difficult, even for the most well-off, to avoid all such risks.

Although those with lower income or resources can be both more exposed and vulnerable to certain morbidity and mortality outcomes and consequential risks, some climate- and weather-sensitive risks can affect anyone, despite the boundaries shown in Figure 7. For example, designated flood zones do not mean that those living outside those zones will be immune to flood risk. In addition, those with lower socioeconomic status (e.g., with lower incomes or who live in a densely populated urban area) in high-income countries may be similarly affected. Similarly, certain hazards, such as heat stress, vectors- or waterborne diseases, can especially affect those whose occupation involves out-of-doors work.

Those who are vulnerable differ by climate change hazard, some of which do not differ by socioeconomic status. Both sudden and slow-onset conditions can occur in many locations; for example:

- Heat-stress for the elderly, for which there were 345,000 deaths globally in 2019 (Atlantic Council 2021), is projected to increase to 59,000 deaths in the U.S. in 2050 without further adaptation action;
- Smoke ($PM_{2.5}$) does not respect a person's status;
- Droughts, for example, are occurring in western Canada and the U.S.; and
- Sea-level rise represents an increasing hazard. Those who live nearby, even in tall, coastal luxury condominium buildings may be at risk, by itself, sea level rise may represent a mortality risk as it

usually takes a long time to rise; however, the effects of accompanying risks such as water surges can cascade and become dangerous.

- Wildfire risks. The number living within wildfire perimeters (wildland-urban interface) has doubled in the last 30 years because of both housing growth (47% of additionally exposed houses) and more burned area (53%). According to Radeloff et al. (2023) more than 55,000 houses in the U.S. burned from 2010 to 2022. By 2020, there were about 44 million houses in the total wildland-urban interface near forests, grassland and shrubland. Many are not aware of their risks when they are not near forests. In addition, everyone downwind of the massive Canadian wildfires in 2023 was exposed to long-term health risks.

As indicated in section 4.9.1, the intensity of most of these effects can differ widely by geography, with, for example, parts of Africa, Asia and South and Central America more at risk than parts of North America and Europe. However, many effects are equal opportunity causes of ill health and deaths that do not respect national boundaries. Droughts, for example, in western North America can affect everyone in the areas affected. Because the world is becoming increasingly urbanized, consequential urban risks (e.g., through heat island effects) will be tied to development and migration. Wildfire smoke emanating from the western U.S. can affect the air quality of the entire northern and western parts of the U.S., which can result in lung damage for all those exposed and a lifelong threat to the health of youngsters forced to breathe smoke-laden air.

Overreliance on adaptation techniques may create further vulnerabilities, including false expectations of invulnerability to these factors. The fastest increase in average temperature has been in the polar regions, which, together with changes in air pressure, will cause polar vortices and floods from atmospheric rivers.[52]

The exposure for life and health insurers to these risks will depend upon their past, current and future markets and products. Some life insurers have an automatic hedge if they have underwritten both life insurance and annuities, although if their sales are concentrated in different markets or regions, they may benefit or suffer depending on the risks involved and their exposures. Or they may suffer from concentration risk or overexposure in exposed areas and become vulnerable, especially the elderly population.

Myth 5. An increase of only 0.4 degree Celsius degrees Celsius or 0.9 degree Celsius (corresponding to 1.5 or 2.0 degrees Celsius over pre-industrial levels, compared to the current global 1.1 or 1.2 degrees Celsius level) is quite small. How can this change represent a catastrophic concern?

Indeed, a 0.4 or 0.9 degree Celsius difference in temperature is usually difficult to discern.

However, equating this seemingly small global average effect to climate change is misleading, because of increased volatility and extreme conditions, more rapid climate change in places such as North America, the fragility of life and the environment, and uncertainty regarding climate tipping points.

[52] Long, narrow plumes of moist air that travel from the tropics to higher latitudes. When these storms move over mountains, they condense into clouds that produce heavy rain and snow. As the atmosphere warms, atmospheric rivers are likely to become more frequent and hold more moisture. California's swings between wet and dry periods are becoming amplified because of climate change.

Every 0.1 degree Celsius change can affect the lives of hundreds of 140 million people (Lenton et al. 2023). Every additional global warming will cause a discernible increase in the intensity and frequency of heatwaves and other consequences of a volatile and changing climate.

In any event, global averages can be misleading. Not only are we dealing with extremes and volatility, but we often deal with people in densely populated urban or even suburban areas where such conditions as urban heat islands can result in higher average temperatures and increase concentration risk. And where the population is concentrated, life insurance is usually similarly concentrated. Also, as a general rule, for every 1 degree Celsius increase in the global average temperature, extreme temperatures, that is, the high highs and the high lows, will increase to more than twice as much.

Regional and local differences can exacerbate these changes. Recently, it is not unusual to hear about somewhere in the world where the temperature is 10 or 20 degrees warmer than long-term averages for the month or record-breaking temperature or precipitation.

When will a tipping point be reached? No one knows for sure, although hints are emerging throughout the world. In addition, small changes in temperature and precipitation can result in large changes in the number, intensity or range of such risks as vector-borne and waterborne diseases and events.

Myth 6. The media says that climate change will be either "the end of civilization as we know it" or "a no-never-mind issue," depending on who is talking or listening. Both cannot be right—so we can wait for further information and new technologies to develop to fix the problem.

Considerable differences in opinion exist as well as many misleading and exaggerated claims involving climate change. These differences have partly arisen because of politicization, misinformation and mass or social media treatment. Language can have a powerful influence on people's views.

The current scientific consensus, as documented in the IPCC (2022) and elsewhere, is that these effects will become an increasing threat to life (and property), the seriousness of which will partly depend on the priority given to addressing it. Objective sources, such as IPCC's documentation of comprehensive studies, were the basis of Watts et al., (2021) that climate change is set to become the "defining narrative of human health." The WHO (2021A) has claimed that climate change is "the single biggest health threat facing humanity," which strongly suggests the seriousness of the impact of climate change on mortality.

Various elements of the media and social media can over- or understate these risks, depending on their biases or perceived audiences. In contrast, facts and objectively developed and maintained models by trusted sources that recognize the considerable uncertainties involved (see section 8) can provide the most appropriate information for decision-making purposes. Society must rely on the results of reputable up-to-date scientific analysis, accompanied by some skepticism that recognizes potential subjectivity and uncertainties regarding how the future will unfold.

The types and extent of adaptation and preparedness will affect the location and degree of adverse mortality. This is an example of the feedback loops and the source of some differing views involved—the greater the concern, the more preparation will develop, in turn favorably affecting future outcomes.

Some studies have indicated that, in countries such as the Netherlands or the United Kingdom, there is a possibility that a net favorable mortality impact due to temperature changes may arise in the short or medium term. If this does occur, particularly in lower greenhouse gas concentration scenarios because of the relatively large number of current cold-related mortality deaths, additional heat-related deaths will still occur. In addition, even in these circumstances, over-reliance on this favorable temporary trend may understate the importance of longer-term adverse risks.

In addition to climate change deniers, others recognize these risks, but also believe that new or existing technologies can be sufficiently utilized to avoid serious consequences. However, although effective use of technology may reduce the impacts from some of the worst-case scenarios, it is doubtful they will be able to reduce the risks entirely.

Adverse climate events and conditions, such as melting ice caps and glaciers, warming oceans, intense storms, temperature and precipitation extremes, and wildfires, are all well-documented effects of climate change that will not disappear. But at times, they may seem too remote and occur with mind-numbing regularity to prompt people, businesses and politicians to adopt behaviors that can slow the warming of the planet and reduce its many possible effects. Unless one's neighborhood is severely damaged by a severe tropical cyclone, flood or wildfire, it is easy to think that such disasters happen only to "other" people and that a person or business cannot do much about it.

The lines of defense described in section 9 will help reduce mortality risk. However, residual mortality risk will remain, the extent of which is currently uncertain as described in section 8.

In any case, realistic alternative scenarios on which risk management can be based will have to be adjusted over time to reflect the most recent information and expectations regarding the effects of climate change. That means risk management techniques such as diversification and adaptation will be increasingly important.

7. Data, Modeling and Measurement Issues

To better understand the effects of climate-induced changes, the risks to human capital and lives need to be identified and, where practical, quantified. This applies both to the effects of long-term gradual changes in climate and to the aggregate effect of changes in the frequency and severity of extreme weather events. Although the prediction of climatic factors is sufficiently challenging, quantifying their impacts on mortality may be even more difficult. Climate change is creating conditions that lie outside the range of past experiences, limiting the applicability of results of empirical studies, especially with respect to combinations of the factors involved. The possible impact of any effects that do not lend themselves to a quantitative approach needs to be acknowledged and effectively communicated.

In modeling, both deaths (numerator) and exposures (denominator) need to be considered. For age, for example, separate estimates for broad age groups or an aggregate age adjustment using a factor representing the approximate effect of the change in population mix could be developed. Alternatively, a more refined demographic projection could be attempted, reflecting estimated mortality rates, aging and net migration by age, plus fertility rates, as applicable.

The first step is to identify relevant and reliable data. Data reporting and attribution issues (see section 3) can differ dramatically by risk, study and country. Although economically developed countries usually have better overall vital statistics (including mortality), their reported data may still distort the true picture or be incomplete. For instance, different definitions or approaches to determining climate- or weather-related deaths have been used. Many deaths are not reported as being due to a climate change outcome, particularly when it is an indirect or contributing cause, for example, heat-related deaths reported as being due to CVD. As a result, reported attribution to these mortality risk drivers may be understated or underestimated.

Two examples follow:

- More than 1,400 excess deaths were reported as being a result of the June 2021 heatwave in the Pacific Northwest in the United States and British Columbia[53] (in addition to contributing to more severe wildfires, triggering blackouts and causing hundreds of millions of marine animal deaths). In contrast, "excess deaths" in the area were significantly larger, possibly by a factor of three, suggesting significant underestimation in geographical locations with usually reliable data reporting.
- A recent study estimated that about 5,600 deaths in the United States could be attributed to elevated temperatures each year, significantly more than the 700 heat-related deaths per year based on official reported causes of death (Weinberger et al. 2020).

In sum, currently reported statistics regarding the morbidity and mortality effects of climate change are likely to be underestimated and underreported. Consistent reporting of morbidity and mortality from a climate change hazard as an underlying or contributing cause is needed. For every person who died from a heat dome[54] situation, possibly 10 or more may have suffered heat stroke, dehydration or other complication, including permanent, life-altering or life-ending injury or medical condition. When the temperature increases, even if only by two to three degrees, the ability of a person to cope can diminish or be lost.[55]

The current approach to assessing the extent of the economic effects of climate change is primarily through the application of integrated assessment models (IAMs) that reflect (1) the effects and interrelations of factors involving greenhouse gas emissions, (2) their effects on climatic factors such as temperature and precipitation and (3) consequential damages, including premature deaths. These are then reflected in economic models that can incorporate financial and human effects, taken to a present value through a social discounting process (Gutterman 2020). Each of the elements involved can benefit from multidisciplinary input. For example, the economic cost of a lost life may be excluded entirely.

Modeling the effects of climate change on future levels of mortality presents formidable challenges due to the complexity and uncertainty involved. This is partly because of the lack of adequate data and the interconnected nature of the systems being modeled, that is, the effects of the physical environment, ecology ("natural processes"), political actions and enforcement, and institutions and households incorporating effects of human physiology and behavior. The combined effects of these elements impact the relationship between climate and health, on both global and local levels. Thus, a change in temperature (physical) and people's reactions (behavioral) can, for example, give rise to an increase in the population of disease vectors in a country that may or may not have the institutional capacity to effectively deal with such a change.

The form in which a mortality analysis is conducted can depend upon the application. For instance, projections can be developed by climate change hazard or by climate scenario that depends on the extent of future emissions, climate change, geographic location and applicable adaptation and population changes. The metric used may be the percentage of the age-adjusted or age group-specific mortality rate, number of years of lost life, life expectancy or effect on the value of a statistical life or mortality risk.

Depending on the application, a model should incorporate the impact of the characteristics and drivers of the hazard, the exposure and those who are vulnerable. Separate models would be applied to study each

[53] https://www.nytimes.com/interactive/2021/08/11/climate/deaths-pacific-northwest-heat-wave.html
[54] A heat dome occurs when a persistent region of high-pressure traps heat over a large area that can linger for days to weeks.
[55] https://www.wcel.org/media-release/physicians-lawyers-call-bc-investigate-thousands-heat-dome-injuries

effect, such as heat stress, vector spread or natural disaster during the period. For example, possible enhancements might incorporate the estimated effects of humidity; Barreca (2012) found that the distribution and interaction of climatic factors affect mortality, as they are likely to decline in cold and dry areas, but increase in hot and humid areas.

In studying the effects of sudden-onset events, the expected impact of "harvesting" might be considered; that is, a hazard such as extreme heat or violent storm might cause deaths that would otherwise have occurred shortly thereafter had the extreme event not occurred. This effect can differ by sociodemographic or socioeconomic status and country. A focus on excess deaths rather than cause-attributed deaths might be taken, although setting appropriate baseline rates can be problematic.

When modeling, the effects of population aging and adaptation actions taken need to be considered and appropriately reflected. Differences in the "before" and "after" scenarios are usually sensitive to the population projection model applied, as the size and age composition of most populations would be expected to change.

For example, based on projected population structures, using 2000–2009 as a base period and assuming no further adaptation action and population change, Hajat et al. (2014) projected that heat-related deaths in the United Kingdom will increase by about 50% in the 2020s, 170% in the 2050s and 330% in the 2080s. Their estimated increases in deaths would have been considerably larger if increases in the size of the population were reflected.

The level of model complexity (in terms of the number and granularity of the parameters) used may depend on the desired accuracy and objectives of the analysis. The degree of refinement used (e.g., whether separate gender or individual age results) will depend on such factors as the length of time projected and aspects of climate change studied. In typical actuarial calculations, expected outcomes might be expressed, for example, as a component of annual mortality improvement rates.

Projections should be dynamic, that is, reflect current information and expected changes in the factors involved, as well as their interrelations. Extended lags between experience data and information used can erode the value of a static model.

Models are usually run under both a baseline scenario and possibly multiple scenarios reflecting alternative level(s) of climate change, for example, based on alternative amounts of current emissions or global average temperature, depending on the model used (further discussed in section 8.1). A set of scenarios might be based on stochastically generated parameter distributions. If a single "best-estimate" effect is desired, probability weightings could be applied to the results of the assessed scenarios; such an approach could be taken if, for example, the uncertainty is large or asymmetric assumptions or outcomes are modeled. In addition, specific scenarios based on alternative mitigation or adaptation strategies or outcomes could be studied.

As an example, in studying the effect of diseases spread by mosquitoes, a model might consist of modules or separate equations involving expected temperature, cumulative rainfall, insect mitigation measures, insect mortality rates, infection rates, types of and extent of adaptation efforts such as vaccines taken or bed net prevalence and disease recovery rates. Such a model would cover all applicable regions in a country, varying population concentration and their closeness to infectious disease outbreaks.

A sea-level analysis could include a model of the rate and size of glacial calving or glacial lake flooding, storm and precipitation history, the height of waves in an area at high tide, and protective sea walls and infrastructure in place, as well as air and ocean temperatures in applicable parts of the world.

In an analysis of the effect of temperature changes, for example, the following two models may be used: (1) a time-series model of the expected changes in average daily temperature (or its volatility or range) for a location or area and (2) a model of the relationship between temperature and mortality rates for a population segment. A time-series model may be needed because daily mortality rates might depend on the temperature experienced over a period of days, as well as the period over which mortality is measured. In addition, the expected change in the population segment exposed, such as the number of people older than a specified age such as 65, may be needed.

In a study of the effects of extreme temperature or precipitation, a model of the effects of adaptive measures available to or taken by the population-at-risk may be appropriate. This might study factors such as the extent of the population staying indoors in air-conditioned rooms in a hot situation, the usage of public cooling areas, how much the population is outdoors and the likelihood of a power outage because of heavy electricity use.

The observed effects are incorporated into the model, especially where the impact on mortality is expected to differ by demographic, socioeconomic or geographic factors that are sensitive to the climate change hazard being assessed, including the adaptation measures taken and the percentage of the population most sensitive to the risks.

The complex feedback loop of change and response represents a challenge to insurers and pension programs that face morbidity or disability risks, as well as mortality and longevity risks. Depending on the type of climate change hazard and its expected consequences, other than immediate injuries and immediate effects on medical conditions and causes of death such as heat stroke, a lengthy time lag may make monitoring the total mortality effect of climate change more difficult.

Some mortality modelers have based their estimates of heat-related mortality on average daily temperatures. However, the curve of mortality versus temperature (see Figure 5) often has a “J” or “U” shape, with a minimum at a particular (optimum) daily temperature. The rate at which mortality increases as temperature increases above this optimum is typically, but not always, greater than the rate of mortality increases shown on the left side of the graph (as temperature falls below the optimum); that is, the change in mortality may be more sensitive to increases rather than decreases in temperature.

Another important characteristic is that the optimum temperature can vary with the location studied, although it is normally greater than the average experienced temperature (Gasparrini et al. 2015). In addition, the length of time exposed to extreme temperatures and the nighttime temperature can also be factors in the extent of mortality. The period over which a given amount of rain falls or over which rain does not fall can be an important factor is studying the effects of flooding, malnutrition or disease vector spread.

Several approaches have been taken to incorporate the effects of climate change into mortality models. For example, Seklecka, Pantelous and O’Hare (2015) added a weather-related factor to a Lee-Carter base mortality model (a popular mortality projection model). Seklecka, Pantelous and O’Hare (2017) applied a similar model to U.K. mortality rates by modeling annual experience and the experience of cold months separately, rather than focusing on the experience just from the hotter months.

In most situations, actuaries develop annual mortality improvement factors that differ by such factors as years from evaluation, attained age and gender. The refinement in the factors applied may depend on the application. Any adjustment will usually be applied to estimates of historical rates of the population or population segment being assessed, a projection of the mortality improvement rates without any climate change reached by a certain year or period, and the estimated incremental effect of climate change. Observations are relevant to the development of these factors:

- Excluding the effect of COVID-19, recent mortality experience from which baseline mortality is estimated may be the result in some countries and situations of relatively favorable climate-related changes in mortality (e.g., a larger decrease in cold-related mortality than the increase in hot-related mortality or a period without an extreme event). If that is the case, the past may not reflect expected future conditions; it may not be appropriate to reflect such a favorable period or trend into the future.
- Although it may be desirable to incorporate an explicit factor to reflect the expected effect of climate change, it may not be possible to estimate the effect on a sound and realistic basis. Possible reasons include the difficulty in predicting the extent of future climate change and its consequences, the effects of human nature and political decision-making, and the uncertainties involved in projecting mortality under unknown future conditions (see section 8 for further discussion). A projection may be better developed given a selected scenario regarding a population and area involved, as well as a climate change trajectory and level of adaptation.
- Alternatively, the estimated effect of climate change could be incorporated implicitly, included in an aggregate mortality parameter also covering other difficult-to-quantify assumptions such as the delayed effect of obesity, or as part of an overall risk and uncertainty margin.
- Other approaches may be useful in certain situations. For example, extreme value approaches may be useful in the modeling of extreme climate risk and extreme mortality risk (tail risk) in an integrated manner (e.g., Li and Tang 2020).

In any case, it is appropriate to disclose to the user of a projection how the effects of climate change were considered and reflected. Note that no attempt has been made here to quantify this adjustment, as it is outside the scope of this paper.

Two interesting metrics developed in estimating the cost of climate change are the following:

- The "mortality cost of carbon,"[56] a potentially useful metric of the costs associated with mortality caused by climate change, was described in Bressler (2021). It is the estimated number of deaths resulting from the greenhouse gas emissions of one incremental metric ton of CO_2. Bressler developed such an estimate based on the IAM developed by William Nordhaus, using an estimated mortality curve and a corresponding cost per life over the period remaining in the 21st century. His estimated cost was then incorporated into an overall "social cost of carbon" that includes financial costs other than mortality. Bressler considered mortality only from heat-related deaths rather than the cost of morbidity or deaths due to other climate-related risks, although it could be expanded to incorporate other sources of mortality. Although the assumptions needed to develop such a calculation are difficult to quantify, it may prove to be a potentially useful concept to consider in some applications.
- Carleton et al. (2022) defined a mortality partial social cost of carbon as the marginal willingness to pay to avoid an additional ton of CO_2. They found that the relationship between mortality rates and temperature is highly nonlinear and can differ greatly with an area's income and climate, among other factors. Using several of the leading IAMs, Carleton et al. studied 40 countries for which mortality costs in 2100 would account for 49% to 135% of total damages due to climate

[56] This can also use "methane" rather than "carbon," depending on the application.

> change across all sectors of the economy. They valued the mean increase in the economic effect of this mortality risk to be roughly 3.2% of global GDP in 2100, with today's cold locations benefiting from warming, with especially large damage to today's poor and/or hotter areas. They estimated that the release of an additional ton of CO_2 (mortality partial social cost of carbon) today will cause mean damage of US$36.60 (with a range of –$7.80 to $73.00) under a high emissions scenario and US$17.10 (–$24.70 to $53.60) under a moderate scenario, each using a 2% discount rate (using a 3% discount rate the mortality partial social cost of carbon would be $14.20 and $7.90, respectively).

Assessing the size of or uncertainties related to the risk, and sometimes even the direction of impact, can be complex, but not impossible, to estimate or project. Helping people to better interpret the data and to understand the risks (and opportunities) to society are both well within the actuarial skillset.

8. Uncertainties

Significant uncertainty surrounds the trajectory of future mortality. As a result, any analysis of mortality must recognize the potential range of future possibilities. This range includes tail possibilities involving dramatic one-off climate-related events and conditions or ongoing adverse trends characterized by nonlinear, compound, exponential, cascading and volatility risks. Climate, weather, damage and response processes will continue to be dynamic, that is, subject to continuous change.

As mentioned above, this uncertainty and range of possible outcomes arise in the following areas:

1. Future level of greenhouse gas emissions;
2. Effects of the concentration of greenhouse gases on the expected frequency and severity of global and local climatic factors;
3. Given the extent of climate change, the type, extent, effectiveness and distribution of adaptation and disaster management actions taken (see section 9) and their effects on ill health and death; and
4. Given the adaptation and disaster management actions taken, the global and local effects of climatic factors on ill health and deaths, including their geographical distribution among the vulnerable.

The first and third sources of uncertainty are subject to political, business, community and personal decisions. It is quite difficult to project both the actions themselves and their effects, partly because of the many interactions and feedback loops involved. In addition, although some decisions and consequences are effective at the local level, others are global in terms of causes and effects. Over time, our understanding of the climate change and risk management processes involved will improve and uncertainties may diminish.

Studies and models of these processes are hampered by attribution issues that include likely under-reporting and under-diagnosing causes of death directly and indirectly linked to climate change-related factors, as well as uncertainties associated with human behavior and political, business, and personal decision-making processes. As a result, they will remain difficult to project and model. Both stochastic analysis and scenario testing approaches may prove beneficial in the analysis and communication of the effects of these risks and uncertainties.

Some of the studies referred to in this paper illustrate the extent of uncertainty and ranges of possible outcomes associated with estimates of climate-related deaths and mortality. These pose challenges for actuaries wishing to incorporate the effects of climate change when developing assumptions regarding future mortality levels. This uncertainty strongly suggests a need to focus on developing a range of plausible outcomes, rather than a single best-estimate set of assumptions.

The full range of uncertainty may be wider than presented here, not only associated with limited experience that is commonly used to calculate confidence intervals, but also with parameter and model risks that are not usually considered. This is further exacerbated by limited or no assumptions in some projections regarding the pace of aging, political and investment decisions, behavioral or physical adaptation, or shifts in population mix (e.g., in the vulnerable population such as an increase in the number of those who are old or physically or mentally fragile).

Most IAMs are limited and may significantly underestimate the economic effects of climate change (Stern 2013). Some of these models focus on economic and physical risks, ignoring the effects of morbidity and mortality. With any model, including an IAM, it is vital to understand both the uncertainties involved and the model's sensitivity to alternative assumptions embedded in the model, as part of understanding a model's limitations and uses.

Although the training of most actuaries does not specifically cover climate science, they are experts in assessing the financial implications and uncertainties associated with similar contingencies based on an approach that can be used to assess their effects. One can anticipate that actuaries will become more involved in the analytical aspects of the climate change process as its effects on lives, health and property become clearer and more immediate.

It is difficult to predict what will happen if, when and where extreme climatic factors occur. Because all we have to base models on is historical information regarding similar, but not identical, situations that may not reproduce historical conditions, informed judgment will be needed.

It is always challenging to predict the effects of low-probability extreme events, especially when outside the range of climate and weather conditions. For example, as temperatures increase, the temperature-mortality curve may also shift. Ballester et al. (2016) hypothesized that both curves might change; that is, adaptation will partly offset the increase in heat-related deaths that would otherwise arise.

8.1 Scenarios

A powerful alternative approach to stochastic modeling to illustrate the possible impacts of climate change on mortality and the uncertainties involved is scenario analysis. Actuaries in all practice areas involved in modeling often subject their projections to scenario analysis or sensitivity testing. Although uncertainty regarding the future baseline level and patterns of mortality for the population segment studied exists, each alternative scenario considers the incremental areas of uncertainty listed above, including the frequency and severity of climatic hazards, adaptation to these risks and sensitivity of mortality to these climatic factors.

Climate-change-related additional mortality, usually increasing over time, can be expressed as a percent of annual change in mortality improvement, an addition or subtraction of a certain number of ages in the mortality table used, or a change in the years of life expectancy.

As in any modeling project, to estimate the impact of alternative future climate scenarios on mortality, actuaries need to understand the most relevant and reliable data regarding the population being assessed and to consider the challenges involved in untangling the interaction between variations in climate and weather-related risks and mortality. Variations in the effects by age group would usually be expected to be incorporated into the alternative or incremental mortality assumption.

In most cases, one finds significant common assumptions across scenarios, with deviations from the baseline assumptions developed only for key factors. The assumptions used should be internally consistent.

The result is usually compared to a "without climate change" baseline scenario, that is, without incorporating the effect of future climate changes on mortality. Refined modeling can be applied to examine the impact of a range of assumptions by hazard type or cause of death, possibly with different assumptions by age group. For example, a smaller percent future mortality improvement adjustment can be made for ages less than age 65 than for ages at least age 65 if it is assumed that climate-change–related mortality rates affect older-age mortality more than younger-age mortality.

A relatively small possibility is found of an extreme tail condition. Assumptions underlying a tail scenario can be especially difficult to estimate accurately, as by definition a great deal of uncertainty is involved because of limited data or experience of it, possibly including compounding or cascading risks in an environment quite different from that of today's conditions. As a result, a sensitivity analysis (incorporating a "what if" scenario) may be the best way to illustrate the effect of such a tail condition. Any such tail scenario needs to be clearly delineated and communicated if its conclusions are to be useful.

If such a tail condition arises, there may be more profound impacts on the investment strategies of an insurer or pension program than on mortality; the political and environmental backdrop within which these programs operate may be severely affected, possibly similar in scale to the recent COVID-19 pandemic. A discussion of these effects is outside the scope of this paper.

Advice and guidance on developing climate change scenarios have rapidly expanded over the last several years. Alternative climate scenarios have been developed by the IPCC (e.g., see IPCC 2022), These are described in guidance prepared by the Task Force on Climate-Related Financial Disclosures (TCFD)[57] and various actuarial organizations, including the International Actuarial Association,[58] although so far none has provided specific guidance regarding projected mortality risks.

9. Lines of Defense

There are three primary lines of defense against the adverse mortality effects of climate change: mitigation, adaptation and disaster management.[59] All three lines of defense are part of a comprehensive risk management process with regard to the climate hazards applicable to the population or area studied. We know what may be coming—but the closer it gets, the more costly and difficult the necessary tasks may become. All three are valuable components of this process.

9.1 MITIGATION

Using climate change terminology, mitigation, the first line of defense, refers to the control of emissions, atmospheric concentration and removal of greenhouse gas emissions. The return on these actions is relatively long-term, but they can reduce increases in the frequency and severity of climate and weather-

[57] https://www.tcfdhub.org/scenario-analysis/.
[58] https://www.actuaries.org/iaa/IAA/Publications/Papers/Climate_Issues/IAA/Publications/Climate_Issues.aspx.
[59] Disaster management is sometimes referred to as "loss recovery" or "loss and damage."

related events and conditions. Many actions can be taken to mitigate climate change by reducing greenhouse gas emissions, which as described earlier can, in turn, result in improvements in health and ultimately mortality. These actions include better management of transportation, energy generation, agriculture, forestry and nutrition. Further discussion of the mitigation of climate change drivers is outside the scope of this paper.

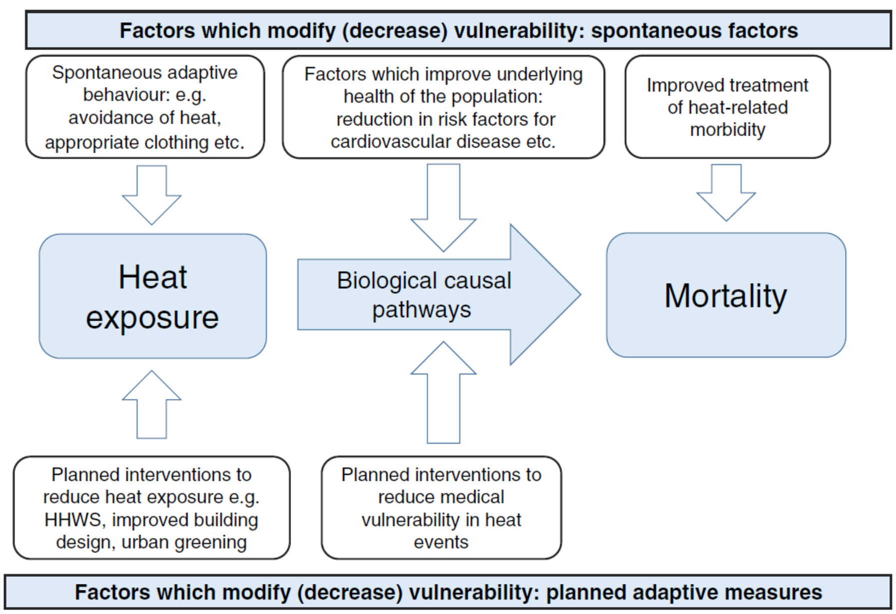
9.2 ADAPTATION

Adaptation, the second line of defense, includes the use of a range of techniques to eliminate or reduce the adverse effects of sudden or slow-onset climate events or conditions. It tends to take a short- or medium-term focus. Actions and behaviors of society and individuals can also play a role in reducing the impact of many adverse climate change–related hazards.

Adaptation actions that can affect mortality due to excess heat are illustrated in Figure 4.

Figure 4

HOW ADAPTATION ACTION CAN AFFECT HEAT-RELATED MORTALITY



Source: Arbuthnott et al. (2016), 89.

Thermal comfort and management of temperature-related morbidity and mortality risks are affected by residential and commercial building characteristics such as temperature and humidity control systems, thermal resistance, solar shading, thermal mass and building orientation and location. Energy-efficient buildings with effective insulation, airtightness and ventilation can reduce hazardous temperature-related outcomes. Protection against excessively hot or cold temperatures may be enhanced in a more cost-efficient manner if incorporated into building design, but periodic technological updates (re-engineering) to existing structures in response to climate change can also be beneficial in the long run.

Access to affordable cooling techniques such as air conditioning can increase the resilience of populations to heat-related health outcomes. For example, there is an association between an increased prevalence of air conditioning and lower heat-related mortality risk (Sera et al. 2020). Excess deaths due to high temperatures decreased between 1972 and 2009 from 1.40% to 0.80% in Canada, 3.57% to 1.10% in Japan, 3.54% to 2.78% in Spain, and 1.70% to 0.53% in the United States, with increased air conditioning usage explaining only part of the observed mortality improvement, estimated to be 16.7% in both Canada and the United States, 20.0% in Japan and 14.3% in Spain.

Other factors involved include population aging, affordability of and reluctance to use adaptation tools, and the risk of consequential power outages in health care and long-term care facilities during times of peak use and need. Other coping strategies may need further development and promotion, including low-tech measures such as the effective use of blinds, natural ventilation and enhanced public awareness, as well as solar-powered air conditioning where feasible and conveniently located community cooling areas.[60]

When given an opportunity in moderate situations, most people are reasonably adaptable; however, there are limits to the adaptive capacity of the human body. Most cases of heat stroke occur within the first three days of a heatwave, usually dissipating within 10 days. Similarly, most (50% to 70%) outdoor fatalities occur in the first few days of working in hot environments because it can take time for the body to build a tolerance to excessive heat.[61]

Evidence has emerged suggesting that there may have been a reduction in population sensitivity to heat arising from adaptation actions, albeit more in high-income countries and areas, such as the implementation of heat warning systems, increased exposure awareness, use of air conditioning, improved overall health care and emergency response infrastructures, as well as an increase in the minimum temperature at which mortality risks arise.

Examples to reduce exposure or vulnerability include zoning or siting buildings in areas not exposed to flooding, infrastructure that can withstand greater levels of adverse effects from sudden events such as floods and storms (e.g., “wet-proofing” buildings in flood-prone areas), increased access to air conditioning and community cooling facilities in times of extreme heat, or relocation to reduce exposure. Further, risks such as desertification, large sandstorms and wildfires can be managed in part by evacuations, proper clothing and masking.

Some cities are developing heat action plans, in some cases by appointed chief heat officers, whose job includes the enhancement of communication of the risks involved to help ensure that residents take these risks seriously and take appropriate adaptive action. These plans include the alleviation of the effects of heatwaves by opening and publicizing public cooling centers, reminding neighbors to check on vulnerable people and providing bottled water. Although these are usually done during daylight hours, some of these approaches may be more valuable at night.

Effectively communicated early warning systems can significantly reduce exposure to increased morbidity and mortality resulting from extreme weather events. Health care services from at least 86 countries are now connected to their meteorological services (Watts et al. 2021). Monitoring and communication mechanisms can be valuable for a wide range of events and conditions, including infectious disease outbreaks, health surveillance and risk awareness campaigns.

Adaptation through physical acclimatization, use of costly technologies and changes in behavior (e.g., staying indoors in periods of extreme temperature and wearing masks when exposed to smoke from wildfires) has decreased the adverse effects of excess heat in the 20th century (Barreca 2015).

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[60] This includes better means of being transported to such facilities, which may not be easily accessible to those needing them, as well as effectively communicated warnings as to when it is beneficial to use such resources.
[61] OHSA, https://www.osha.gov/heat-exposure.

Nevertheless, adverse effects have persisted because adaptation and self-protection can be costly and thus not universally implemented.

The availability of relevant and reliable data is an adaptation tool that can make effective development and implementation of national and local comprehensive risk management processes possible. Appropriate surveillance and monitoring systems can increase simultaneous knowledge about the hazards, as well as provide useful information to enhance future adaptation efforts.

In some cases, maladaptation has arisen.[62] For example, although increased use of air conditioning has reduced the impact on extreme heat mortality, especially as it affects the elderly, it can at the same time increase the number or severity of allergies, increase the extent of being overweight and obesity, and contribute to vitamin D deficiencies due to lack of exposure to the sun.[63] A significant increase in electricity demand can also adversely affect climate mitigation due to the greenhouse-gas emissions resulting from its use of energy, as well as contributing to urban heat islands. As another example, the protection of one community against river flooding might have the opposite effect on a downstream community.

Rising temperatures pose an imminent threat to millions of workers exposed to the elements outside, to children in schools without air conditioning, to seniors in nursing homes without cooling resources, and in general to disadvantaged communities. In contrast, appropriately protected schools and other public buildings can serve as community cooling centers, particularly for the poor, disabled and elderly. However, although community cooling centers are good in theory, they do not always work in practice: for those who get out of breath doing simple household tasks, it may be difficult to provide appropriate transportation to these centers.

Self-protection can be costly, and communities, states and individuals continually have to make judgments about its relative costs and benefits. More self-protection will be taken if prices of adaptation actions decrease (or are subsidized by the government or the community). However, if their cost increases, for example, due to inflation, fewer of the most vulnerable will be able to afford these measures. Insurance premium discounts for the implementation of effective adaptation measures can nudge some into taking proactive adaptation action.

The elderly and long-term disabled experienced long-term mortality improvement after Hurricane Katrina devastated New Orleans and surrounding areas in 2005 (Deryugina and Molitor 2020). About 70% of the post-Katrina mortality decline was the result of relocations to areas with better overall mortality outcomes. However, the authors pointed out that this approach may not mean that individuals' overall welfare increased, because of their loss of physical assets and welfare utility. Also, although relocations to areas with better services can be beneficial, if they are to areas with worse services, the opposite situation can arise.

9.3 DISASTER MANAGEMENT

Disaster management is the third line of defense. A well-thought-through and realistic emergency response plan is needed, whatever the entity and for all public sector levels, including training for first responders, effective and well-communicated early warning systems, and services or policies to ensure that low-income and other vulnerable groups can afford and access adaptation resources and other loss reduction

[62] Maladaptation means a change in natural or human systems that inadvertently increases vulnerability to a climatic factor or an adaptation that does not succeed in reducing vulnerability but instead increases it.
[63] https://climatechange.chicago.gov/climate-impacts/climate-impacts-human-health and Wacker and Holick (2013)

approaches. Although extensive resources may be expended in the first two lines of defense to attempt to eliminate or at least reduce the adverse effects of climate change, illness, accidents and death will inevitably occur.

Although a high-quality health care infrastructure, early warning systems and rapid emergency response systems can also be viewed as adaptation measures, they can also represent important components of an effective response process to reduce the sensitivity of those who are exposed and vulnerable.

Rushing international assistance to a disaster area is neither the most desirable nor most effective method to respond to the range of climate-related disasters, such as extreme events, floods, droughts or heatwaves. Nevertheless, this fallback approach is necessary where the climate-related disaster is sufficiently severe or where proactive responses have not been embedded in and driven by the affected communities themselves.

10. Areas for Further Research

Although the climate change process and its risks have been subject to a great deal of research over the past several decades, further research and proactive action planning are still needed, including in the following areas:

- Enhanced mortality and morbidity data and information regarding their underlying drivers and consequential risks by age and gender, including those partly or totally attributable to weather, climate or the environment.
- Quantitative projections of the effect on morbidity and mortality of climate risks and climate change risks by hazard and sociodemographic variables, such as age, income and geographic region. These could differ by cause of death.
- Quantification of mortality assumptions relating to climate-related risks that can be used in alternative scenario development and regional or local application.
- Whether or how the temperature-mortality relationship is changing, particularly at moderate and extreme temperatures (and other climatic factors relative to mortality, including their interactions), how it might change in the future, and its implications for future numbers of hot and cold-related deaths. Also, if practical, how the curve could differ by geographic region, age and extent of adaptation.
- Identification of effective incentives that will make it more likely for more people to take appropriate adaptation actions, in response to public sector health actions (such as publication of a template to facilitate the development and updating city or state plans) and private sector incentives (such as insurance discounts or credit adjustments for loans to adopt safer practices).
- Effects of prolonged exposure to volatile or extreme temperatures (in combination with various humidity levels) or precipitation.
- Since temperature-related deaths are largely preventable, the more that is understood about these deaths and potential adaptive action such as outside working conditions, the more effective management of these risks can be.
- Identification of methods to close the insurance gap to expand insurance coverage among the most exposed and vulnerable to climate change risks, while at the same time maintaining the solvency and sustainability of affected insurance programs.
- Comprehensive climate change risk management techniques (particularly with respect to adaptation) that can be applied to control mortality and morbidity risks. This can, for example, take the form of a comprehensive heat action plan and flood action plan on, for instance, a city-

wide or river-wide basis. This includes methods appropriate to reducing the extent of urban heat islands and considering applicable vulnerable populations.

- Enhanced early warning tools and techniques to address all significant types of climate and climate change risks.
- Effective communication methods for informing the public as to the seriousness of the upcoming risks and methods of limiting losses, with respect to both their expected outcomes and realistic scenarios for mortality and morbidity risks. This can be done, for example, by cities for their occupants and businesses and insurance companies for their clients. These need to be sensitive to applicable stakeholders—for example, covering practical rather than hypothetical aspects; possible debilitating heat rather than emissions; parched crops rather than scenarios; and infectious microbes in drinking water rather than carbon targets. This also includes dispelling current widespread climate misinformation.
- Analysis of mortality due to alternative levels of air quality and their contributing causes, such as wildfire smoke.
- Analysis of the mortality and longevity effects on insured and pension lives, including by age and gender, rather than having to rely on studies of the total population.

Since the health implications of climate change may be greater than currently imagined, adding a climate change lens to existing lines of research may broaden the benefits achieved.

To reflect the effect of climate change in assumptions about future mortality rates, actuaries need to understand the drivers of and changes in the number and severity of climate-related mortality risks, including both hot- and cold-related deaths that implicitly form the basis of mortality projections for a wide range of applications. It is also important to recognize that temperature-related deaths are just one aspect of mortality likely to be affected by climate change.

11. Conclusions

> Climate change is a public health crisis that threatens the health and well-being of all people and supports policies that reduce U.S. greenhouse gas emissions aimed at carbon neutrality by 2050. (American Medical Association, June 13, 2022[64])

We as a civilization face significant challenges concerning climate change, some of which we have recently seen, both domestically and globally, related to temperature and precipitation, in addition to the adverse sudden and slow-onset effects from other climatic factors and their interactions. These factors, especially for those who are vulnerable to the effects of each hazard described in this paper, can have a significant effect on future mortality and longevity.

To date, most attention by life and health insurers and pension programs has been given to the adverse effects of climate change on the valuation of their assets as a result of carbon emissions and potential damage to property and other resources, as well as the result of decarbonization and mitigation efforts. Actuaries and the entities to which they provide service and advice should give increasing attention to the insurance risks for which they provide coverage.

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[64] https://www.ama-assn.org/press-center/press-releases/ama-adopts-new-policy-declaring-climate-change-public-health-crisis

To do so, actuaries need to understand the associated mortality and longevity risks, together with morbidity risks. This paper describes the current understanding of these key climate and climate change risks. They represent direct and indirect consequences of key climate hazards, including their expected trends and uncertainties.

Increasing and volatile temperatures and the consequential climatic disasters caused by extreme precipitation and other important climatic factors pose an imminent threat to millions of Americans and others around the globe, including workers exposed to the elements, children in schools without air conditioning, seniors in nursing homes without cooling resources and disadvantaged communities. However, in the short and medium term in certain countries, they may be offset by reductions in cold-weather–related risks.

Some regions and urban areas already have a high level of exposure and vulnerability, such as in many developing countries, cities, population segments and infrastructures of developed countries. Exposures and vulnerabilities are bound to increase.

A wide range of health risks are caused by the various hazards associated with climate change, especially, but not exclusively, cardiovascular, respiratory diseases, infectious diseases, cancers and mental illness from excess temperature, poor air quality, vector-borne pathogens and water-related risks (e.g., flooding and waterborne pathogens) as well as food insecurity.

It is important to recognize the role and limitations of the three lines of defense of losses against morbidity and mortality risks: mitigation, adaptation and disaster management. Premature loss of human life and associated costs need to be assessed holistically, with their relative importance dependent upon the geographic location and extent of exposure and vulnerability of the population segment being assessed. Best practice measures may be a function of the population involved, for example, in the case of excess heat, although reliance is often placed on techniques such as air conditioning, public cooling facilities and early warning systems, each of which has its advantages, disadvantages and limitations.

Other significant factors are involved in mortality and longevity processes, including the quality of available health care and emergency response systems, and education or information accessible to the public. Except in the worst-case climate change scenario, behavior, medical and technological advances, political and business decisions, and external factors such as pandemics may prove at least as important in determining the extent of illness, injury and mortality. In any case, climate change can be a mortality risk multiplier.

Data, modeling and measuring issues also need to be addressed. This is a complex issue, with much left to be learned, and requires constant attention as more information and understanding are obtained.

It is time for actuaries to pay attention to these risks.

> The public health benefits from implementing ambitious climate actions far outweigh the costs. … [P]rotecting people's health requires transformational action in every sector, including energy, transport, nature, food systems and finance. (WHO 2021A)

Appendix: Eight Case Studies

The IPPC (2022) included eight case studies of climate-related disasters between 2017 and 2021. These disasters resulted in the loss of lives and livelihoods, with adverse impacts on health, biodiversity, infrastructure and the economy. Their study can enhance our understanding of climate change, exposure, vulnerability and equity. They also offer lessons concerning the need for and role of effective adaptation in managing these risks and the importance of processes that can help reduce losses. They illustrate that climate change can be a source of catastrophic outcomes with considerable damage. Data regarding these risks can be extremely important to enhance preparedness for such disasters. Although not producing nearly as many deaths as in earlier periods, they strongly suggest that climate change is an increasingly important global issue that requires significant resources to reduce the consequential effects of a wide range of risks. Since the publication of IPCC (2022), many further catastrophes have occurred, including a record heatwave in Europe, floods that covered one-third of Pakistan and record-breaking wildfires in California, Canada and Russia.

Case 1. Compounded Events and Impacts on Human Systems: Cyclones Idai and Kenneth in Mozambique, 2019

Although an individual event can lead to a major disaster, when several events occur in close spatial and temporal proximity, impacts are compounded, with even worse outcomes. In March 2019, Cyclone Idai (category 2) was the deadliest cyclone on record to strike Africa. Mozambique was particularly hard hit, with at least 602 deaths, as well as massive housing, water supply, drainage and sanitation destruction. Its impact extended to South Africa through the disruption of the regional electricity grid. In April 2019, amid heightened vulnerabilities, Cyclone Kenneth (category 4) hit Mozambique, affecting about 250,000 people and destroying more than 45,000 homes, resulting in about 45 deaths. A rapid spread of cholera ensued, which triggered a massive vaccination program (about 80% of the public was vaccinated within a week) to control the epidemic. The rainfall associated with such tropical cyclones has been more intense, although the impact of climate change on their frequency and strength remains uncertain.

Takeaways: Several events in close spatial and temporal proximity are likely to lead to more-than-additive damages and can lead to compound catastrophic results. Although often lessons can be learned from the first catastrophe, given the possible proximity of events, resources may not be available to recover from the first or prepare for a succeeding one.

Case 2. COVID-19 as a compounding risk factor: Cyclone Amphan in India and Bangladesh, 2020

Cyclone Amphan hit coastal West Bengal and Bangladesh in May 2020. It was the first supercyclone to form in the Bay of Bengal since 1999 and one of the fiercest to hit West Bengal in the last 100 years. The cyclone intensified from a cyclonic storm (category 1) to a supercyclone (category 5) in less than 36 hours. Several hours before, there was heavy cumulative rainfall, flash flooding and landslides in several adjoining areas. Initial estimates indicated that about 1,600 square kilometers of mangrove forests were damaged, with more than 100 deaths. Damage was somewhat reduced by the mangroves. The estimated damage was US$13.5 billion. Cyclone Amphan was the largest source of human displacement in 2020, with 2.4 million in India, of whom 800,000 were preemptive evacuees. Because it happened during COVID-19, evacuation plans were constrained. Social media played a key role in disseminating pre-cyclone warnings, as well as providing information on post-cyclone relief work.

Takeaways: Multiple drivers can be self-reinforcing, increasing the overall adverse outcomes. More rapidly developing tropical cyclones can create additional risk by not allowing an adequate amount of time for appropriate preparedness. Social media can play a positive role in reducing losses.

Case 3. Further exacerbating inequities in Human Systems: Hurricane Harvey, U.S., 2017

Hurricane Harvey, a category 4 hurricane, made landfall in Texas and Louisiana in August 2017, causing catastrophic flooding and 80 deaths and inflicting US$125 billion in damage, of which US$67 billion was attributable to climate change. Several studies found that climate change increased the likelihood of such an event by a factor of about three. The impact of Hurricane Harvey was exacerbated by extensive residential development in flood-prone locations. A study showed that urbanization increased the probability of such extreme flood events several times through the alteration of ground cover and disruption and redirection of water flow. Water quality in cities also deteriorated, and 85% of flooded land subsided at a rate of 5 millimeters a year subsequently. The impacts of Harvey were unequally distributed along racial and social categories in the greater Houston area. Neighborhoods with larger nonwhite and disabled populations were the worst affected by flooding following the storm and rainfall.

Takeaways: Multiple types of damage can be incurred as a result of such an event, ranging from physical damage to houses to disruptions in mental health. Racial and ethnic inequities can adversely impact post-disaster outcomes. Residential movement from flood-prone areas should be encouraged.

Case 4. Impacts worsened due to sociocultural and political conditions: the "Coastal Niño" in Peru, 2017

The Coastal Niño event of 2017 led to extreme rainfall in Peru, which was made more likely by at least 1.5 times as compared to pre-industrial times due to anthropogenic climate change and Coastal Niño and comparable to the El Niño events of 1982–1983 and 1997–1998. This event showed evidence of larger anomalies in flood exposure and sediment transport. In Peru this El Niño event led to US$6 billion to US$9 billion of monetary losses, more than a million inhabitants were affected, 6,614 km of roads were damaged, 326 bridges were destroyed, 41,632 homes were damaged or became uninhabitable, and 2,150 schools and 726 health posts were damaged, leaving half of the country in a state of emergency. In addition, institutional and sociopolitical conditions at multiple levels significantly worsened disaster risk management, which hampered response and recovery. Citizen responders proved more effective and provided a more rapid response than national public efforts.

Takeaways: It is important to establish a coordinated emergency response, using all available resources to respond to a climate-related emergency. The lack of a comprehensive risk management process to minimize losses and damage can increase damage from a climate catastrophe.

Case 5. Triggering institutional response for future preparedness: Megafires in Chile, 2017

The severity of megafires that occurred in January 2017 was the highest recorded on the planet, burning an area close to 350,000 hectares in south-central Chile over three weeks. These events have been associated with a prolonged ongoing drought that persisted for more than a decade and with an increase in heatwaves. This extreme drought and the total burned area of the last decades have been attributed to climate change for at least 25% and 20% of their severity, respectively. The megafire of summer 2017 resulted in 11 deaths, more than 1,500 houses destroyed, and the destruction of the small town of Santa Olga. The smoke from these fires exposed 9.5 million people to air pollution, causing an estimated 76 premature deaths. The direct costs incurred by the state exceeded US$360 million. The 2017 megafires led to the development of risk management plans that included preventive forestry techniques, regulatory plans regarding rural-urban interface areas, an emergency forest fire plan and the promotion of native tree species.

Takeaways: Ongoing droughts accompanied by a heatwave can result in catastrophic wildfires and consequential air pollution. Unfortunately, it usually takes a catastrophe to lead to better planning and management processes.

Case 6. Loss of human lives and biodiversity: Bushfires in Australia, 2019–2020

In the summer of 2019–2020, bushfires in Australia killed 417 people due to smoke, between 0.5 and 1.5 billion wild animals and tens of thousands of livestock. These fires also destroyed approximately 5,900 buildings and burnt 97,000 square kilometers of vegetation that had provided habitat for 832 species of native vertebrate fauna. Millions of people experienced levels of smoke 20 times greater than the government-identified safe level. The year 2019 was Australia's warmest and driest year on record. In the summer of 2019–1920, the seasonal mean and mean maximum temperatures were the hottest by almost 1 degree Celsius above the previous record. Eight of the 10 hottest days on record for national mean temperature occurred in December 2019. Although prevailing weather conditions were strongly influenced by the Indian Ocean Dipole pressure pattern, with a contribution from weakly positive El Niño–Southern Oscillation conditions in the Pacific, the fact that Australia is approximately 1 degree Celsius warmer than in the early 20th century demonstrates links to climate change, which made the heat conditions of December 2019 more than twice as likely.

Takeaways: Anthropogenic-caused climate change can result in highly unusual hot and dry conditions that result in such health risks as air pollution, drought, and animal and plant destruction and possible extinction.

Case 7. Improved preparedness reduced mortality: Heatwave in Europe, 2019

In 2019 (followed by an even hotter 2022), Europe experienced several record-breaking heatwaves. In June, the first featured record heat for that time of year, with temperatures 6 to 10 degrees Celsius above normal in most of France, Germany, northern Spain, Italy, Switzerland, Austria and the Czech Republic/Czechia. The second heatwave also resulted in all-time records for Belgium, Germany, Luxembourg, the Netherlands and the United Kingdom in July. Attribution studies demonstrated that the likelihood would have been extremely small or would have been 1.5 to 3 degrees Celsius colder without climate change. They concluded that state-of-the-art climate models can underestimate trends in local heat extremes compared to observed trends. Since the 2003 heatwave, which resulted in tens of thousands of deaths across Europe, many European countries implemented heatwave plans, including new early warning systems and enhanced health care disaster recovery infrastructure. Therefore, mortality in 2019 was substantially lower than it would have been without these actions. Since mortality is not registered systematically across Europe, a comprehensive analysis is not available. Nevertheless, for the countries that provided such numbers, that is, France, Belgium and the Netherlands, this heatwave resulted in over 2,500 deaths.

Takeaways: A lack of uniform reported data and model underestimation of deaths can reduce the priority of planning for future catastrophes by rendering it difficult to estimate the impact of climate change. Climate change can contribute to increases in the frequency, intensity and duration of heatwaves anywhere. A comprehensive risk management-based plan can save lives.

Case 8. Loss of human lives and property: Floods in Europe, 2021

From July 12 through 15, 2021, extreme rainfall in Germany, Belgium, Luxembourg and neighboring countries led to severe flooding, caused by extremely heavy rainfall over a period of one to two days, wet conditions prior to the event and local hydrological factors. The rainfall substantially exceeded previous rainfall records. An attribution study focused on the heavy rainfall rather than river discharge and water levels, because adequate hydrological data were not available, in part because hydrological monitoring systems were destroyed by the event. Considering a larger western European region, in any given location one such event could, on average, be expected every 400 years. The floods resulted in at least 222 deaths, with substantial damage to houses, roads, communication infrastructure, motorways, railway lines and bridges.

Takeaways: Appropriate, relevant, comprehensive and accurate data are necessary for effective planning for future disasters. Too many seemingly improbable events continue to happen all over the world.

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