# Climate Change and Mortality

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# Acknowledgements

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The IAA is the worldwide association of professional actuarial associations, with several special interest sections and working groups for individual actuaries. The IAA exists to encourage the development of a global profession, acknowledged as technically competent and professionally reliable, which will ensure that the public interest is served.

The role of the REWG is to identify issues related to resources and the environment of interest to actuaries and to which the actuarial profession, at an individual or national level, can make a useful contribution in the public interest.

The views expressed in this paper are not necessarily the views of the IAA.

**International Actuarial Association**
**Association Actuarielle Internationale**

99 Metcalfe Street, Suite 1203
Ottawa, Ontario
Canada K1P 6L7

www.actuaries.org
Tel: 1-613-236-0886 Fax: 1-613-236-1386

Email: secretariat@actuaries.org

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# Executive Summary

Climate change will have significant and wide-ranging effects around the world. One important impact is on the mortality of the population, which is the focus of this paper. This paper includes a summary of some of the leading research done by major organizations around the world. It describes some of the possible future impacts on the total global population, particularly vulnerable population segments and the portion of the population covered by insurance and retirement programs. Especially at risk of adverse mortality are vulnerable population segments – for example, those areas/regions that are most likely to be affected by extreme variations in temperature and precipitation. However, it is likely that future changes in climate will in some way affect the population of all countries and in all socio-economic categories.

Some of the effects are directly due to climate change, while others are indirect. This is a result of a wide and complex range of interacting causes and effects, which for example include changing patterns of disease from sources such as certain strains of mosquitoes, drought/famine, conflicts, storms and wildfires, and slow-onset conditions (i.e., slowly developing conditions with a cumulative developing effect, such as ocean acidification or rising sea levels) that in turn may lead to migration of vulnerable populations and to high population densities in certain areas.

But not all the effects on mortality of climate change are adverse. Beneficial effects can also occur as a result of direct climate change itself (e.g., changing crop patterns that may reduce food insecurity in some areas) or from mitigation activities (e.g., increased use of air conditioning may reduce deaths resulting from extreme heat conditions).

Since the areas in which actuaries are more active (e.g., private and public-sector insurance, annuity and pension programs) tend to focus on non-vulnerable populations, the direct effect on mortality in these programs may not be as significant as on the entire population or its vulnerable segments. In addition, other factors, including changes in medical treatment, medical infrastructure and lifestyle, may have a greater effect on mortality than climate change, in most population segments where actuaries are currently involved. Nevertheless, a pragmatic current message for actuaries is for them to recognize that climate change represents an additional source of uncertainty in future mortality rates and to consider its implications for the assumptions they make and communication of the associated uncertainty to their clients.

Modelling the possible impacts of climate change and different future climate scenarios on future levels of mortality presents formidable challenges, in part due to the interconnected nature of the systems being modelled and the significant uncertainties involved. Both stochastic modelling and scenario analysis can provide valuable insights into the extent and populations primarily affected. This is clearly an area in which actuaries need to develop new tools, techniques and insights, as extrapolating historical trends will not provide a reliable guide to future developments. Detailed work will be required both in developing such tools for use globally by the profession, and at the local level in applying them to the analysis of the specific set of circumstances of a region or area.

The authors of this paper have not attempted to derive an overall estimate of the number of deaths due to climate change, although on a worldwide basis mortality will likely be adversely affected by it and related factors. This reluctance is due to the uncertain extent of the effects on climate change and the attribution under future conditions, including the extent and success of future mitigation and adaptation efforts. It is something that demands further research and consideration.

# 1. Introduction

Climate change represents a long-term peril to our planet. In large part, this will result from significant increases in greenhouse gases in the Earth's atmosphere and oceans that have been accumulating for the last several decades and are expected to continue. This peril will adversely affect our water, air, weather, and ecosystems, resulting in many changes to our environment, including increases in temperature, changes in precipitation such as heavy rains and longer-lasting droughts, increases in the frequency and intensity of extreme weather events and weather-caused conditions, and rises in sea level. These will in turn affect glacier size and sea level, as well as water and air quality, taking the form of both sudden and slowly developing factors.

The ultimate effects of these climatic changes will affect human health, life and property. However, the extent and timing of such affects are subject to a great deal of uncertainty. The expected and range of effects on human mortality are the focus of this paper. This paper does not address other effects of climate change, such as adverse consequences to human health (except to the extent directly related to mortality), property damage, and death and reduction in diversity of other living species (for example the bleaching of coral resulting from warmer and more acidic oceans).

## Objectives

The objectives of this paper include providing background information and raising the awareness of actuaries and others regarding one of the key effects of climate change. Secondarily, it is hoped to provide such information to national actuarial associations and policy-makers, as applicable. One conclusion is that further research is clearly needed to highlight particular effects and to study ways that they might be mitigated over the short, intermediate and long-term future. Such research will need to be multi-disciplinary in nature, given the complexity of the issues involved.

### *Roadmap to the paper*

This paper first provides a brief overview of this issue in chapter 2, *Background*, covering the range of significant effects of climate change on our environment and human health and life. The remainder of the paper is organized as follows:

- Chapter 3, *Adverse effects on mortality*, covers the major sources of additional premature deaths, including the types of events and conditions precipitating death and attributable diseases likely to be significant in the future.
- Chapter 4, *Favorable effects on mortality*, covers the major sources of reduced number of premature deaths due to climate change and adaptation/mitigation efforts to reduce climate change. To some extent, these offset the effect of adverse climatic trends.
- Chapter 5, *Insured effects*, addresses the effects of climate change and corresponding adaptation/mitigation efforts on the mortality of participants in financial programs advised by actuaries in contrast to the effect of climate change on overall population mortality.
- Chapter 6, *Quantitative analysis*, provides an assessment of the net effect of climate change on mortality, focusing on approaches to modelling and communication.

- Chapter 7, *Case study*, studies an example of the effects of climate change, focusing on the effects of variation in temperature on the population of the United Kingdom.
- Chapter 8, *Next steps*, outlines some of the further analysis and research that would provide further insight into likely future effects of climate change.

# 2. Background

### *Climate change – types of effects*

Robert Glasser, the UN Special Representative for Disaster Risk Reduction, said "It is clear that weather and climate are implicated in 90% of major disaster events attributed to natural hazards. Droughts, floods, storms and heat-waves have the potential to undermine many developing states' efforts to eradicate poverty. Climate change is adding to pre-existing levels of risk fueled by exposure and socio-economic vulnerability."[1] Those who are vulnerable with respect to a particular hazard related to climate change are those most at-risk, who may live in an especially exposed geographic area or those with the lowest income or at extreme ages.

According to the UNISDR (2016), between 1995 and 2015 extreme temperatures directly or indirectly caused 27% of all deaths attributed to weather-related disasters, with the overwhelming majority (148,000 out of 164,000 lives lost or 90%) being the result of too much heat rather than too much cold. In total, 92% of deaths from heat-waves were recorded in high-income countries, with Europe reporting the lion's share at 90%. Note that other studies, such as some of those cited in the United Kingdom case study, consider deaths associated with less extreme temperatures and find more cold-related deaths than heat-related ones. In fact, the case study has been primarily included to illustrate the process that can be followed in conducting such an analysis – for example, Forzieri et al. (2017) indicates that there is a significantly greater number of heat-related deaths in the southern latitudes of Europe than in the United Kingdom.

It is important to note that data reporting and attribution can be quite different by study and country. For example, high-income countries may have better overall mortality reporting, which may distort the true picture, or different definitions of temperature-related deaths may be adopted.

While not all these deaths are attributable to climate change, it is likely that this problem will become more severe in many regions as temperatures and variations in temperatures (and other components of climate) increase further in the future. Climate change has amplified—and will likely continue to amplify—the impact of many extreme weather events, including heat-waves and droughts.

The current scientific consensus is that our climate has changed since the beginning of the industrial revolution, especially recently, and will continue to affect the atmosphere and oceans over the next several centuries. This consensus indicates that this has primarily been due to an increase in greenhouse gas emissions, which in turn has resulted in an increase in the concentration of greenhouse gases in both the atmosphere and the oceans. Future international mitigation and adaptation[2] actions reflecting national commitments that underlay the agreement reached at the 2015 United Nations' Climate Change Conference held in Paris (COP21) may reduce what would otherwise become an even greater accumulation of greenhouse gases.

[1] U.N. News Release 21Apr2016: http://www.un.org/apps/news/story.asp?NewsID=53749#.WMhPS6Lavcc

[2] 100% adaptation means that the assumed optimum temperature for people is whatever temperature climate change brings, while 0% adaptation means that the optimum temperature is whatever it is currently. 50% adaptation is the midpoint.

Modelling the effects of climate change on future levels of mortality presents formidable challenges. This is in part due to the interconnected nature of the systems being modelled. The Intergovernmental Panel on Climate Change (IPCC) framed it in its 5th Assessment Report (2014) as a combination of: the physical environment, ecology ("natural processes"), and institutions incorporating effects of human physiology and behavior. These three factors combine to impact on the relationship between climate and health. They also interact with each other. Thus, a change in temperatures (physical) may support the conditions that give rise to an increase in the population of disease vectors (natural processes) in a country that may or may not have the institutional capacity to deal with such a change (institutions).

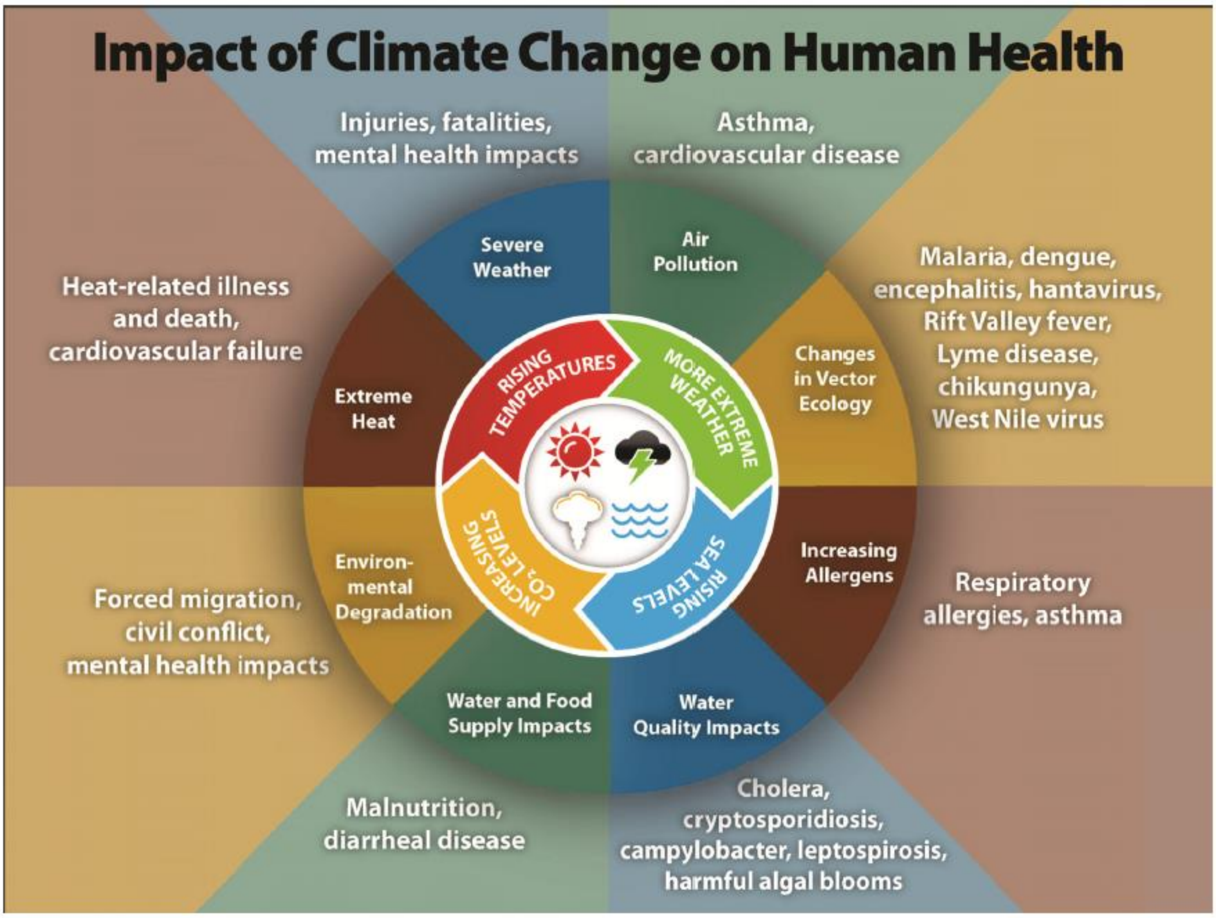
A specific example is that higher temperatures lead to the spread of the ranges of deer, mice, and ticks— "the ecologic causal chain that brings Lyme disease to humans" (Balbus (2014)). As a result of significant efforts, death from malaria has, according to the World Health Organization (WHO), experienced a 60% reduction in new cases over the last 15 years. Nevertheless, this progress may be at risk in several regions as temperatures increase and rainfall patterns shift over the long-term future. This combination will likely increase the number and range of mosquitoes that can spread this disease, although it may in part be offset by improved education and access to healthcare.

Equally, severe storms, such as Hurricane Katrina (U.S.), can overload the functionality of even the best health-care systems, which in turn can have negative consequences for the elderly and those who have chronic medical conditions. According to Molly Brown of the U.S. National Aeronautics and Space Administration (National Research Council (2014)), an analysis conducted in the wake of Superstorm Sandy in 2012 showed that what most affected human welfare and public health were factors that officials were not aware of before and had never modeled, such as electricity generators that were below sea level and unexpected cascading power outages. Hurricane Katrina might be described as a "complex emergency", as 800,000 people were displaced and health facilities were taken out of operation, with impacts felt in a wide number of cities not restricted to New Orleans.

The effects of climate can be mediated by other physical, environmental and socio-economic factors. Any approach to modelling will therefore benefit from being multi-disciplinary, involving complex systems thinking. There are many scientific disciplines and tools in addition to climate science necessary to understand the interactions among the three factors and to model the associated health outcomes, including hydrology, geography, ecology, agriculture, sociology, economics, biomedical science, and clinical medicine.

A summary of some of the major adverse effects of climate change on human health is shown in Figure 1.

**Figure 1.** Adverse impact of climate change on human health




*Source: George Luber, US Center for Disease Control and Prevention*

Science tells us that fossil fuel use is driving climate change, and hence the mortality effects discussed in this report and pictured above. However, past impacts should perhaps also be acknowledged, in so far as the use of coal, oil and gas powered global economic development over the last century, and has wrought profound changes in many socio-economic measures including life expectancy. This is highly germane when considering the developing countries that have yet to benefit in full or in part from these improvements. It will be important, therefore, to continue to pursue economic growth, leap-frogging to newer, more environmentally-friendly technologies, as the case study on solar home systems in Bangladesh illustrates (see Chapter 4).

### *Positive and negative impacts*

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 efforts may not only reduce the adverse mortality effects due to climate change, but may also reduce non-climate-change mortality. The 5$^{th}$ IPCC Assessment Report concludes, however, that the overall impacts on health of more frequent heat extremes greatly outweigh the benefits of fewer cold days, and that the few studies of the large developing country populations in the tropics, point to effects of heat, but not cold, on mortality (Smith et al., 2014). These are discussed further in chapter 4.

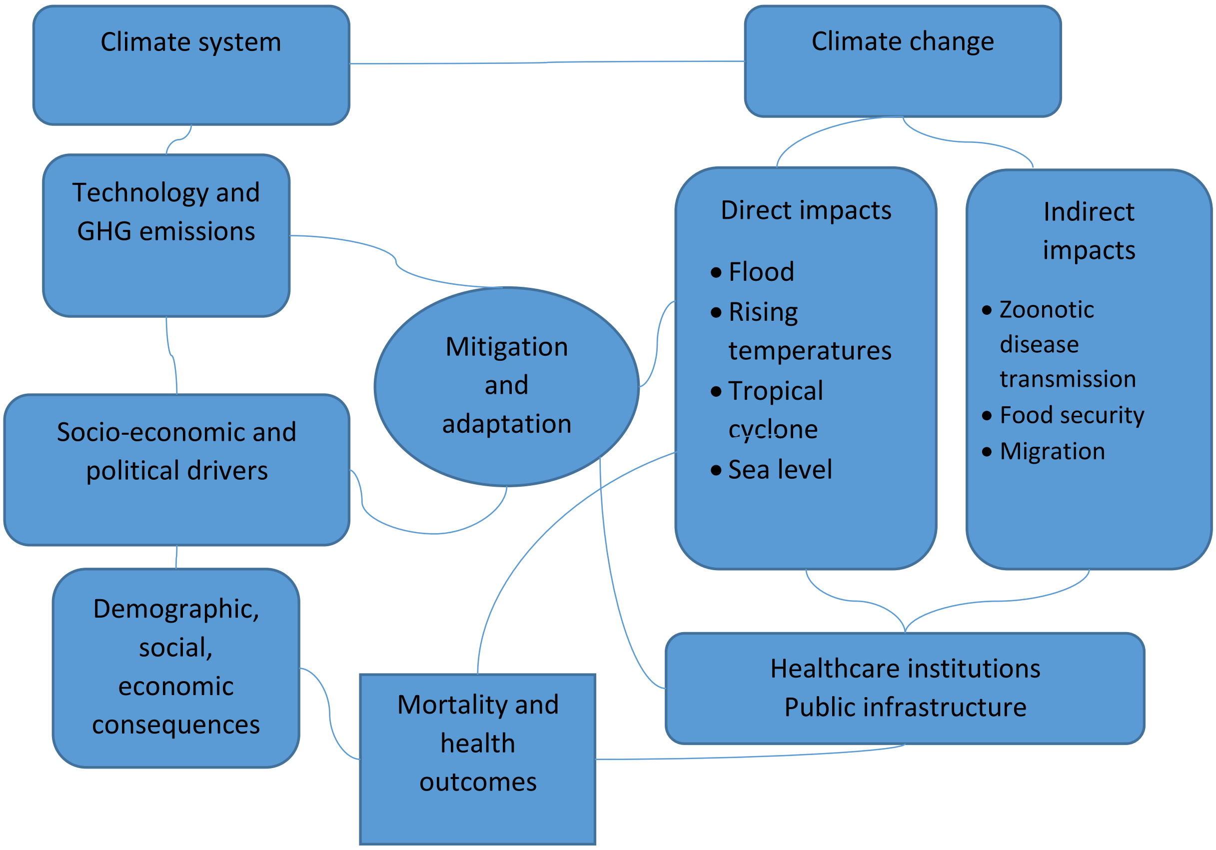
## *Systems thinking*

The development and application of complex interdependent sets of models require systems thinking. This is clearly true of the models of slow-onset drivers of mortality such as long-term temperature changes or changes in rainfall patterns. But systems thinking is also relevant in the context of extreme weather-related events. According to Georges Benjamin, of the American Public Health Association, “many health systems are designed for just-in-time management for the mean; we cannot afford to build for extremes.” This implies that increased number and severity of weather shocks has the potential to critically overload, albeit temporarily, local or even national health systems. Such shocks will have immediate and medium-term consequential impacts that need to be considered.

The Committee on Climate Change (2016) discusses the unintended consequences that can arise when single issues are addressed in isolation, rather than looking at the entire system. For example, improvements in building insulation (which reduce cold-related deaths) may reduce indoor air quality and increase the risk of over-heating in summer (therefore increasing other types of death that are not as easy to attribute to climate change).

The overall adverse effects of climate change on mortality in most regions of the world should be considered in the context of what have been quite favorable overall mortality trajectories since the time of the industrial revolution. Unfortunately, this revolution has at the same time had undesirable side effects, such as those that have brought about climate change. Those countries that are currently developing economically, have the opportunity through effective use of green-technology to avoid some of these adverse consequences.

**Figure 2.** A simplified system representation




As indicated in Figure 2, changes in the number and types of deaths around the globe, together with other consequences such as health and property damage, are among the adverse consequences of this process. Greenhouse gas (GHG) emissions contribute to the amount of greenhouse gasses in the atmosphere, which can take a very long time to dissipate naturally. These, in addition to other drivers such as adverse land-use and deforestation, contribute to climate change. This in turn directly and indirectly results in ill health, deaths and property damage. For example, and as discussed further below, more extreme heat-waves and rainfall can directly lead to each of these three types of damages, as well as indirectly through a greater increase in the mosquito population than would otherwise be the case.

### *Climate components*

Four major components of the effects of climate change and related environmental impacts that will likely influence the level of future deaths are discussed below.

- **Temperature** - Possibly the most advertised effect of climate change is the effect on average and extreme global temperatures (usually measured from the average temperature level experienced immediately prior to the inception of the industrial revolution), influencing many facets of water, air and land temperatures. An increase in extreme heat and a decrease in extremely cold weather may also become increasingly common (although see "extreme events" below for one-off local swings in temperature in either direction). It appears that in recent decades heat-waves have become more common. Warmer temperatures can also increase water evaporation.

There has been a great deal of discussion regarding whether heat or cold is a greater cause of mortality. Gasparrini et al. (2015) noted that “more temperature-attributable deaths were caused by cold (7.29%, CI 7.02–7.49) than by heat (0.42%, CI 0.39–0.44). Extreme cold and hot temperatures were responsible for 0.86% (CI 0.84–0.87) of total mortality”. This study was limited to a selected number of countries and did not discuss the effect of future changes. It would therefore be incorrect to draw a sweeping conclusion that global warming will be beneficial to mortality by reducing numbers of deaths from extreme or sub-optimal cold temperatures. In fact, the 5$^{th}$ IPCC Assessment Report concluded that, depending on the country or region, the effects on health of more frequent heat extremes can significantly outweigh the benefits of fewer cold days. In any event, this ignores indirect effects such as drought, food scarcity, disease and sea level rises.

Nevertheless, the magnitude of the differences between cold- and heat-related deaths found by Gasparrini et al. is too great to ignore. Careful assessment of both the upside and downside effects of climate change is needed in any such study. We should apply models to reflect a reasonable baseline and ensure that variations consider an appropriate range of underlying conditions and both direct and indirect effects, based on reasonable assumptions and scenarios over that range.

In a review of 783 cases of excess mortality observed from the experience of 164 cities in 36 countries as documented in papers published between 1980 and 2014, Mora et al. (2017) identified a global threshold beyond which daily mean surface temperature and relative humidity becomes lethal. About 30% of the world’s population is currently exposed to conditions in excess of this threshold. They projected that by 2100 this percentage would increase to about 48% in a world with drastic reductions in greenhouse gas emissions and about 74% where there was a growing level of emissions. This suggests that a warmer earth may lead to a far greater level of mortality risk due to heat stressed conditions than in the recent past. In addition, it suggests that the amount of these deaths in the future is quite sensitive to changes in future greenhouse gas emissions.

Shi et al. (2015) demonstrated that long-term survival was significantly associated with both seasonal mean values and standard deviations of temperature among the Medicare population (aged 65+) in New England (United States) during 2000-2008. An increase in summer mean temperatures of 1°C was associated with a 1.0% higher mortality rate, while an increase in winter mean temperatures corresponded to a 0.6% decrease in mortality. In addition, the findings suggest that increases in standard deviations of temperature during each of summer and winter were harmful. Increased mortality rates in warmer summers were entirely due to temperature anomalies, while it was long-term average differences in summer standard deviations across ZIP codes that drove the increased mortality risk. Shi et al. expect that the health effects of seasonal mean temperature and temperature variability can vary greatly among different climate zones. They indicate that “the negative health impacts of climate change may stem from the increase in year-to-year fluctuations of temperature from a level that people have been acclimatized to for a long time, or an increase in daily variability within season, rather than the warmer temperature itself.”

In the past three years in Europe where excess winter (December to March) mortality peaked, the populations in southern countries have been more affected than those in the northern ones. A study described by Kovats et al. (2011), using a medium-to-high emission (A1B) scenario with no further climate change or mitigation or adaptation efforts, resulted in estimates of an additional 26,000 deaths per year from heat by the 2020s (2011-2040), rising to 89,000 per year by the 2050s (2041-2070) and 127,000 per year by the 2080s (2071-2100). While heat-related mortality in Europe is projected to increase in all regions, there are relatively higher levels of climate change-attributable heat deaths in Southern Europe. This may imply that the more prepared a country's population is for cold temperature, the less severe is the effect of extremely cold temperatures.

As average mean temperature in India has increased, Mazdiyasni et al. (2017) indicated, based on a study of data from the India Meteorological Department between 1960 and 2009, that there has been a substantial increase in mass heat-related deaths (mortality events of more than 100 people). Their "results suggest that even moderate increases in mean temperature may cause great increase in heat-related mortality." With an increase in summer mean temperature of 0.5% (to 27.5$^{o}$C), the probability of these mortality events increases by a factor of 2.5 to 32%.

Although mortality risk associated with temperature spikes have sometimes been thought to strike mostly those at older ages, other population segments can also be affected. For example, Carleton (2017) reported that climate, especially temperature increases, has contributed to a significant number of suicides during the growing season in India, extending to some 60,000 farmers and farm workers over the last three decades. Carleton indicated that the number of suicides was sensitive to the size of temperature spikes – an estimated increase of 1$^{o}$C on an average day was associated with 67 additional suicides and an increase of 5$^{o}$C with an additional 335 deaths per day. (Temperature increases outside the growing season did not show this correlation. Additional rainfall of 1cm in a year was linked to a 7% drop in the suicide rate, with strong rainfall reducing suicide rates for the two following years.)

- **Precipitation** - Changes in precipitation can lead to both more intense individual downpours and swings into drought conditions. Droughts in already arid regions will continue and may spread and increase in severity. Water scarcity in vulnerable populations will adversely affect human health and mortality. In other areas, excessive precipitation can result in flooding and soil erosion. These very different climate patterns will vary by geographic area, humidity, barometric pressure and ultra-violet radiation, all of which may reach extreme and damaging conditions, especially when related. For example, drought conditions have caused significant public health catastrophes, resulting in mass migration, malnutrition, poor living conditions and increased deaths in areas such as eastern Africa. The threat from multi-year drought conditions is not restricted to what people drink but what they eat, as the human activity that consumes the most water is agriculture.

- **Extreme events** - Increases in both the frequency and severity (including their financial effects, which will increase in the future as population both increases and becomes further urbanized) of extreme natural events are expected. These include tropical cyclones (although the frequency of those making landfall in North America may not increase), tornadoes, floods, windstorms, drought (that can result in famines) and heat-waves. They not only affect mortality, but also can cause infrastructure and property damage, along with injuries and sickness. Roughly 315 weather-related extreme events were recorded each year between 1995 and 2014, according to UNISDR (2016), with key statistics given in Table 1 (in 2015, there were nearly 350 reported natural disasters, with more than 22,000 deaths among the 98.6 million people affected, with US$66.5 billion of damages). The five countries hit the hardest during this period were the United States, China, India, Philippines and Indonesia, with most deaths occurring in Asia.

**Table 1. Number of natural disasters and resulting deaths by type of disaster and country's income level**

| Types of natural disasters | Resulting deaths | | Number of natural disasters |
|---|---|---|---|
| | Percent of total | Number | Percent of total |
| **Storms** | 40% | 242,000 | 28% |
| **Extreme temperatures** | 27% | 164,000 | 6% |
| **Floods** | 26% | 157,000 | 43% |
| **Droughts** | 4% | 22,000 | 5% |
| **Landslides and wildfires** | 3% | 20,000 | 9% |
| **Earthquakes and volcanic activity** | -- | -- | 9% |
| **Income of country** | | | |
| **Higher income** | 4% | 22,000 | 41% |
| **Upper-middle income** | 5% | 30,000 | 26% |
| **Lower-middle income** | 88% | 533,000 | 26% |
| **Lower income** | 3% | 20,000 | 7% |

*Source: UNISDR (2016)*

As seen in Table 1, between 1995 and 2015, flooding contributed about 43% of the number of recorded disasters and about 26% (157,000) of these deaths, while storms constituted about 28% by number and killed about 40% (242,000). Deaths were far more concentrated in the lower-middle income countries than were the number of disasters. Of those who died from extreme temperatures, 148,000 deaths were the result of heat while 16,000 were the result of cold. Although most of these extreme events were not directly due to climate change, the severity if not the frequency of these events may result in larger numbers of deaths due to population and property concentration risk. (Problems of attributing extreme events to climate change are discussed below under Attribution.)

- **Sea level** - A rise in sea levels can affect water quality, as well as causing increases in coastal flooding and insect-related diseases. It could also impact food security and may have direct and indirect consequences for mass migration and the number of deaths.

The four major components of the effects of climate change and related environmental impacts discussed above include both long-term gradual changes and an increase in the severity of extreme events over both the short- and long-term. In addition, a wide range of secondary effects are possible, including deteriorating air quality (including excessive amounts of ozone and particulate matter) and food and water insecurity including malnutrition. Secondary effects may also include mass migration / human conflict, and changes in insect population and other disease vectors. In turn, economic damages and decreases in quality of life, including excess stress, may also result in deterioration in human longevity. It is also possible that some of the effects of climate change are positive, which is discussed further in Chapter 4.

### *Attribution*

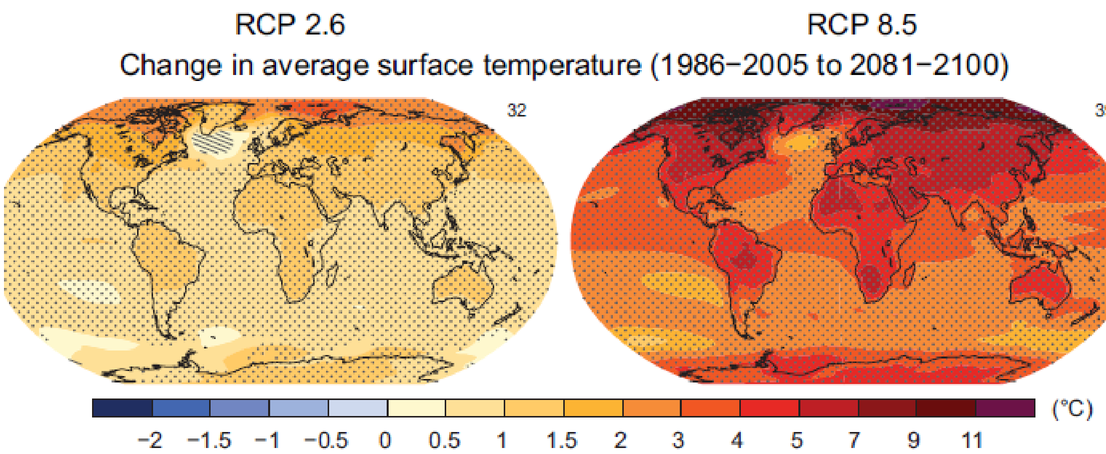
Of course, natural disasters and relating deaths can be the outcome of one of many causes. For this paper, it is relevant to identify which ones (in whole or in part) are attributable to climate change. This is an important, but potentially challenging, element of determining the effects of climate change. At a seminar given at the Institute and Faculty of Actuaries on 13 April 2016, Professor Myles Allen from Oxford University described the relatively new science of climate attribution. This aims to quantify the probability or extent that a weather event was caused or worsened by emissions.

A hypothetical example of such a quantification would be, “it is likely with 90% confidence that past human influence on climate was responsible for at least half the risk of last summer’s heat-wave”. The models and the mathematics used to justify such statements are complex, although this new area is developing rapidly. It primarily involves a study of actual outcomes with the corresponding situation if there had been no change in climate. If attribution becomes more widely embedded within the scientific community, there may then be implications for potential future litigation in loss and damage.

### *Regional Effects*

Much of climate change’s characterizations and consequences have been expressed in terms of global averages (e.g., average global temperature increases). Even more dramatic changes will likely arise on a regional, if not local basis. It is also possible that there will be significant (regional or local) volatility of temperature over time, which may be particularly relevant from a mortality perspective.

**Figure 3**. IPCC projections under two future scenarios




*Source: 5th IPCC Assessment Report (Working Group 1, Summary for Policymakers)*

Figure 3 shows the projected change in average surface temperatures over the next 85 years under two scenarios developed by the IPCC. Broadly speaking, the IPCC’s

Representative Concentration Pathway[3] (RCP) 2.6 is a greenhouse-gas emission scenario in which very substantial mitigation efforts are rapidly implemented. RCP 8.5 by contrast is a projection that assumes little change in emission levels. In either case, the point is that there will be substantial regional variation. Some regions will experience wider and more volatile temperature and precipitation swings and significant adverse natural events. Of course, everyone is exposed to weather variations; nevertheless, the extent, suddenness and duration can differ tremendously, with only the most severe posing a truly adverse weather hazard.

It has been often noted that these changes will arise to a different extent or even in opposite directions (i.e., the effects on some will be favorable while on others, adverse) by region, with impacts differing between demographic segment (e.g., as a result of age, level of mobility and location). Thus, for example, in the United States, the Northeast and Midwest regions are expected to experience significant increases in precipitation, while the Southwest region is expected to receive less precipitation and increased drought—the most extreme conditions of which can result in serious consequences.

### *Age-related effects*

It is expected that climate change will affect age segments to a different extent. For example, the oldest and youngest members of a population may be most at risk to many mortality hazards. The oldest will likely be most affected in the case of weather extremes (particularly heat). Many of the youngest are expected to experience stunting arising from malnutrition due to such climate-related conditions as droughts, which can in turn expose those affected to other diseases. For example, children and infants would be expected to suffer higher rates of mortality from diarrheal disease.

### *Relative wealth*

Many climate-change effects are likely to especially affect the health of more vulnerable populations, e.g., those with lower incomes and in areas with scarce resources, limited technology and weaker health and other infrastructures. Many of those in Africa and South Asia are especially vulnerable.

### *Estimating the effects*

As mentioned, not all increased deaths due to environmental causes, such as floods, can be attributed to greenhouse-gas-induced climate change. There have always been climate- or weather-related deaths, and there will continue to be, whether climate is changed or not. Thus, it is important to assess the marginal effect of climate change from these intermediate and other causes to better prioritize mitigation and adaptation efforts.

As set out above, developing reasonable projections involves many issues, some highly complex, which would benefit from the involvement of many different scientific disciplines. It involves multiple feedback loops from such factors as land-use, increased urbanization and

[3] These RCPs are labeled according to a range of possible radiative forcing values in the year 2100, energy taken up by the Earth relative to pre-industrial values (e.g., low +2.6 $W/m^2$ and high +8.5 $W/m^2$). RCP 2.6 assumes greenhouse gas emissions peak between 2010 and 2020, while in RCP 8.5 greenhouse gas emissions continue to increase.

energy planning, infrastructure design and implementation, adaptation and mitigation approaches, economic effects and technology.

The most sophisticated attempts to examine impacts of climate change on mortality have not modeled all the above. Rather, they have concentrated on a limited set of specific health models that focus on specific drivers of climate-related changes and health outcomes known to be sensitive to climate change.

For example, WHO (2014) examined the following climate-related factors:

- Heat-related mortality in elderly people;
- Mortality associated with coastal flooding;
- Mortality associated with diarrheal disease in children aged under 15 years;
- Malaria population at risk and mortality;
- Dengue population at risk and mortality; and
- Malnutrition (stunting) and resultant mortality.

The WHO indicated that climate change is expected to cause approximately 250,000 additional deaths per year between 2030 and 2050. This burden of disease resulting from climate change will continue to fall mainly on children in developing countries, but other population groups may also be affected. A main limitation to its projections is the inability of current models to account for major pathways of potential health impact, such as the effects of:

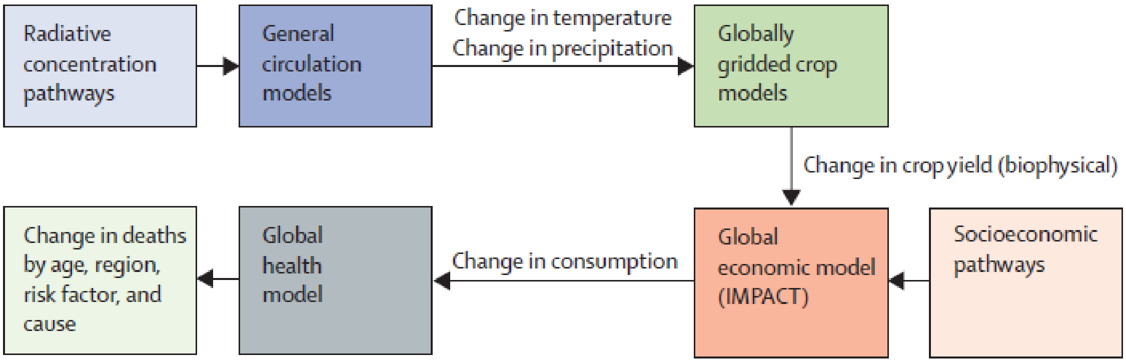
- Major heat-wave events;
- River flooding;
- Other extreme weather events;
- Water scarcity;
- Resulting increases in migration or conflict; and
- Consequential economic damage.

Indeed, we are not aware of major studies examining the mortality impacts of potential discontinuities in climatic, social or ecological conditions. Nor are there extensive studies of what are referred to as slow-onset conditions, such as rising sea levels or ocean acidification.

Instead, WHO’s mortality forecasts are based on empirical models of specific key mortality causes, examining observed mortality patterns and trends in relation to major drivers such as socioeconomic development, education and technology, together with projections of the future trajectories of these drivers on a national scale. An example of a general modelling approach that can be applied at different scales is shown in Figure 4.

Regression equations can be used to quantify the current and historical relationships between mortality and a set of independent variables such as gross domestic product (GDP) per capita, years of education and time (assumed to be a proxy for health benefits arising from technological developments). For example, malaria is modeled as a function which incorporates temperature, precipitation and GDP per capita.

**Figure 4.** A general model examining impacts of climate change on diet-related mortality




*Source: Springmann et al. (2016)*

The projections therefore attempt to look at relative or comparative levels of mortality in the future based on comparing “with and without climate change” scenarios. Thus, by looking at alternative future greenhouse-gas emissions pathways or radiative concentration pathways and by using different climate models, a range of “before and after” climate scenarios can be generated. These are combined with global population projections and alternative future economic-growth scenarios. In addition, assumptions are required for future levels of adaptation responses.

In addition, especially in analyzing certain of those in vulnerable populations, such as the frail elderly, some of the deaths associated with climate change may simply be deaths that have moved forward or been “displaced” by a matter of a few days or months. Thus, it can only be claimed that these are premature deaths, which may not necessarily significantly affect overall mortality rates. Vardoulakis et al (2014) indicated: "some of the estimated temperature-related mortality may arise as a result of short-term mortality displacement (harvesting), whereby the deaths of already frail individuals are brought forward by only a few days or weeks because of exposure to hot or cold weather (Hajat et al. 2005). Previous work has indicated that some heat-related deaths may be explained by short-term mortality displacement, but this is less clear in the case of cold-related deaths (Braga et al. 2002)." Existing models and considerations for their development and use are discussed further in chapter 6.

# 3. Adverse Mortality Consequences

*Background*

WHO (2016) estimated that some 12.6 million deaths globally are attributable to the environment (overall – not restricted to that due to climate change), which is about 23% of all deaths and 22% of the disease burdens expressed in terms of Disability-Adjusted Life Years (DALYs, a common measure used to assess the effect of a factor affecting healthy life expectancy). However, although it is expected that climate change will have a significant effect on society in the decades ahead, there is a great deal of uncertainty regarding the nature of these impacts, as only a fraction of these deaths can be attributed to climate change. This chapter covers areas for which additional deaths may arise, while Chapter 4 covers areas for which there may be a reduction in deaths.

A significant number of deaths will result from climate change, which will have a greater relative effect on vulnerable segments of the population, varying in significance in different countries. Vulnerable populations are from both less and more developed countries who cannot afford to take advantage of adaptation and mitigation tools. The very young and very old may be particularly at greater risk, as they are more sensitive to some of these effects.

*Increase in certain diseases*

The incidence of certain diseases will be affected and will likely increase as a result of the overall warming of our planet.

For instance,

- Diarrheal disease - Compared with a future without climate change, WHO (2014) estimated that about 48,000 deaths annually[4] (especially affecting children younger than age 15) is expected to be attributable to climate change by the year 2030 (about 33,000 in 2050, which would be further reduced without climate change). About 60% of these deaths are expected to be in sub-Saharan Africa and 25% in South Asia. Although the WHO projects a dramatic decline in childhood mortality over the period, economic development and improved sanitation will more likely drive this decline. This progress may be undermined if environmental changes damage urban infrastructure or reduce overall availability of water. Diarrheal disease is also affected by both temperature and rainfall, although the WHO study was restricted to temperature effects. In terms of the absolute numbers in the WHO projections, the difference in the “before” and “after” scenarios is also sensitive to the population projection model itself, as the absolute level of the human population is expected to continue to expand, although fertility rates have fallen in many countries.
- Malaria and dengue - The transmission and spread of these diseases, due to mosquitoes, are sensitive to higher temperatures. The warmer the weather, the more frequently mosquitoes bite humans and animals and the longer the summer season, the farther the spread of mosquito-related diseases. Although focused in

[4] This estimate is the average of the results of five different global climate models, all on a “base case” economic scenario and a “medium-high” emissions scenario (referred to as A1b). The highest and lowest projections from the five models were 68,000 and 21,000 respectively.

Africa, these diseases are not limited to that continent. According to WHO (2003), the number at risk of contracting malaria may increase by some 5% (150 million people) if temperatures rise 2ºC to 3ºC higher than pre-industrial levels. There have been significant reductions of deaths from these conditions over the last several decades. However, the WHO (2014) estimates that, compared with a future without climate change, by 2030 there will be an additional 60,000 deaths per year due to malaria alone, more than 95% of which are expected to be in sub-Saharan Africa.

- Gastrointestinal-tract illnesses and infections due to increases in water temperature - Climate change may be associated with staple food shortages, malnutrition, contamination of seafood from chemical contaminants, biotoxins, pathogenic microbes and crops adversely affected by pesticides.
- Asthma, respiratory and lung diseases, such as reduced lung function, coughing and wheezing - Respiratory allergies and diseases may become more prevalent because of increased human exposure to pollen (due to altered growing seasons), molds (from extreme or more frequent precipitation), air pollution and aerosolized marine toxins (due to increased temperature, coastal runoff, and humidity) and dust (from droughts and erosion). Cardiovascular and respiratory diseases due to increased ozone and other air pollutants. Climate change can exacerbate existing cardiovascular disease by increasing heat stress, increasing the effect of airborne particulates, and changing the distribution of zoonotic (animal to human transmission) vectors that cause infectious diseases linked with cardiovascular diseases.

  In a meta-analysis, Bunker et al. (2016) identified substantially elevated risks for the elderly for temperature-induced cerebrovascular, cardiovascular, and respiratory outcomes. Bunker et al. found that the effect on mortality was similar or slightly larger for cardiovascular causes than for respiratory causes for high temperatures, although for morbidity they estimated that the effect for respiratory causes was much greater than for cardiovascular causes with both high and low temperatures. They indicated that the underlying mechanisms through which high temperatures increase the risk of morbidity from respiratory causes are as yet unclear. In addition, Bunker et al. found an increased risk for heat-induced diabetes, renal, and infectious disease morbidity, all of which are likely to increase further with climate change and global aging.
- Cancer - There are many potential direct effects of exposure to cancer, such as increased duration of exposure and intensity of ultraviolet (UV) radiation.
- Heat-related conditions affecting the elderly - According to the UNISDR, during the period 2005 to 2014, an average of 25 major heat-waves were recorded each year, resulting in an annual average death toll of 7,232. In 2015, the hottest year on record (until 2016), there were 3,275 reported deaths from heat-waves in France, 2,248 in India, and 1,229 in Pakistan.

The aging of the population of many countries will tend to increase the adverse effect of climate change. This increase in the number of those who are elderly is expected to increase future temperature-related mortality and morbidity. This and the increased sensitivity of this population segment to other effects of climate change will contribute to an increase in the numbers vulnerable to climate change.

WHO (2014) estimated that there will be about 38,000 heat-related deaths of those aged 65 and older in 2030 associated with climate change, with a range of 27,000 to 48,000. This was based on their A1b emissions and base-case socioeconomic scenario, assuming a 50% adaptation to optimum temperature. 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. By 2050, WHO estimated an annual total of 95,000 heat-related deaths.

These estimates can be compared with those presented by Hajat et al. (2014) for the UK in which an estimated 2,000 heat-related deaths per year in the UK alone occurred in the period 2000 to 2009 (see the United Kingdom Case Study for further discussion). The discrepancy may be due to different definitions of heat deaths. Hajat et al. used a regression model to isolate the temperature-mortality effect -- excess deaths above 93rd percentile temperatures were deemed to be heat-related. In contrast, the WHO model was derived from studies that analyzed the effects of temperature on all-cause mortality, including external causes, which therefore includes deaths of those over age 65 from both heatstroke and heat-related accidents and injuries. This difference illustrates some of the difficulties in comparing the results of these studies, as there is no universally accepted definition of a heat death, or climate-related death. A further difficulty arises in comparing numbers of additional deaths, because they are highly sensitive to the applicable overall population.

According to Hajat et al. (2014) based on projected population structures using as a base period 2000-2009 assuming no further adaptation activities, heat-related deaths in the UK will increase by about 50% in the 2020s, 170% in the 2050s and 330% in the 2080s, without reflection of changes in population size. The increases may be considerably larger because of increases in the overall size of the population.

It is important to note that there is a very large amount of variability between countries not explained by obvious differences in climate – as shown in Gasparrini et al. (2015) and Ballester et al. (2016). Thus, there is a need to look at country-specific results. Although the results reported in the UK may be a bit anomalous, a case study for temperature-related deaths in the UK is included in this paper, from which useful approaches and considerations for future studies can be found.

### *Drought and resulting famine*[5]

Many areas of the world will experience extreme droughts. This lack of water may seriously affect agriculture and the production of food. Famine can result from several causes, including over-population, bad government policies and conflicts, as well as climate change – the likelihood of a famine increases when more than one of these factors are present. Drought and severe lack of rainfall can have severe ramifications for health. Two examples are:

[5] A famine is declared when at least 20% of households face a complete lack of food, levels of acute malnutrition exceed 30% and more than two people per 10,000 die each day.

- Food security - Severe decreases in water availability can contribute to severe loss of food and liquid input. The direct result is significant increases in malnutrition and undernutrition, which in children can lead to stunting. Both immediate deaths and a long-term increase in mortality can result. See below for an aggregate estimate developed by WHO of the effect of malnutrition. The agricultural sector is crucial to food security and nutrition, not only because they supply food to eat, but also because of their crucial role in the livelihood and income of a considerable number of those who are vulnerable; when they experience food insecurity, their health and in turn their longevity can suffer.

  The primary reason for the food catastrophe in Somalia is rising temperatures in the Horn of Africa and unpredictable weather patterns – 3.2 million people are facing potential famine according to the World Food Program (WFP) country director in Somalia, Laurent Bukera[6].

  The number of people who have died of starvation has decreased over the last several decades. Nevertheless, if appropriate agricultural practices and government actions are not taken in a timely manner, and health care infrastructure is not established or maintained, famine can still arise.

- Conflicts and violence - Drought, especially when the result of extreme increases in temperature, has been known to result in conflicts and violence, especially due to conflict over depleted natural resources. The World Bank (2016) expressed the view that the likelihood of future conflicts may increase significantly near a 4$^{o}$C global temperature increase compared to pre-industrial climate. Some of these effects have already occurred, although it is especially difficult to attribute a conflict to a single cause. Smithsonian (2013) stated: "'In Syria, a devastating drought beginning in 2006 forced many farmers to abandon their fields and migrate to urban centers. There's some evidence that the migration fueled the civil war there' says Aaron Wolf, a water management expert at Oregon State University."

  The *Economist* (2012), discussing the Arab Spring, noted that "… Middle East and North Africa depend more on imported food than anywhere else. Most Arab countries buy half of what they eat from abroad and between 2007 and 2010, cereal imports to the region rose 13%, to 66m tons. Because they import so much, Arab countries suck in food inflation when global prices rise. In 2007-08, prices spiked, with some staple crops doubling in price. In Egypt, local food prices rose 37% in 2008-10."

  Schleussner et al. (2016), using event coincidence analysis for the period 1980-2010, found a coincidence rate of 9% regarding armed-conflict outbreaks and disaster occurrences such as heat-waves or droughts. They found that during this period about 23% of conflict outbreaks in ethnically highly fractionalized countries coincide with climatic calamities. Although they did not find direct evidence that climate-related disasters acted as direct triggers of armed conflicts, the disruptive nature of these events seems to play out in ethnically fractionalized societies in particularly tragic ways. Social capital, such as institutions and relationships of trust on which human well-being depends can, for example, be destroyed. Thus, the risk of armed-conflict may be enhanced by climate-related disaster occurrences in ethnically fractionalized countries

[6] Interview on 20 June 2017, https://www.voanews.com/a/famine-in-somalia-averted-for-now/3908196.html

and implies that disasters might act as a threat multiplier in several of the world's most conflict-prone regions.

Projecting deaths from possible future conflicts sparked at least in part by mass migration or other pressures resulting from changes in climate has not, to the best of our knowledge, been attempted. Even if that modelling were carried out, there would remain questions of attribution. How many of the deaths caused by warfare in the Syria conflict could reasonably be said to have been due to the four-year drought that may have in part created the conditions in which warfare became inevitable? And, a further layer of questions would be, "how much of that drought was attributable to (anthropogenic) climate change?" The same questions of attribution can then be asked of those who died fleeing the conflict or because of excessive strain on medical facilities as a consequence of large influxes of people. The difficulty of such questions notwithstanding, it does appear likely that increased pressure, whether caused by drought or sea level rises, will give rise to increased mortality through conflict or migration.

WHO (2014) indicated that one of the most substantial health effects of climate change was projected to be undernutrition and malnutrition. They estimated the number of deaths due to the malnutrition of children under the age of five. Using a model of national food availability developed by the International Food Policy Research Institute, WHO estimated the extent of child stunting due to food and non-food causes using published data concerning the association between stunting and mortality – about a rate of 95,000 deaths per year in 2030 using the same scenario assumptions used to study the effect of heat-related conditions, with a range of about –120,000 to 310,000. In 2050, the corresponding estimate is about 85,000 deaths per year.

Springmann et al. (2016) projected that by 2050 climate change will be associated with 529,000 annual climate-related deaths worldwide (95% CI 314,000–736,000), representing a 28% (95% CI 26–33) reduction in the number of deaths that would be avoided because of changes in dietary and weight-related risk factors (including changes in fruit and vegetable consumption, red meat consumption, and the prevalence of underweight, overweight, and obesity) between 2010 and 2050.

Most of these additional deaths are expected in Asia. Expected changes in temperature and precipitation due to climate change 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 and the profile of dietary and weight-related risk factors and associated mortality. Even a modest reduction in per-person food availability could lead to changes in energy content and composition of diets associated with negative health implications. Although food availability and consumption is projected to be higher in 2050 than in 2010, by 2050 climate change could lead to reductions of 3.2% 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.

Nevertheless, in examining the impact of climate on calories consumed or available, Springmann et al. (2016) indicated that the composition of future diet may have a greater impact than all the climate factors considered by the WHO combined. Twice as many climate-related deaths were associated with reductions in fruit and vegetable consumption than with climate-related increases in the prevalence of malnutrition. Most of the climate-related deaths were projected to occur in South and East Asia. The model used was based on broadly comparable greenhouse gas emissions and future economic growth projections.

### *Increased number and more frequent severe weather conditions*

Increasing average global temperatures will likely increase the frequency and severity of extreme heat conditions and may moderate the frequency of cold weather incidences. Extreme heat surges can especially affect the elderly and others among the most vulnerable. Deaths will increase from heat stress (for example, in 2003 during the European heat-wave, there were about 70,000 additional deaths out of a total of about five million total deaths).

There have been many studies of heat-waves that resulted in deaths, especially of the elderly. These especially affect those already suffering from respiratory or cardiovascular diseases. However, where affordable, the use of air conditioning can reduce these effects. At the same time, significant increases in the use of air conditioning can increase electricity demand, which in turn can contribute to more greenhouse gas emissions, as well as exacerbating the underlying climate change cycle. Therefore, other coping strategies need to be developed and promoted, including use of blinds, natural ventilation, and increased public awareness. The far lower number of deaths in Paris associated with heat-waves of the last several years compared with those of 2003 has been attributed to better preparedness of the public, health infrastructure and emergency procedures.

As mentioned above, based on its central (base-case) economic assumptions, the WHO projected 38,000 extra deaths per year by 2030 due to heat. This estimate relates to those over 65 years only, and assumes a fairly high level (50%) of adaptation. With no adaptation, this would have been 92,000 annually. This projection increases to a central estimate of about 100,000 extra deaths per year by 2050 (with 50% adaptation) or over 250,000 with no adaptation. The increases are not distributed evenly over the globe: the impact is greatest in South Asia, East Asia and Southeast Asia.

Barreca (2012) found that, in the United States, each additional day of extreme heat (more than 90ºF) increased mortality by about 0.2 deaths per thousand or about 0.02%, while reported effects of extreme cold appear to be driven more by low humidity than cold temperatures. In India, Deschênes and Greenstone (2011) found that an additional day with mean temperatures exceeding 36ºC relative to a day in the 22-24ºC range increases the annual mortality rate by about 0.75%, about seven times larger than the current effect in the United States (but about the same impact as in the United States in the 1920s and 1930s, before significant use of air conditioning).

As shown in Gasparrini et al. (2015), deaths at moderately cold temperatures are more important than deaths at the extremes, at least under current climate conditions. This follows from the way temperature-related deaths have been defined in terms of statistical correlations. A common mistake is to think that temperature-related deaths only occur at extreme temperatures.

As to what will happen as temperature curves shift to the right, (i.e., temperatures increase), the key question is whether the temperature-mortality curve also shifts, which is difficult to predict. Ballester et al. (2016) hypothesized that both curves shift, i.e., adaptation will partly mitigate the increase in heat-related deaths that would otherwise arise from the increase in temperature – the effect of adaptation is an important area that needs further research.

Projections of temperature-related deaths can make the potentially-flawed assumption that the temperature-mortality relationship is static.

In studying the effect of sudden-onset events, it is important to address the impact of “harvesting”, i.e., extreme heat may cause deaths that would otherwise have occurred soon thereafter if the extreme temperature had not occurred. This effect differs by income level and country.

### *Increase in natural disasters*

Extreme events may result in deaths due both directly and consequentially to the effects of environmental degradation and climate change. A significant increase in natural disasters are expected, both in number and in intensity. Examples of sudden events include tornadoes, tropical cyclones, wildfires and storms. Nevertheless, the frequency of North American tropical cyclones (hurricanes) may be suppressed due to other effects of climate change. Extremely dry conditions can result in increased wildfires, such as the one that forced the evacuation of Fort McMurray in Canada in 2016.

In addition, there will likely be an increase in the intensity of these natural disasters. For example, the El Niño of 2014-16 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 the extent of this attribution is not agreed by all.

While El Niño and its counterpart La Niña occur cyclically, mainly due to the effects of global climate patterns, extreme weather events associated with these phenomena – such as droughts and floods – have increased in frequency and severity, according to U.N. agencies.

“Millions of children and their communities need help to prepare for the eventuality La Niña will exacerbate the humanitarian crisis. And they need help to step up disaster risk reduction and adaptation to climate change, which is causing more intense and more frequent extreme weather events” according to UNICEF's Director of Emergency Programs, Afshan Khan.

But these don’t just follow El Niño and La Niña patterns. For example, regarding powerful thunderstorms over the Sahel region of Africa, Taylor et al. (2016) indicated that, between 1982-2016, the “Frequency of extreme Sahelian storms tripled since 1982 in satellite observations”.

Some 26.5 million children in Eastern and Southern Africa need support, including more than one million who need treatment for severe acute malnutrition, according to UNICEF (2016). The report warns that the future of children in the worst affected areas is at risk, as the extreme weather has disrupted livelihoods and schooling, and has brought increased disease and malnutrition. This tends to decrease their educational attainment. Lower educational attainment has in turn been associated with higher levels of mortality over the long-term. This does not imply that these adverse consequences can be attributed to climate change; however, it does indicate that adverse consequences of future climate change can lead to some of these consequences.

Undernutrition and malnutrition at an early age can have long-lasting effects, including increased risk of illness, delayed mental development and premature death, and indeed can be passed on to the next generation. UNICEF (2016) also reported that mortality of children living with HIV is two to six times higher for those who are severely malnourished than for those who are not. Reduced access to safe water has been linked to increases in diseases such as dengue fever, diarrhea and cholera. According to UNICEF, in South America and particularly Brazil, El Niño created favorable breeding conditions for the mosquito that can transmit Zika, dengue, yellow fever and chikungunya. UNICEF also noted serious concerns that Southern Africa could see increased transmission of HIV as a result of El Niño, as lack of food affects access to anti-retroviral therapy, as patients tend not to take treatment on an empty stomach and many people will use their limited resources for food rather than on transport to a health facility in another village or town.

In addition, increased numbers of refugees, destabilization of communities and the resulting conflicts, as well as reduced access to life-support systems and other health-care infrastructure, will likely result in increases in the number of deaths. In many situations, it is the overall strength of a neighborhood and social infrastructure, including public spaces, local institutions, emergency procedures and community organizations, that determine the extent of mortality that results from a disaster. Local conditions that can isolate people from each other under normal circumstances can, under stressful conditions, become lethal.

### *Coastal flooding and rising sea levels*

Water-related deaths arise from two principal sources: sudden disasters, such as coastal flooding, and slow-onset conditions, such as rising ocean levels. If recognized far enough in advance and if economically possible, migration away from exposed areas (such as low-lying areas next to the sea or low-lying islands, such as those in the Louisiana delta area in the United States in 2016) will save lives. Assuming sufficient warning, although immediate deaths may be minimal, consequential effects of crowded emigration areas (e.g., water-borne and infectious diseases and violence) can nevertheless also impact mortality, with those of lower income more likely to suffer because of inferior temporary living conditions.

If, in the process, medical facilities and resources are destroyed with no accessible backup, the delivery of health services will likely be adversely affected, which would inevitably result in increased mortality. In extreme situations, the effects of water-related events could result in migration of masses of people, with consequential increases in disease and conflict.

Loss of land for agriculture could also exacerbate problems. Climate change is expected to affect the agriculture in South East Asia in several ways. According to the International Fund for Agricultural Development (IFAD), a specialized agency of the United Nations, "irrigation systems will be affected by changes in rainfall and runoff, and subsequently, water quality and supply".[7] Clearly sea level rises have the potential to compromise affected coastal paddy fields, adding to the problems of displacement highlighted above.

### *Impact on poverty and inequality*

Climate change will likely affect the air, water, food, shelter and health in many areas of the world. The most vulnerable, the poor, may not be able to afford the adaptation and mitigation tools available to others to avoid many of these effects. For example, there are over half a million premature deaths per year (compared to a total number of about 9.5 million deaths) due to air pollution in India (Global Burden of Disease (2013)), although a switch to cleaner energy and away from coal is likely to reduce this horrific effect in the future. Food and water-

[7] https://www.ifad.org/documents/10180/41587621-d96e-4aed-8b22-e714bcecd58e

borne infectious diseases are also likely to increase – technology will be used to fight the sources of these diseases, although it is unlikely that they will be eliminated.

It has long been understood by actuaries that wealth and income are closely correlated to increased longevity. It is therefore unsurprising that the WHO (2014) noted "[Climate change] impacts are greatest under a low economic growth scenario because of higher rates of mortality projected in low- and middle-income countries".

However, based on their models and other research, the WHO goes on to say that, even under optimistic scenarios of future socio-economic development and with reasonably effective adaptation measures, climate change is still projected to have substantial adverse impacts on future mortality.

They conclude "This indicates that 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".

The WHO work indicates that the most substantial effects of climate change on health are projected to be caused by malnutrition and infectious diseases (e.g., diarrheal disease and malaria). In 2030, sub-Saharan Africa is projected to have the greatest burden of mortality attributable to climate change, due to changes in climate, demography and relative economic conditions. By 2050, South Asia is projected to be the region most affected by the health effects of climate. However, WHO only focused on certain specific drivers of mortality and did not look at several major factors including economic development, conflict, mass migration, river flooding, or increased incidence of sudden-onset (extreme) events such as major heat-waves or tropical cyclones.

### *Air Pollution*

Climate change and air pollution are closely related. The main sources of $CO_2$ emissions (e.g., the extraction and burning of fossil fuels) are key drivers of both climate change and air pollution. 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, which significantly affect the climate; methane and black carbon are among the top contributors to global warming after $CO_2$.

Since some of the contributing causes of climate change also cause air pollution and because of its significant cumulative effect on human health, it is worth discussing some background on this risk, taken from Lelieveld (2016). This study, using a global atmospheric chemistry model, assessed the effect of seven emission sources, including ozone and fine particulate matter (PM2.5) diameter smaller than 2.5 micrometers) on global premature mortality. Changing weather patterns, including warmer temperatures and increased incidence of wildfire are projected to increase exposure to two local and regional air pollutants with significant health impacts – PM2.5 and ozone, across large swaths of the

United States (Garcia-Menendez et al., 2015), which are associated with premature mortality as well as increased incidence of non-fatal respiratory and cardiovascular disease.

Air pollution is currently the leading environmental cause of premature death. Lelieveld estimated that premature deaths worldwide from outdoor air pollution will increase from 3.3 million per year in 2010 to 6.6 million per year by 2050 (about 12% of total deaths) if nothing is done to improve air quality. This increase is largely due to increases in population and economic activity. Somewhat more than half of these deaths are expected to occur in China and India. This is in addition to estimates of 3.54 million premature deaths per year from indoor pollution (e.g., from residential heating and ovens) in 2010 (Global Burden of Disease Study 2010 (2012)).

To express this loss of life in economic terms, in a joint study with the Institute for Health Metrics and Evaluation, the World Bank (2016a) found that premature deaths due to air pollution in 2013 cost the global economy about US$225 billion in lost labor income (about US$5.11 trillion in welfare losses) worldwide. This paper indicated that a global estimate of premature deaths in 2013 was about 5.5 million (indoor and outdoor pollution), about 10% of total global deaths, while WHO (2015) estimated that there were about 7.3 million premature deaths (4.3 million due to household air pollution and 3.0 million due to ambient air pollution in 2012, about one-eighth of total deaths. No matter whose estimates are most reliable, there is an enormous number of such deaths. Differences in these estimates may be due to definitions. An alternative estimate, provided in Landrigan et al. (2017) from output of a Lancet Commission, found that pollution is the largest environmental cause of disease and death in the world today, responsible for an estimated 9 million premature deaths. They indicated that no country is unaffected by pollution.

Immediate causes of death that result from air pollution include chronic obstructive pulmonary disease (COPD), acute lower respiratory disease, cerebrovascular disease, ischemic heart disease and lung cancer. Although the relative importance of these causes differs significantly by country and region, the top seven sources of death globally from air pollution are: residential and commercial (31%), agricultural (20%), natural sources (18%) such as desert sand, power generation (14%), industry (7%), land transportation (5%), and biomass burning (5%). Premature deaths from outdoor air pollution are heavily concentrated in Asia, including China (about 41%) and India (about 20%), Pakistan (about 4%) and Bangladesh (3%). Whereas in much of the United States and in several other countries pollution from traffic and power generation are important, in eastern United States, Europe, Russia and East Asia pollution from agricultural processes results in the largest relative contribution.

The sources of deaths from both outdoor and indoor air pollution point to several sources of possible mitigation, including reduced use of coal, reduced burning of wood, reduced deforestation, more effective agricultural practices, more fuel-efficient cars and trucks and better public transport. It appears that, although air pollution is decreasing in many more developed cities, it is moving in the wrong direction in developing cities, including those in China, India and Iran.

# 4. Favorable Mortality Consequences

While the most likely overall global impact of climate change is an increase in mortality outcomes, there are several favorable mortality outcomes that may arise either directly from future changes in temperature and precipitation or indirectly resulting from mitigation and adaptation efforts that governments and other stakeholders may take in response to the challenges ahead. As with the impacts of climate change, these trends will differ significantly by region, social class and income. However, despite these possible favorable outcomes, according to WHO (2015), the net effects of climate change on longevity and health are likely to be adverse.

This chapter considers likely favorable outcomes. First, it considers direct positive effects solely resulting from future climate change. Second, it looks at the indirect impacts referred to above that result from mitigation and adaptation measures that may be taken.

## *Direct favorable impacts*

This section analyses possible impacts by type.

- **Warmer winter temperatures**

  While increasing the number of heat-waves in the summer, average winter temperatures will also increase in many areas, with fewer cold-related deaths likely, although this relativity will likely differ significantly by region and country. Although there will still be extreme cold events, according to IPCC (2014), "it is virtually certain that there will be … fewer cold temperature extremes" in the future. Hajat et al. (2014) projected that, without any adaptation, cold-weather-related deaths in the UK will increase by 9% in the 2020s, then decrease by 26% in the 2050s and by 40% in the 2080s. However, this assumes no change in population size, and as noted these estimates are highly sensitive to the population projections used. In addition, it is likely that there will be some adaptation efforts, thus presumably the rate of decrease will be somewhat larger.

  The UK experience contrasts with the overall European picture presented by Forzieri et al. (2017) that considers that "About 50 times the number of (heat-related) fatalities occurring annually [in Europe] during the reference period (3,000 deaths) could occur by the year 2100 (152,000 deaths [although with a wide estimation range of between 80,500 and 239,800])… Future effects show a prominent latitudinal gradient, increasing towards southern Europe".

- **Better agricultural outcomes in certain regions due to temperature**

  Variations in warm weather make it possible to grow certain crops (and more of other crops that are currently limited) in some regions where it was previously difficult or impossible. An anecdotal example – although not a food staple – would be the increasing areas where grapes will be able to be grown. On its own, this may improve local health outcomes, but its effects need to be considered in conjunction with the increasing number of extreme events, including more variable precipitation patterns. Thus, the effect of favorable developments will likely be offset to some extent by such factors as more extreme events, increased food insecurity, the loss of agricultural land to sea level rises (particularly in Southeast Asia) and increased drought. It has been estimated (Ray et al. (2015)) that climate variation will explain about one third of global crop yield variability.

- **$CO_2$ Fertilization effect**

  In addition to the temperature effect above, there is also a "CO2 fertilization effect", which increases carbohydrate production in plants with improved growth and yield as CO2 levels rise[8].

  While this effect has been recognized for quite a while, it has recently been highlighted in "Greening of the Earth and its Drivers" in Nature Climate Change[9]. This showed significant "greening" or increased leaf production data from satellites of the National Aeronautics and Space Agency (NASA) and the National Oceanic and Atmospheric Administration (NOAA) over the past 33 years. Green leaves produce sugars using energy in the sunlight to mix carbon dioxide (CO2) drawn in from the air with water and nutrients pumped from the ground. These sugars are the source of food, fiber and energy for life on Earth. More sugars are produced when there is more CO2 in the air – this is called CO2 fertilization.

  However, some "studies have shown that plants acclimatize, or adjust, to rising CO2 concentration and the fertilization effect diminishes over time," according to Dr. Philippe Ciais.

### *Indirect positive impacts*

This section looks at both adaptation and mitigation activities whose effects will likely reduce mortality.

- **Adaptation measures**

  Adaptation is essentially the use of technology, combined with changes in behavior, to reduce the effect of sudden or slow-onset climate events or conditions. Examples include the use of buildings and infrastructure that can withstand greater levels of sudden events such as flood and storms; or which can be put back to use more rapidly following such an event (e.g., "wet-proofing" buildings in flood-prone areas). Increased access to air conditioning in hot temperatures is a further example of adaptation.

  Increased use of air conditioning, enhanced house insulation and more accessible and prepared healthcare infrastructure have reduced the impact of hotter weather and extreme heat events and therefore the effect on mortality of climate change in areas that are susceptible to hot conditions. However, at the same time this also may have an impact on climate itself due to the greenhouse-gas emissions resulting from any associated energy use. In addition, living in air-conditioned buildings is thought to be associated with an increase in the number of allergies over recent decades. Thus, adaptation measures may themselves have adverse side effects.

  While migration away from the areas more susceptible to losses and damage, either in advance or through evacuation at the same time or immediately after the adverse conditions that resulted from climate change may be possible for some, those who are most vulnerable often do not have the resources to move or may lose much of their

[8] http://www.fao.org/docrep/w5183e/w5183e06.htm
[9] http://phys.org/news/2016-04-co2-fertilization-greening-earth.html

wealth upon migration or evacuation. They may also be more reliant on their local community structures and institutions. Therefore, whether there is a net positive impact (or the extent of this impact) on mortality is problematic.

- **Mitigation effects**

In general, mitigation in the context of climate change primarily means reducing greenhouse-gas emissions. Measures taken to reduce emissions are also actions likely to reduce mortality due to many causes. Particularly important are those actions leading to a reduction in household air pollution, the effects on mortality of which are discussed above. These mitigation efforts have arguably another favorable effect – in contributing towards a more efficient use of limited resources, the increase in prices of such resources resulting from their rarefaction (which in general would primarily affect the least well off most) are mitigated.

**Transport** - Increasing car use (and ownership) and moves away from public transport are significant contributors to climate change[10]. Therefore, reduced use of cars by favoring public transport, encouraging car sharing, cycle use and walking (e.g., Nashville, which is putting back sidewalks earlier removed to create more room for car use) are all examples of effective measures that can be taken. Several favorable effects are likely to arise from such measures. First, a reduction in air pollution directly improves population health. Second, increasing physical activity leads to direct health benefits. Finally, mental well-being is improved. Indeed, it is widely accepted that there is a direct positive correlation between exercise and mental well-being (Helliwell, Layard and Sachs, 2013). The switch to low-impact transport options at the same time usually leads to fewer road traffic accidents and injuries, freeing up health resources for other uses. The switch from petrol to electric powered cars can also have positive effects, depending on how electricity is generated -- but the ‘grey’ energy used to construct the vehicle also needs to be considered in assessing the net effect of this sector.

**Energy** - Reduced fossil fuel use and a move toward renewable energy and to increased energy efficiency measures is a large favorable contributor to population health, as well as a reduction in greenhouse gas emissions. The mining and burning of coal also exacerbates air pollution, which has a significant adverse effect on health, including respiratory infections, cardiovascular diseases, asthma and cancer, with between 20% and 40% due to environmental effects (WHO (2014)). The substitution of electricity and solar energy for wood and coal for domestic heating and cooking reduces both indoor and ambient pollution. The International Energy Agency, IEA, (2016) indicated that poor air quality is the world’s fourth leading cause of premature death (behind high blood pressure, unhealthy nutrition and smoking). The IEA predicts that premature deaths due to air pollution will rise to 7.5 million annually by 2040 from 6.5 million (an increase from 3.0 million to 4.5 million from outdoor air pollution and a reduction from 3.5 million to 3.0 million from indoor pollution), unless significant action occurs to reduce soot and fumes from vehicles, industry and household stoves/heaters.

[10]The amount of $CO_2$ emissions per passenger-kilometer is between 50 and 100 times greater for a car than a bicycle and between 5 and 10 times greater than for a bus. That a bike has a non-zero footprint is due to the carbon emissions created in its manufacture and sale.

These deaths, concentrated in Asia, are heavily linked to poverty and an inability to access modern energy.

**Solar home systems in Bangladesh**

Since 2003, the installation of solar home systems ("SHS") has been a priority of the government of Bangladesh and contributes to several objectives, including meeting renewable energy targets and poverty reduction. By 2013, nearly 2 million households had been so equipped. The project has:

- Reduced the number of households without energy, a significant factor in reducing poverty.
- Partially replaced the use of less powerful, polluting and climate-change contributing kerosene lamps. SHS households consume less than 1 liter of kerosene per month, compared to almost 3 liters per month by households without SHS. There are also direct health benefits; SHS adoption reduces respiratory disease of women by 1.2%.
- Reduced the time of fuel collection (traditionally carried out by women and children).
- Encouraged several small-scale projects (e.g., households sell mobile phone charging facilities).
- Increased the hours during which children can study for school and adults can access information (e.g., health-related) via internet, TV or radio.
- Created an estimated 100,000 directly related jobs.
- Resulted in an increase in food consumption (with positive health impacts).

The World Bank estimates that the accrued benefits of a solar unit exceed its cost by 210%.

*Source: Samad et al. (2013)*

Fossil-fuel subsidies arise where the price for fossil fuel is less than its cost, which can take the form of tax credits to fossil-fuel producers or price reductions to consumers. They can contribute to incentives for excessive fossil fuel consumption, which can also contribute to air pollution.

**Agriculture and diet** - Agriculture is a significant contributor to climate change. The trend to eating more meat is particularly harmful to the environment and produces significant amounts of greenhouse gases.[11] At the same time, the increase in consumption of dairy products and meat has resulted in several adverse and expensive health effects (e.g., cancer, diabetes and other obesity-related diseases), which put pressure on health-care systems and lead to significant losses in productivity. Healthier nutrition initiatives, e.g., reduction in eating red meat, soda taxes and promotion of physical activity are effective ways to improve population health while mitigating greenhouse gas emissions.

Springmann et al. (2015) found that "Transitioning toward more plant-based diets that are in line with standard dietary guidelines could reduce global mortality by 6–10% and

[11]Between 10% to 35% of climate-change emissions are due to agriculture, with 80% of this amount related to livestock farming. Beef cattle farming is a particularly inefficient way to produce protein, resulting in four times as much $CO_2$ as the same quantity of chickens and around 15 times more than for soya. See <www.ewg.org> and <www.unep.org>.

food-related greenhouse gas emissions by 29–70% compared with a reference scenario in 2050.” Vegetarian diets were more beneficial than the standard dietary guidelines, and vegan diets were more beneficial than vegetarian diets. Standard dietary guidelines would mean cutting global meat consumption by 56%, with a 25% increase in the consumption of fruits and vegetables.

The Indian Mahatma Gandhi National Rural Employment Guarantee Scheme (NREGS) program contributes to an effective response to risk events and provides earlier anticipatory interventions to reduce risk. The impact on people of climate change varies significantly, but the poor are usually the most vulnerable to its adverse effects. By providing incentives for projects oriented towards constructing infrastructure and supporting projects focused on water conservation, water harvesting, drought prevention measures (including re-forestation and tree plantation), flood control, irrigation and horticulture, the program helps insulate local communities from the adverse effects of climate change. According to the findings of a pilot study conducted in the Chitradurga District of Karnataka, there has been an increase in groundwater level and in water percolation plus an improvement in soil fertility, which leads to improved land productivity. The findings also suggest a reduction in water vulnerability and risks to livelihood in these areas.

It has been estimated that climate change mitigation efforts in the Amazon river area (to curb deforestation) have resulted in 1,700 fewer premature deaths due to reduced levels of air pollution and air quality (Reddington, et al. 2015). However, there is no guarantee that such efforts will be able to be maintained in the future; if not, this progress may be reversed.

The overall impact of mitigation measures on mortality and population health is difficult to quantify, as they depend on the interaction of several factors. However, where measures have been taken, results have been favorable. There is greater positive potential for those less well-off who, without intervention measures, are likely to be more adversely affected by climate change.

# 5. Insured / Pension Effects

As described in prior chapters, climate change will likely have a wide range of adverse (and favorable) effects on future mortality—varying tremendously by geographical area and extent of vulnerability. So far in this paper, most of the discussion has addressed mortality risks for the total population. The effect on insureds and pension plan participants will be different, primarily because most of these participants tend not to be among the most vulnerable to climate change. These plans have generally consisted of people in the more economically developed world, although that is gradually changing. This chapter deals with the expected direct and indirect effects on that portion of the population more likely to participate in plans in which actuaries more often practice.

It is anticipated that many risks associated with climate change will increase over time. As a result, more of the effects on mortality will be felt by most insurance and pension plans over the long-term, rather than during the immediate future. The adverse effects may not be as noticeable as those of other factors on mortality, although they will tend to occur in bunches, significantly affected by concentration risk, especially in areas of the world where those who are vulnerable reside. However, since many mortality risks are undertaken over long periods, these effects and risks will likely begin to affect decisions regarding insurance and retirement programs earlier than in many other areas. In the future, this may affect the long-term sustainability of those programs and entities whose mix of business is in concentrated areas and population segments that are more affected.

"According to available global statistics, least developed countries represent 11% of the population exposed to [climate change] hazards but account for 53% of casualties (Peduzzi et al., 2002). On the other hand, the most developed countries represent 15% of human exposure to hazards, but account only for 1.8% of all victims. Obviously, similar exposures with contrasting levels of development lead to drastically different tolls of casualties." (Peduzzi et al., 2009) As a result, the mortality of most developed countries, which have the largest insurance and pension plan penetration, will not be as severely affected as that in the least developed countries.

Of course, increased mortality, while constituting adverse economic results for life insurance, represents a reduction in costs and risks for a writer of annuities and defined benefit retirement programs.

To provide perspective, it is important to note that in the populations that most actuaries around the world consider, other factors, including changes in medical treatment, medical infrastructure and lifestyle, may have a greater effect than climate change. In addition, some climate-related mortality impacts may be said to be "displacement" of deaths that would have occurred anyway in a matter of days or weeks among people already frail, disabled or elderly, as mentioned previously.[12]. Nevertheless, this does not imply that the underlying effects discussed in this paper should necessarily be ignored.

### *Direct effects*

In aggregate, climate change will have a larger direct mortality effect on vulnerable populations, whether in developed or developing countries. Since the people more likely be

[12] See discussion under subheading "Estimating the effect" at the end of Chapter 2.

covered by life insurance or pension programs are more likely to be comparatively affluent, many of whom are among the less-vulnerable groups, those participating in these programs will tend to be less directly affected.

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. Since relatively limited insurance, annuities and pensions—are provided for the very young, additional mortality for this group has less of an effect on insurers and plan sponsors.

In the WHO (2014)'s modelling, for example, heat-related mortality focused on those aged 65 and over – this would include people who participate in life insurance and pension programs, although those who participate in such programs may be more likely, for example, than an "average person" to have air conditioning in their homes. In addition, although the affluent may live, on average, in buildings with better storm-protection than those who are less well-off, they may still live in highly concentrated or risk-prone areas.

If, for instance, a tropical cyclone, tornado or flood hits that area, there may be a greater number of deaths in that concentrated area than if at-risk lives had not been so concentrated. In contrast, some who are better-off may be able to better afford to live in ocean-front property, thus being more exposed to risks related to rising sea levels or to increasingly severe storm surges or slow-onset ocean conditions due to melting glaciers, even though they may be able to better afford to move away from the areas expected to be affected.

For vulnerable populations living in areas with a heightened risk of mosquito infestation, drought or conflict, actuarial issues may still arise despite the relative lack of traditional pension and life insurance penetration. In Africa, for example, there has been a rapid rise in mobile phone usage for day-to-day transactions. This in turn has driven an explosion in microinsurance, often on a "loyalty" basis as part of a phone package. For example, EcoLife Zimbabwe reached 20% of the adult population within 7 months on a loyalty model[13]. The spread of mobile insurance through mobile phones (including life, accident and hospital cover as well as funeral plans) is not limited to Africa. Telenor Talkshawk Pakistan / MicroEnsure reached 400,000 participants in two months with a loyalty scheme.

Other distribution models also have proved successful, whether through "freemium" distribution (a pricing strategy by which a product or service (typically a digital offering or app such as software, media, games or web services) is provided free of charge, but money (premium) is charged for proprietary features, functionality, or virtual goods), mobile or other traditional microinsurance routes. Millions of people now have coverage, including some of the poorest and most vulnerable. An increasing number of deaths attributable to climate change (resulting in a drag on mortality improvements that otherwise might have been anticipated) will have actuarial ramifications in these markets.

### *Indirect effects*

Indirect impacts on mortality related to climate change include deaths caused by a sustained surge in demand beyond the capacity of a healthcare system to cope effectively. Although usually associated with developing countries as discussed in Chapter 2, it can also happen in

[13] Presentation dated 7 April 2016 by Henry Yan, Chair of the Institute and Faculty's A MicroInsurance Working Group. https://www.actuaries.org.uk/documents/microinsurance-and-rise-mobile-insurance

developed countries as seen in 2005 when Hurricane Katrina in the United States caused massive displacement of people and a consequential overload of healthcare services, which did not have a significant amount of spare capacity.

As with direct effects, it seems probable that those with a smaller amount of resources will be most vulnerable, which implies that areas such as South and South-East Asia and large parts of Africa will be more likely to experience the indirect mortality consequences. However, Hurricanes Katrina and Sandy serve as powerful reminders that these mortality effects may not be limited to developing economies and population segments. And, as above, the elderly in most situations are also a vulnerable group.

To the extent that these indirect effects impact mortality experience, they have the potential to impact reserving for pensions and life insurance, although in opposite financial directions.

### *Beyond the mortality impact*

In discussing the potential impact of climate-change-related effects on pension and insurance programs, the scope of this paper is limited to the effects of climate change on mortality. As indicated earlier, there will likely be a wide range of effects on other areas of significant issue to the financial institutions, public programs and the general society in which actuaries deal. For example, health insurance, property damage insurance, business interruption insurance, liability insurance, agricultural damage and crop insurance and directors' and officers' liability insurance.

In addition, there exists the potential of tail conditions in which significant changes will arise in the social and economic fabric of countries across the world. If such other changes occur, there may be more profound impacts to investment strategies of financial institutions such as insurers and retirement programs, and indeed the political backdrop within which these programs operate. Discussion of these effects is outside the scope of this paper.

### *Role of Actuaries*

Although actuaries are generally considered experts in financial risk analysis and projection, the profession has been more closely associated with its expertise in life insurance, property and casualty insurance and pension programs. Due to the long-term nature of these programs, actuaries will have to come to grips with the future effects of these programs and mitigation and adaptation efforts to offset the adverse effects of climate change earlier rather than later.

One of the key challenges that actuaries face is the uncertainty associated with the future. This is particularly acute in pensions and life insurance due to their long duration. Assessing the financial sustainability of these systems requires projections of mortality and economic conditions decades into the future. The enormous uncertainly associated with climate change is in and of itself an actuarial problem, regardless of whether or how mortality is affected – it creates forecast risk. Since increased risk has an economic cost, uncertainty in future forecasts will likely increase the risk of errors and inevitably the cost of such programs. Stakeholders should be kept informed of the possible effects of this uncertainty.

It is clear to the authors of this paper that it is incumbent on the profession to lead the debate on the likely impacts of climate on mortality, as well as its implications for life and pension products and to society at large – rather than let it passively emerge as an implicit "experience item" in annual reconciliations of actual versus expected experience.

An example of actions that have been taken by actuaries is the development of the Actuaries Climate Index[14], an actuarial product that provides an objective measure of quarterly extreme climate-related conditions, such as temperature and precipitation compared to a reference period. Future developments in this area, including the Actuaries Climate Risk Index expected to become available in 2018 that will include an assessment of the relationship between extreme heat and mortality and injuries, and applications by actuaries in related areas are expected.

Perhaps the most pragmatic current response for actuaries is to recognize that climate change represents an additional source of uncertainty in future mortality rates and to consider its implications for the assumptions they make and for their communication of the associated uncertainty to their clients.

[14] Available at http://actuariesclimateindex.org/home/, developed by North American actuarial organizations

# 6. Quantitative Analysis and Modelling

To understand the effects of climate-induced changes, the risks involved need to be identified and those climate-related risks that lend themselves to a quantitative analysis need to be rigorously assessed. This applies both to the effects of long-term gradual climate changes and the frequency and severity of extreme weather events. We also need to acknowledge the impact of any effects that do not lend themselves to a quantitative approach, and to disclose the likely direction and magnitude of their effects.

Any analysis must recognize the wide range of uncertainty associated with the future, especially tail risks associated with possible enormous one-off events/conditions and exponential or cascading effects. Both stochastic analysis and scenario testing approaches may prove useful in the analysis and communication of the effects of risks and uncertainties, as shown by assessment of alternative possible futures.

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 incorporate (1) the effects and interrelations of factors affecting greenhouse gas emissions, (2) their effects on climatic factors such as temperature and precipitation and (3) resulting effects on damages, including premature deaths. These are then reflected in economic models that incorporate their financial and human effects, taken to present values through a discounting process. Each of these effects is subject to multi-disciplinary inputs. However, IAMs have limitations and may significantly underestimate the economic effects of climate change (Stern (2013)). With any model, including an IAM, it is vital to understand both the uncertainty and also the sensitivity associated with the assumptions made, as a part of understanding a model's limitations and uses. Although the training of most actuaries does not involve climate science, they are experts in assessing the financial implications and uncertainties of such contingencies and methods that can be used to address their effects, including the approaches described in this chapter. The authors of this paper anticipate that actuaries will become more involved in these steps as their effects on lives, health and property become more clear and immediate.

The following discusses the general methodology used to analyze the direct effects of temperature on mortality. A similar approach can be taken with respect to other aspects of climate-change analysis, although in many cases several intermediate steps may be needed – including estimating the future amount of greenhouse gas emissions, their effects on cumulative greenhouse gases in the atmosphere and oceans, their direct and indirect consequential effects (such as the number of disease-bearing mosquitoes) on the amount and variability of the components of climate, and the effectiveness of mitigation and adaptation approaches used.

Simple or highly complex models might be used, depending on the accuracy desired and the objective of the analysis. They are usually run on both a baseline scenario and on a scenario (or a series of scenarios) reflecting a given level of climate change (e.g., temperature). A series of scenarios may be stochastically selected. The differential effect is then taken as being the expected effect of climate change. In addition, scenarios based on alternative mitigation or adaptation strategies can also be studied.

For example, in studying the effect of mosquito-spread diseases, a model might consist of modules involving temperature, cumulative rainfall, insect mitigation efforts, infection rates and recovery rates, all by regions in a country varying by population concentration and closeness to infectious disease outbreaks. Sea-level analysis may include a model of the rate of glacier calving or glacial lake flooding, as well as air and ocean temperatures in various parts of the world.

In a temperature-related analysis, at least the following is needed: 1) a time-series model of the expected changes in average daily temperature (or its volatility) for a location or area and 2) a model of how changes in temperature affect the mortality rates experienced by a population segment. A time-series model is needed because daily mortality rates might be expected to depend on the temperature experienced in the preceding days, not just during the period over which mortality is measured. In addition, expected changes in the population segment potentially exposed, such as the number of people older than a specified age such as 65, are needed and – in a study of the effects of extreme temperature or precipitation – a model of the adaptive measures taken by the population-at-risk, such as staying in air conditioned indoors in a heat-related situation. Separate models would be applied to study each type of effect, such as by heat stress, mosquitoes or natural disasters.

Especially where the effects on mortality rates are expected to differ by demographic, geographic or socioeconomic factors that are sensitive to the type of climate change being assessed, such as age or proximity to a vulnerable body of water and a long-term period is involved, it is important to incorporate in a model the effects of climate change by such factors. A bias may otherwise be introduced by ignoring such factors. For age, this can be done through an age-adjustment based on an aggregate factor representing the estimated change in population at those ages or a more refined age and demographic projection, reflecting estimated rates of mortality and net migration by age, plus fertility rates by age and year. The degree of refinement used (e.g., whether categorized by gender or individual age or age category) will depend upon the period and aspect of climate change studied.

Many models of direct temperature effects attempt to replicate the short-term effects of changes in weather-related temperature on a population segment (for example that of a large city currently in a temperate climate) by modelling the changes in mortality associated with changes in the average daily temperature. Studies taking this approach have found that the curve of mortality versus temperature has a "J" shape with a minimum at a particular (optimum) temperature. The rate at which mortality increases as temperature increases above the optimum is typically greater than the rate of increase as temperature falls below the optimum. A key finding is that the optimum temperature varies with the location studied, although it is greater than the average ambient temperature in most places (Gasparrini et al. (2015)).

Temperature effects on mortality resulting from climate change were reviewed in the IPCC 5th Assessment Report (IPCC (2014)) and more recently in WHO (2016).

A large-scale study of mortality risk attributable to high and low ambient temperatures (Gasparrini et al. (2015)) attracted significant comment. There is clearly more work to be done in this area. Attribution of events and their effects to cause, such as climate change, is of growing interest – see Committee on Extreme Weather Events and Climate Change Attribution et al. (2016) for further discussion of this topic.

Several approaches can be taken to modelling mortality in response to climate change. O'Hare et al. (2015) added a weather-related factor to a Lee-Carter base model (a popular mortality model used for mortality projections). They indicated that a better fit was achieved than without such an add-on factor. Sekleka et al. (2015) indicated that, using a similar model applied to UK mortality data, an improvement in fit was observed by modelling the annual experience and the experience of cold months separately, rather than focusing on experience from the hotter months.

The statistical model underlying (Gasparrini (2013)) is open source and published as a package in the R language (Gasparrini (2016)). The same type of statistical model underlies the quantitative modelling in WHO (2014). (Honda et al. (2014)).

The use of a published model such as R means that the entire modelling process is transparent and could be reproduced by anyone with access to the data. Actuaries can therefore engage with the modelling of temperature-related mortality in several ways:

- Attempt to reproduce the results of existing research groups;
- Use the same model to calculate different results;
- Use the same model with different data sets; and
- Present results from distributed lag non-linear models (DLNM, a modelling tool for describing potentially non-linear and delayed dependencies, i.e., associations characterized by a delay between an input and a response in time series data) such as those used in Gasparrini in different ways that are perhaps more relevant to actuarial applications or that are designed to encourage discussion of different aspects of the results.

The R modelling ecosystem includes tools that make creating and sharing interactive visualizations relatively easy. An example is in https://actsci.shinyapps.io/dlnm_app-1/, which:

- Applies the model to different data sets;
- Extends or otherwise adapts the DLNM model; and
- Compares the DLNM with completely different modelling approaches.

It would be desirable if historical observations regarding past periods of weather could be used, although the effects of future climate scenarios are bound to differ, if for no other reason than the extent of preparation and infrastructure of local communities or countries, either by means of mitigation activities (more often applied at a broader geographical area) or adaptation to changed conditions, e.g., greater use of air conditioning.

### *Use of scenarios*

A powerful alternative to stochastic modelling to illustrate possible impacts of climate change on mortality is the use of scenarios. Actuaries in all sectors who carry out modelling work, no matter what level of refinement, should subject their projections to sensitivity testing. Typically, in relation to mortality this might include variations in the underlying base table or the rate of projected improvements over time. Another common approach is to add or subtract a year or more to or from the calculated age.

In 2014, the UK's National Association of Pension Funds (since renamed the Pensions and Lifetime Savings Association (PLSA)) commissioned a study (PLSA (2014)) to examine possible future trends in longevity, based in part on analysis of 2.5 million pensioners from some of the UK's largest occupational pension schemes. It considered several possible future scenarios, shown in Table 2. Two "low trend scenarios", "Back to the Fifties" and "Challenging Times" incorporate the expected effects of climate change as well as other factors.

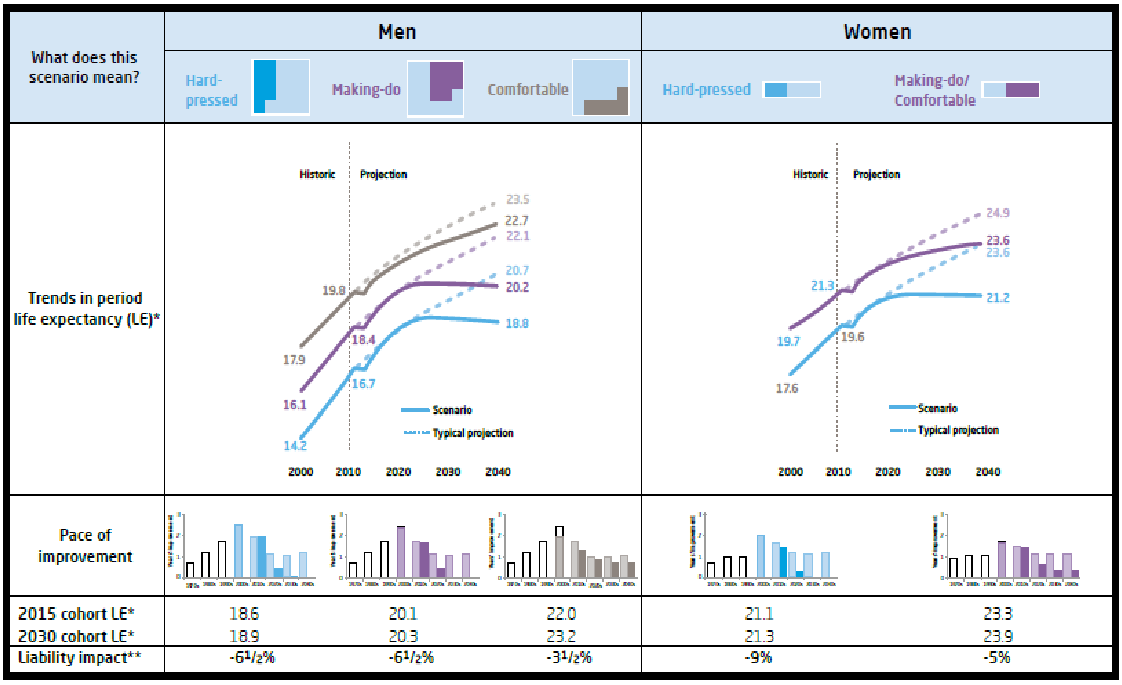
**Table 2. Example of the use of scenarios**

| | Low trend scenarios | | Central(ish) scenarios – 'best estimates' | | High trend scenarios | |
|---|---|---|---|---|---|---|
| **Description** | "Back to the Fifties" | "Challenging Times" | **"Improvement Decline"** | **"Health Cascade"** | "Cancer Revolution" | "Extended Youth" |
| **Summary narrative** | There are multiple negative impacts on life expectancy | NHS funding is severely constrained. Many people cannot afford and/or access necessities | Improvements slow over as the frequency and impact of medical advances diminish. This is coupled with rising obesity and other detrimental lifestyle factors. | Beneficial health behaviours filter through the population. Longest lived are first to adopt positive behaviours with the rest of society adopting these later | Accelerated implementation of cancer therapies, causing cancer mortality reductions of the same magnitude as recently seen for circulatory disease | Increases in life expectancy over the last 10 years continue for many decades |
| **Potential catalysts** | Dissolution of NHS, climate change, resource constraints | Severe constraints on NHS funding and consumer spending | Increased funding to cancer research bears little fruit; treatment of other common diseases eg diabetes is neglected; rising obesity | Introduction of plain cigarette packaging. Improvement in eating and drinking behaviours | Earlier diagnosis and much more effective treatment Effective national and genetic screening "Pill" developed to target hard to treat cancers. | Breakthroughs in anti-ageing and dementia treatments Stem cell / gene therapies |

source: Pensions and Lifetime Savings Association (2014)

In the PLSA's "Challenging Times" scenario of increasing costs of energy, economic growth is severely impacted and consequently health service provision is challenged. Reduced access to and increased costs of food are a further consequence. The poorer sectors of UK society would thus be unable to afford a trio of basic needs: heating, medicine and a balanced diet. They also assume two consecutive harsh winters will occur early in the projection period. Their results are shown in Figure 5.

**Figure 5.** PLSA Challenging Times scenario




*from age 65 in the year shown. **vs CMI model with CMI starting improvement and 1.5% long-term rate

*source: Pensions and Lifetime Savings Association (2014)*

The use of this scenario therefore led to a lowering of life expectancy in comparison with the central assumptions, with a greater impact on the poorer segments of society. However, it is not the specific scenario that is of most interest here, but rather the technique used. Actuaries in different countries could construct similar scenario-based sensitivity analyses of their model results. If combined with consistent economic scenarios this could potentially prove to be a far more powerful test of a model or of a proposed solvency level than simply altering the rate of longevity improvement or the discount rate by varying amounts.

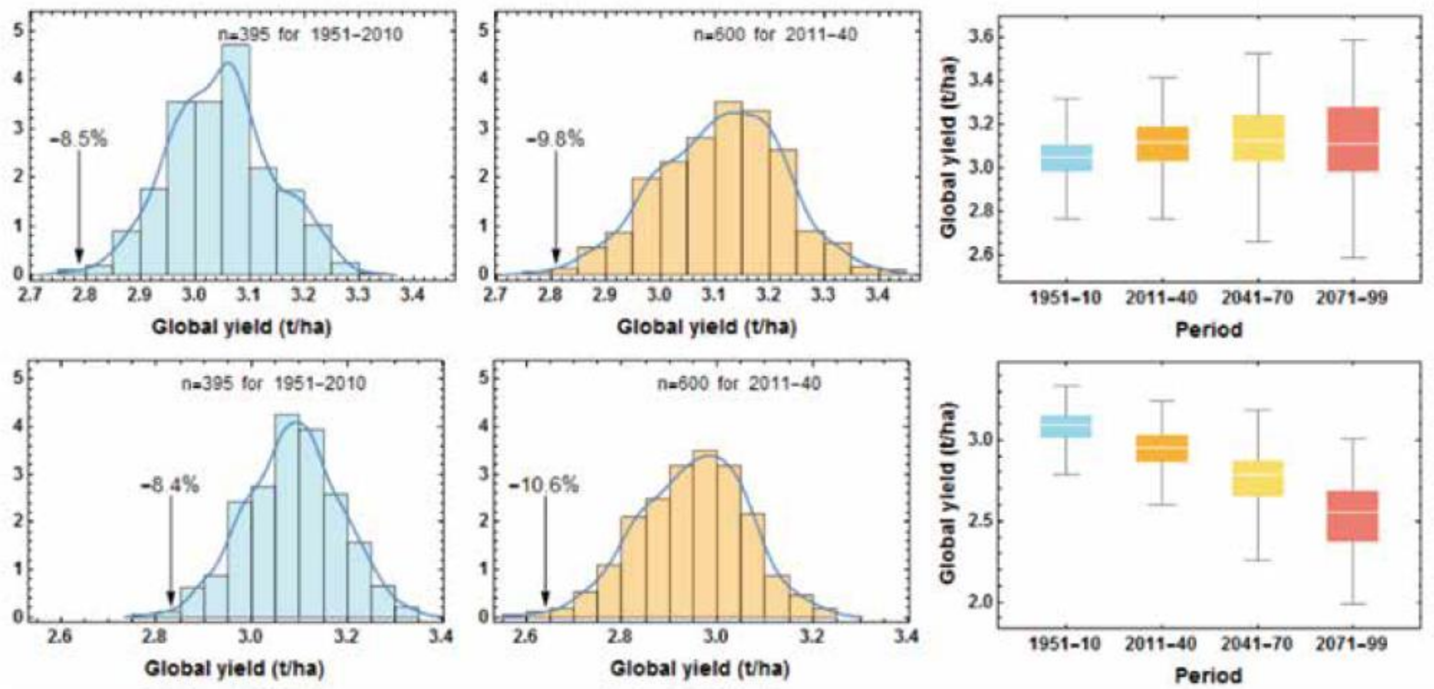
This work also included a "Back to the Fifties" scenario, which, although not directly linked to specific climate impacts, could plausibly be used as a narrative for a future in which climate changes have directly or indirectly caused increasing austerity and resource constraints with knock-on effects on for example heating or access to a good diet.

### *Dealing with non-stationary risks*

While not a direct link to insurance or pensions disciplines, it is instructive to realize that the climate scientists looking at the impact of climate on, say, grain production, deal with non-stationary risk. This is illustrated in Figure 6, taken from The Global Food Security Program (2015).

Figure 6 shows how distributions for the annual yield in cereal crops are expected to change. On each row, the left hand (blue) diagram shows the current observed yield. The middle diagram shows the projected yields for the period 2011-40. The final right hand diagram shows how this distribution / volatility changes over longer periods. The top row shows the effect including the effect of $CO_2$ fertilization (see chapter 4 and Myers et al. (2014)).

**Figure 6.** Illustrative scenario of climate change on cereal crop yields




*Source: Myers et al. (2014)*

This analysis suggests that what is referred to as an "extreme food production shock" in the late 20th century will become more common. These data indicate that a 1-in-200 year event for the climate in the late 20th century equates to a loss of approximately 8.5% (top left). Over the next three decades (2011-2040) a 1-in-200 year event is about 15% larger in magnitude and equivalent to the loss of 9.8% of calorie production. Furthermore, according to the model, an event that would have been called a 1-in-100 year event over the period 1951-2010 may become as frequent as a 1-in-30 year event before the middle of the century.

Similar techniques may be needed to project, for example, impacts of climate change on mortality or economic development.

# 7. Case study – Temperature-related mortality in the United Kingdom

The Climate Change Act 2008 requires the UK Government to carry out a Climate Change Risk Assessment every five years. Extensive evidence reports prepared to support these assessments (Hames and Vardoulakis (2012); Committee on Climate Change (2016)) present detailed information on potential risks to UK health from climate change, including:

- Extreme temperature;
- Flooding, including that caused by sea level rise;
- Disruption to health and social care services, and damage to related infrastructure, due to extreme weather (in part from coincidental increased demand);
- Air quality, both outdoor (e.g., ozone, particulates) and indoor;
- Vector-borne disease (e.g., West Nile and dengue viruses);
- Food safety (as infection rates are sensitive to temperature); and
- Water quality and water supply interruptions.

They also cover health opportunities such as an increase in outdoor leisure activities prompted by the warmer weather and active travel.

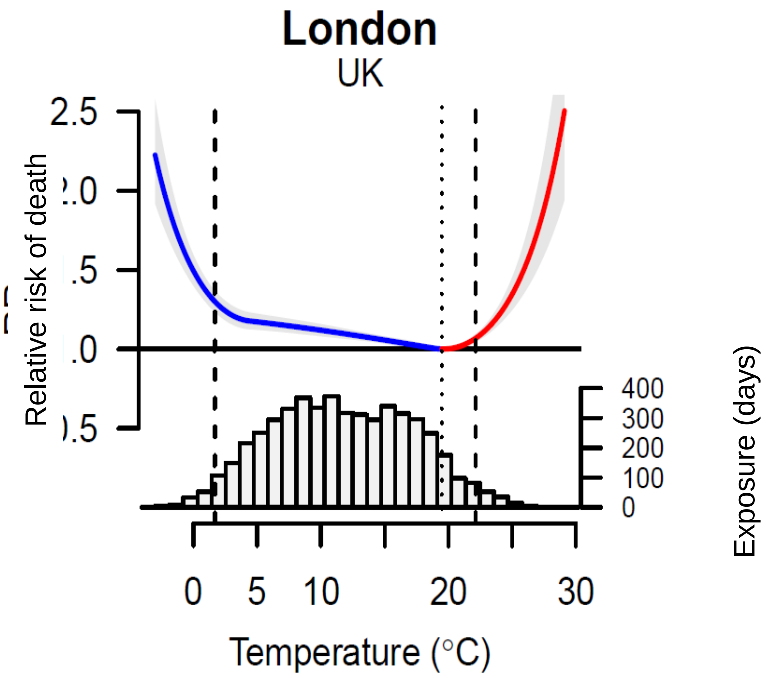
Hames and Vardoulakis (2012) state that, of the various quantitative estimates provided, there is most confidence in those relating to heat-related deaths, followed by those for cold-related deaths. This case study therefore focuses on temperature-related deaths. However, it is clear from other papers published on this topic (e.g., Arbuthnott et al. 2016; Ballester et al. 2016; Staddon et al. 2014) that there is considerable uncertainty even in these estimates. Many studies assume that the temperature-mortality relationship will remain constant over time, whereas in practice it is likely to vary due to physiological, behavioral and policy responses to changes in temperature and wider socio-economic factors (see below), especially in extreme temperature conditions where there are likely to be tipping points where significantly larger numbers of deaths are possible.

Moreover, some of the less quantifiable effects of climate change could be more material than the direct mortality effects of changing temperatures. For example, less money may be available for healthcare if the economy is damaged by climate change (PLSA 2014), and fruit and vegetable consumption may fall if they become more expensive due to crop failures and higher fuel costs (Springmann et al. 2016).

Estimates of UK temperature-related deaths usually use statistical definitions of heat-and cold-related deaths rather than the underlying cause of death. Very few UK deaths have been directly attributable to temperature extremes, for example hypothermia or heat stroke (Arbuthnott et al. 2016). Instead, temperature-related deaths are determined using the "J-curve" (or U- or V-curve) relationship between temperature and mortality, such as the one shown in Figure 7. All excess deaths above a certain threshold are classified as heat-related deaths and those below a certain threshold are classified as cold-related deaths. For example, Hajat et al. (2014) used the 93$^{rd}$ and 60$^{th}$ percentiles respectively, whereas

Gasparrini et al. (2015) used the optimum temperature – which they found to be the 90th percentile – for both.

**Figure 7**. Overall cumulative exposure-response relationship to heat in London



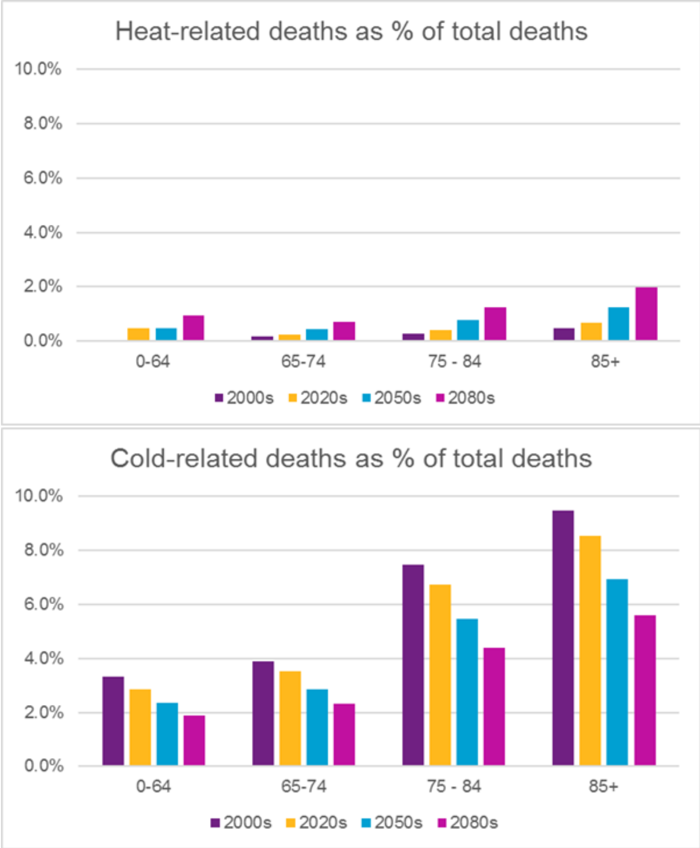

*Source: Gasparrini et al. (2015), Figure S1.* Uses daily data between 1 January 1993 and 31 December 2006. The optimum (minimum mortality) temperature is shown by the dotted line, and the 2.5th and 97.5th percentiles of the temperature distribution are shown as dashed lines. Daily temperature is calculated as the 24-hour average of hourly measurements. Exposure is the number of days during the 14-year period for each mean temperature.

Hajat et al. (2014) estimated heat- and cold-related deaths for the 2000s, 2020s, 2050s and 2080s, split between twelve UK regions, using a medium emissions scenario (A1B) and nine climate sensitivities. From the perspective of actuaries setting assumptions regarding future mortality rates, perhaps the most relevant estimates are the UK-wide temperature-related deaths as a percentage of all-cause death rates in each of four age groups, as shown in Figure 8. The modelling implies that, for the UK:

- Cold-related deaths are currently far more frequent than heat-related deaths;
- Cold-related deaths are expected to decrease due to 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+, which is expected to continue as the climate warms.

This analysis does not make an allowance for other changes in mortality rates over time. In practice, mortality rates will change for other reasons, which will affect the number of temperature-related deaths, for example, due to changing incidence of the causes of death that are associated with hot and cold weather.

**Figure 8**. Projected UK 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)




*Sources: Hajat et al. (2014) Figure 4 (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).*

Several studies have shown that countries similar to the UK with temperate climates have tended to have proportionately more cold-related deaths than naturally colder countries like Sweden. Reasons for this relativity may include: (1) housing stock which is not suited to colder temperatures – many UK homes are poorly insulated, hence both difficult and expensive to heat, (2) individuals may not always dress appropriately in cold weather, as a result of underestimating temperature risks and (3) generally the population is less well-prepared for the cold. The UK also has relatively high heat-related deaths: air conditioning is not common in UK homes and overheating is a problem, for example on public transport in London. Efforts to make homes warmer in winter by making them more airtight have unintentionally made them hotter in summer.

It is important to note that the annual expected death rates per 100,000 people calculated by Hajat et al. (2014) vary significantly; for example:

- Heat-related in the 2000s, mean of the nine climate sensitivities – from 0.7 (Scotland) to 6.3 (South East England), with a UK-wide rate of 3.3;
- Heat-related in the 2080s, UK-wide – from 7.4 (minimum climate sensitivity) to 21.5 (maximum climate sensitivity), with a mean of 14.0;

- Cold-related in the 2000s, mean of the nine climate sensitivities – from 46.7 (Northern Ireland) to 83.9 (Wales), with a UK-wide rate of 68.7; and
- Cold-related in the 2080s, UK-wide – from 28.2 (minimum climate sensitivity) to 56.0 (maximum climate sensitivity), with a mean of 40.9.

A similar study by Vardoulakis et al. (2014) found that projected temperature-related deaths in England and Wales varied significantly depending on the emission scenario assumed (B1, A1B or A1F1), although the range of results was narrower than in Hajat et al. (2014).

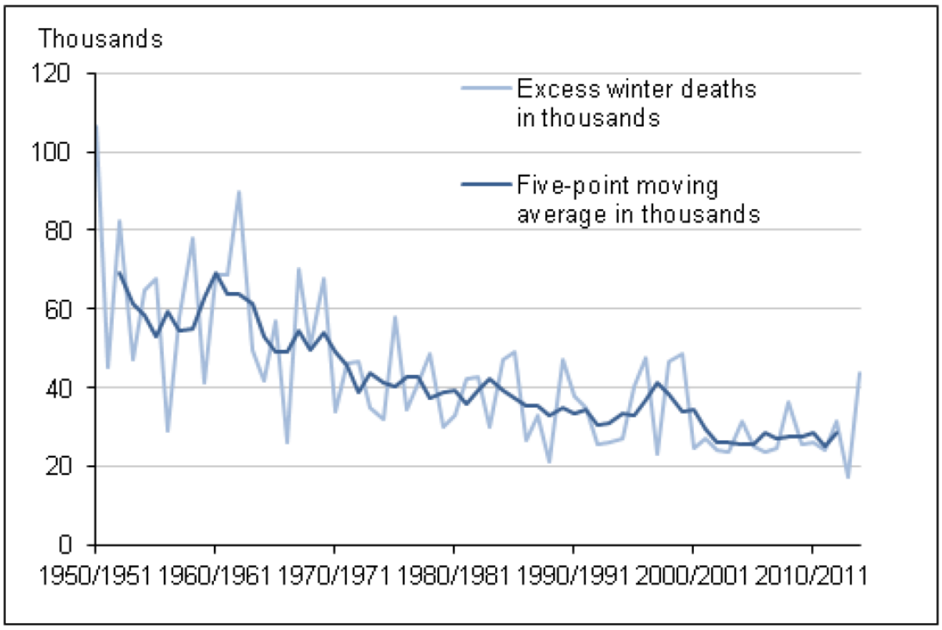
These studies illustrate the level of uncertainty associated with estimates of temperature-related deaths, which poses challenges for actuaries wishing to incorporate the effects of climate change when setting mortality assumptions and currently suggests a focus on illustrating a range of plausible outcomes, rather than a single assumption. Indeed, the full range of uncertainty is much wider than presented here, not only associated with climate modelling, but also because Hajat et al. (2014) and Vardoulakis et al. (2014) assumed that the temperature-mortality relationship will remain constant, i.e., there is no behavioral or physiological adaptation to changing temperatures.

In contrast, the belief that cold-related death rates in the UK will decrease under climate-change conditions has been challenged in several recent studies (e.g., Ballester et al. (2016), Staddon et al. (2014), Ebi and Mills (2013)). One of the sources of disagreement is based on the distinction between cold-related deaths and excess winter deaths.

An important consequence of the definition of attributed deaths used in papers such as Hajat et al. (2014) is that UK “cold-related” deaths occur throughout the year, not just during winter, many at quite mild temperatures. However, UK public health officials tend to focus on Excess Winter Deaths (EWDs), defined using the month of death (Hajat and Gasparrini (2016)). The definition used by the UK Office for National Statistics (2015) is the number of deaths in the period of December to March, minus the average of deaths in the previous four months and deaths in the following four months. Hajat and Gasparrini (2016) point out that this measure can be distorted by cold weather occurring outside the four “winter” months and by other seasonal variations such as an increasing number of heat-related deaths in summer (which would decrease EWDs).

Despite the flaws in the EWDs measure, the Office for National Statistics regularly publishes EWDs data for England and Wales, including that shown in Figure 9. In the second half of the last century, there was a declining trend in EWDs, but with significant fluctuations. For the first twelve years of this century, EWDs were more stable, but then were much lower in 2013/14 and much higher in 2014/15. EWDs are higher for females than males, which is at least partly due to there being more females than males in the oldest age groups which are most vulnerable to winter deaths (Office for National Statistics 2015).

**Figure 9**. Number of excess winter deaths and five-year central moving average, England and Wales, 1950/51-2014/15




*Source: Office for National Statistics 2015, Figure 1*

The Office for National Statistics (2015) reported that the main causes of EWD in England and Wales during the winter of 2014/15 were respiratory disease (36%), circulatory disease (23%) and dementia, including Alzheimer's disease (21%). The seasonal effect is strongest for respiratory disease. Although the seasonal effect is only moderate for circulatory disease, it still causes many EWDs since circulatory disease is a common cause of death in England and Wales. Although 2014/15 was a colder winter than 2013/14, the Office for National Statistics (2015) concluded that this is not the main cause of the huge increase in EWDs. They indicated that influenza was a more important reason -- not just because of a high incidence rate, but also because that year's vaccine had relatively low efficacy and the dominant influenza strain was particularly harmful to the elderly.

This conclusion is consistent with that of Staddon et al. (2014), who performed a regression analysis of EWDs in England and Wales between 1951 and 2011. They found that the key factors associated with year-to-year variation in EWDs were:

- 1951-1971: housing quality and number of cold days (less than 5°C);
- 1971-1991: number of cold days (less than 5°C) and influenza activity; and
- 1991-2011: influenza activity.

In other words, the authors determined that there is no longer a strong association between cold temperatures and EWD. They suggested that this might be due to improvements in housing and healthcare, higher incomes and increased awareness of cold weather risks. They therefore disputed the belief that UK mortality rates will decline due to climate change, a conclusion that Hajat and Kovats (2014) disagreed with, pointing out flaws in the EWDs measure.

Recently, Ballester et al. (2016) attempted to reconcile the two approaches. On the one hand, their findings were similar to those indicated in Staddon et al. (2014) for the period 1998-2005, namely that year-to-year variations in deaths no longer correlate strongly with temperature in England and Wales, either for the winter months (December to March) or for the coldest 50% of days. On the other hand, they also found that day-to-day variations in deaths are strongly correlated with temperature. This paradoxical result is shown in Figure 10, which also shows that England and Wales are unusual in this respect. It is one of the few European regions without a strong yearly correlation, while simultaneously having one of the highest daily correlations (contrary to the usual pattern that daily correlation is highest among the warmest European countries). The significant variation between countries emphasizes the importance of using country-specific research when considering temperature-related deaths.

**Figure 10**. Contrasting pictures of temperature-related mortality in Europe

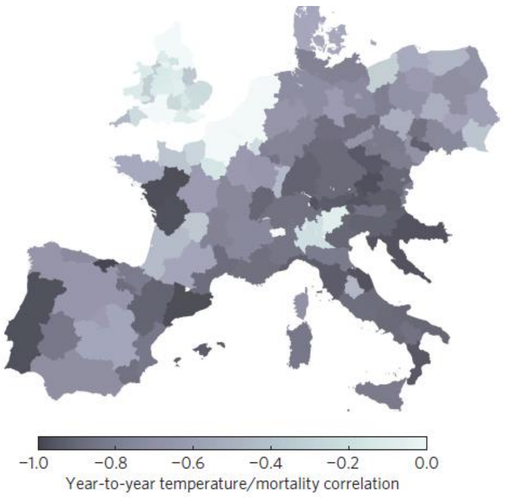



**Figure 1 | Year-to-year correlation between winter (December to March) mean temperature and mortality.**

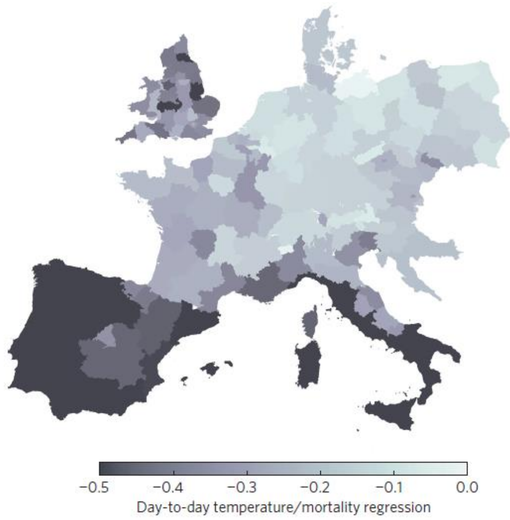



**Figure 3 | Regression coefficient between daily temperature and mortality for winter (December to March) days (daily cases per million per 1 °C).**

*Source: Ballester et al. 2016*

Ballester et al. (2016) hypothesize that the anomalous UK results reflect the effect of partial adaptation: in warmer years, the temperature-mortality curve (see Figure 10) is further to the right than in colder years, with a larger shift in the UK than in other countries. Hence UK deaths do not fall as much as might be expected in warmer winters, but within a given year the pattern of deaths reflects daily variations in temperature. However, it is not clear why the UK would display greater adaptation than other countries. Although some physiological and behavioral adaptation from year to year is plausible, other adaptation measures, such as improvements in housing stock, represent one-off reductions in vulnerability to the cold that would shift the cold end of the curve to the left.

These findings underscore the importance of considering changes in the temperature-mortality relationship over time when projecting the impact of climate change on temperature-related deaths. Although studies like Hajat et al. (2014) typically assume a constant relationship, other research is being conducted about the effects of adaptation. Arbuthnott et al. (2016) carried out a literature review of studies, most of them from the United States and Europe, that investigated the changes in the relationship between temperature and mortality over time. They found evidence that populations are becoming less susceptible to heat and heat-waves, although the results for susceptibility to cold were inconclusive, partly reflecting the smaller number of cold-related studies.

# 8. Areas of further research needed

Further multi-disciplinary work is needed in modelling the effects of climate change and sensitivities to a range of warming outcomes. The dynamic nature of risk exposures, such as increased urbanization and relative food security, should be identified, quantified and considered. Enhanced modelling approaches that might be considered include predictive analytics that consider social factors, although statistical studies of historical experience have to be accompanied by adjustments due to what may be relatively different circumstances and forces in the future, as well as both direct and indirect effects.

Further research is needed, including the following areas:

- Regional and local modelling, in part because of the uneven effect of climate change and temperature sensitivity by region.
- Effects of prolonged exposures to variable temperatures, as they are yet unclear.
- Analysis of the effects on segments of insured/pension lives, including by age and gender, rather than just focusing on the total population, which will make this analysis more useful to practicing actuaries.
- Enhanced and effective communication of both the expected results and scenario ranges, both of mortality (major components of which are discussed in this paper), but also on other effects, such as human health, property damage and other environmental effects.
- Further development of attribution methods, to better discern the effects of climate change from normal climate variations.
- Estimates of the economic value of lives lost (e.g., through GDP measures) in both economically developed and developing countries from climate change, as well as from mitigation and adaptation approaches. In addition, the effect of climate change on the solvency and sustainability of insurance and pension programs, as well as areas in which actuaries are involved in other consequences of climate change.
- Further development of comprehensive risk management techniques (in respect of adaptation) applied to the effects of climate change to reduce its effect on mortality (and other perils) to all countries and population segments. This especially includes methods applicable to vulnerable populations, both with respect to sudden effects, including extreme temperatures and storms, and slow-onset conditions, including rising sea levels and ocean acidification.

Further research is needed to understand how the temperature-mortality relationship is changing, particularly at colder temperatures; how it might change in the future; and its implications for future rates of heat- and cold-related deaths. To reflect the effect of climate change in assumptions about future mortality rates, it is important for actuaries to understand the changes in the number of heat- and cold-related deaths in the past that implicitly form the basis of existing mortality projections that represent extrapolations from historic data. It is even more important to recognize that temperature-related deaths are just one aspect of mortality that will likely be influenced by climate change, and not focus on these simply because they are the most readily quantifiable. Other factors that influence mortality such as the socio-economic impacts of the transition to a low carbon economy, or economic damage caused by a failure to transition quickly enough, could swamp the direct mortality effects of changing temperatures.

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