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Effects of Climate Change on Heat- and Cold-Related Mortality: A Literature Review to Inform Updated Estimates of the Social Cost of Carbon

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Abstract

As the climate changes, the frequency and intensity of hot and cold days will shift across the globe, with considerable implications for human health. In this review, I survey the available literature on the projected effects of climate change on heat- and cold-related mortality, with the goal of identifying studies that can be most useful in updating the social cost of carbon (SCC). I identify and discuss in detail several studies that are strong candidates for use in updating the SCC. However, major challenges continue to exist in the literature, including estimating damages for parts of the world where data are limited or nonexistent and quantifying the effects of future adaptation. In general terms, most studies estimate that climate change scenarios with high levels of warming will, on average, result in increased global mortality, with the most acute effects in warmer and low-income regions. At the same time, numerous studies estimate that under lower levels of warming, higher income regions in cooler climatic zones will experience modest reductions in mortality. However, all studies report large uncertainty ranges for future effects.

JEL codes

I0, I1, I3, Q0, Q5

Contents

1. Introduction

As the Earth's climate changes, shifts in temperature, precipitation, sea level, and other physical drivers have the potential to affect human health in a variety of ways, both positive and negative. Some of these effects occur indirectly, mediated through pathways such as disease vectors, changes in agricultural productivity, or the potential for human conflict.

Along with these indirect effects, heat and cold contribute directly to human mortality. Such effects occur when an individual's physiological response to heat or cold (e.g., increased heart rate) endangers their well-being, particularly through cardiovascular, cerebrovascular, and respiratory pathways (a recent review of reviews is presented in Song et al. 2017).

A large body of public health literature has examined the potential effects of a changing climate on human health and is reviewed in the 11th chapter from Working Group II of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Smith et al. 2014).[1] A smaller but growing body of economics-based work has also examined the topic.

The purpose of this review is to examine the most recent economics and public health literature, with the goal of identifying which studies may be most appropriate to improve estimates of the social cost of carbon (SCC), as recommended by the National Academies of Science, Engineering, and Medicine (2017). The SCC is an estimate, presented in dollar terms, of the economic damages caused by each additional ton of carbon dioxide (CO2) emissions. The SCC is used widely across the public and private sectors to inform decisions regarding public policies and other measures to reduce CO2 emissions, and a robust literature has emerged to update and improve it (e.g., Greenstone, Kopits, and Wolverton 2013; Moore et al. 2017; Tol 2019; Daniel, Litterman, and Wagner 2019).

This article provides a comprehensive review of the economics-based research and an updated review of the public health literature focused on studies carried out within roughly the last five years, along with major studies from earlier years. Table 1 presents a concise summary of the 67 studies reviewed here.

This review does not focus on the mortality effects of other climate-related impacts, such as crime and civil conflicts (e.g., Ranson 2014; Buhaug 2015; Burke, Hsiang, and Miguel 2015; Carleton, Campbell, and Collard 2017; Abel et al. 2019), suicide (Carleton 2017; Burke et al. 2018), vector-borne diseases (e.g., Martens et al. 1995; Campbell-Lendrum et al. 2015; Gaythorpe et al. 2020), or other risks such as malaria, undernutrition, and diarrhoeal disease (Honda et al. 2014).

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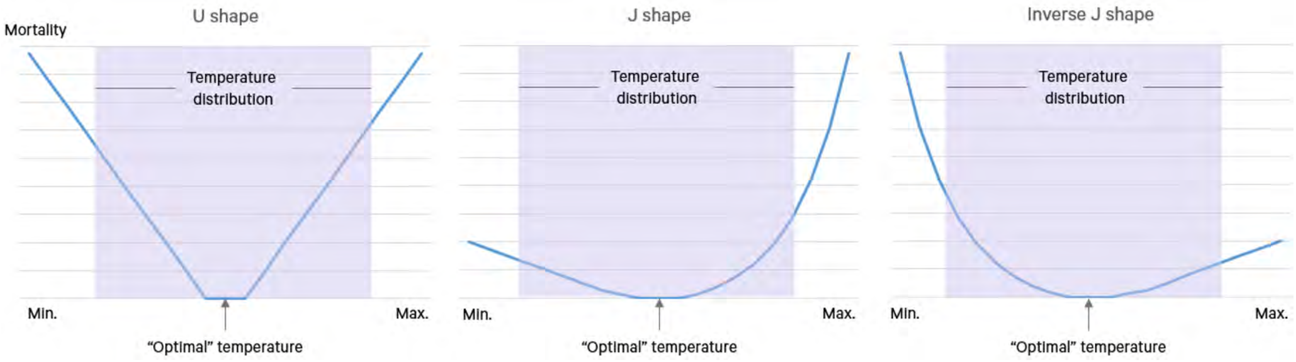
[1] The chapter also reviews other impact pathways that could be affected by climate change, including vector-, food-, and water-borne diseases and impacts on nutrition and occupational health.

1.1. Understanding the temperature–mortality dose–response function

As a changing climate shifts temperatures toward a warmer distribution, the direct effects on human mortality are not straightforward. For example, several studies have estimated that, in regions where data are available (typically high-income northern regions, including the United States and Europe), a larger number of deaths have historically been attributable to cold rather than heat, suggesting that warmer temperatures could reduce net mortality in some regions (Deschênes and Moretti 2009; Hashizume et al. 2009; Guo et al. 2014; Gasparrini et al. 2015).

The net effects of warmer temperatures, therefore, depend in part on the nature of the temperature–mortality relationship, which can be expressed mathematically as a "dose–response function." While all temperature–mortality dose–response functions increase at the extremes of the distribution, their specific shapes have different implications. Figure 1 illustrates the principle. Under the stylized U-shaped function, the mortality effects of cold and heat are equal for moderate changes in temperature. In this simplified example, as temperatures shift from a cooler historical range to a warmer future, decreased mortality from cold offsets increased mortality from heat, resulting in no net change in mortality. For the hypothetical J-shaped function, warmer temperatures will lead to an increase in net mortality. And for an inverted J-shaped function, damages are more severe at the cold end of the temperature range, meaning that a rightward temperature shift reduces net mortality.[2]

Figure 1. Dose–response function shapes



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[2] Note that these stylized examples are simplified and intended for illustrative purposes only. The actual effects will depend crucially on the extent of temperature change, detailed shape of the dose–response function, initial distribution of heat- and cold-related mortality, and other factors.

Early work on this topic (Martens 1998) estimated inverse J-shaped dose–response functions for several nations, resulting in estimates of reduced mortality from climate change, which has informed the SCC through application of the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model (e.g., Tol 1997; Anthoff and Tol 2014).[3] But in recent years, studies have more often found U- or J-shaped functions, as I describe in Section 4.

Importantly, the nature of the temperature-mortality relationship varies across regions. A substantial number of studies find that, absent adaptive measures, J-shaped functions are more common, but U and inverted J shapes are also found in some regions (McMichael et al. 2004; Hajat et al. 2014; Gasparrini et al. 2015; Mills et al. 2015; Schwartz et al. 2015; Bunker et al. 2016; Hsiang et al. 2017; Heutel, Miller, and Molitor 2020). The IPCC concludes that "the increase in heat-related mortality by midcentury will outweigh gains due to fewer cold periods, especially in tropical developing countries with limited adaptive capacities and large exposed populations" (Smith et al. 2014), though this conclusion is not quantitatively described in the report.

Some studies develop different dose-response functions for a single region based on different methodologies. For example, Longden argues that the dose-response function in Australia is more J-shaped, while Gasparrini et al. (2015) and Vicedo-Cabrera et al. (2018) estimate a more U-shaped curve. The studies also differ in their choice of reference temperature (i.e., the median temperature or the mortality-minimizing temperature) and take different statistical approaches to estimate future risk. I do not take a position on which approach is preferable, but note that the methods developed by the research group including Gasparrini et al. (2015) and Vicedo-Cabrera et al. (2018) is the most widely published and widely cited approach that I am aware of.

1.2. Variation across regions and populations

The shape of the temperature–mortality dose–response function can vary between regions due to technological, socioeconomic, and physiological factors,[4] with important implications for how society adapts to a changing climate. A number of studies suggest that, in the United States, northern populations are more susceptible to heat (Curriero et al. 2002; Anderson and Bell 2009, 2010; Heutel, Miller, and Molitor 2020). Similarly, studies with a global focus have found that thresholds for heat-related mortality are higher in warm regions and lower in cold regions (McMichael et al. 2008; Basu 2009; Hajat and Kosatky 2010; Yin et al. 2019).

In addition to technological adaptation strategies, populations can adapt to their

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[3] The FUND, DICE, and PAGE models are the primary tools used by the US government to calculate the SCC. The FUND model is the only one to currently include an explicit accounting of heat- and cold-related mortality. See Appendix A for additional details.

[4] Humans can physiologically adapt to changes in temperature, protecting their health. For example, athletes can improve their performance in high- and cold-temperature settings through heat (Rahimi et al. 2019) and cold (Gordon et al. 2019) acclimatization training, respectively.

surroundings through acclimatization, via changes in physiology and behavior. While such acclimatization can help moderate the effects of hotter temperatures, including extremes, they may not be sufficient to fully negate such changes, especially at higher levels of warming (Hanna and Tait 2015).

Yin et al. (2019) find that the optimal temperatures (the temperature at which excess mortality is lowest, sometimes known as the "mortality-minimizing temperature") vary widely across regions, from as low as 12°C in Greenland to 32°C in parts of the Middle East, suggesting that humans have adapted considerably across regions over time. Of course, socioeconomic conditions also affect the capacity of individuals to cope with heat and cold, and changes in future socioeconomic conditions will affect the ability to adapt by paying for air conditioning or other protective measures.

Along with regional variation, studies find disproportionate risks for certain populations within a given geography. These include small children (including the effects of neonatal exposure), the elderly (Smith et al. 2014; USGCRP 2016), and residents of rural regions (Burgess et al. 2017; Chen et al. 2017). Importantly, the majority of existing evidence comes from wealthier regions and cities, potentially limiting the findings' applicability to lower-income and rural regions.

1.3. Estimating future adaptation to heat and cold

Adaptation can play a major role in reducing the risk of temperature-related mortality, illustrated by considerable reductions in heat-related mortality over time (Arbuthnott et al. 2016). Work examining the United States has shown large declines in heat-related mortality due to the adoption of air conditioning (Barreca et al. 2016) and declines in cold-related mortality due to migration to warmer regions (Deschênes and Moretti 2009). Both adaptation strategies can be effective but require resources, again highlighting the role of wealth and the adaptative capacity it enables.

Although the public health literature recognizes the importance of adaptation (e.g., Ebi et al. 2006; Gosling et al. 2017), few studies from the field attempt to quantitatively account for its future effects under climate change. Instead, most studies apply dose–response functions based on historical data to future temperatures (Deschênes 2014). This is a significant limitation. For example, Barreca et al. (2016) found that the adoption of air conditioning reduced heat-related mortality by 75 percent in the United States during the twentieth century.

Some public health studies attempt to account for future adaptation by applying an "analogue cities" approach. As discussed in Hondula et al. (2015), this approach assumes that as temperatures warm, future cities experience the dose–response function of cities with analogous historical temperatures. For example, if Boston experiences the same climate in 2100 as Atlanta did in 2015, researchers apply the dose–response function from 2015 Atlanta to 2100 Boston. One considerable limitation of this approach as applied in most epidemiological studies is that it does not account for socioeconomic differences, such as age distribution, income, and other factors that vary across cities, which will vary over time as the climate changes.

Other work from the public health literature provides alternative adaptation scenarios: where one scenario assumes zero adaptation, a second assumes 50 percent adaptation, and a third assumes full adaptation (e.g., A. McMichael et al. 2004; Honda et al. 2014; G. B. Anderson et al. 2018). A related approach emerges from Yin et al. (2019), who find that historically, the optimal temperature is roughly equal to the most frequent temperature (MFT) in each region over time. If the optimal temperature continues to equal the MFT in each location in the future, and the shape of the dose–response function does not change (an uncertain prospect), warmer temperatures would have little effect on future mortality. This approach essentially assumes full adaptation over time.

None of these studies, however, attempt to account for the costs of adaptation.[5] One notable study that does so comes from Carleton et al. (2020), who use a method similar to the "analogue cities" approach to estimate future mortality, building upon it by estimating the effects of differences in baseline and future income. To estimate the costs of adaptation, the authors use a revealed preference approach to estimate willingness to pay for protection against heat and cold under warming, and they account for future changes in demographics and income. The authors derive historical dose–response functions in locations with different temperature ranges and rely on the crucial assumption that the private marginal benefits of each individual's adaptive behavior equals or exceeds their private marginal costs (and that this holds true for the future). This assumption can produce plausible cost estimates but may fail to capture certain dynamics, such as individuals not having full information about their risks and benefits, particularly as the climate changes.

1.4. Challenges for comparing research results

Comparing results across studies is challenging for several reasons. First, some studies report the change in relative risk ratios (defined in this case as the probability of mortality for a group exposed to climate change divided by the probability of mortality for that same group prior to changes in climate), and others apply those risk rates to a population, resulting in a point estimate or range of the number of excess deaths. A small number of studies take the additional step of estimating life years lost, and only one study that I identified (McMichael et al. 2004) reports the number of disability-adjusted life years (DALYs) lost. Mortality damages are monetized primarily in the economics literature, but these studies also vary, with some doing so using the value of a statistical life (VSL) and others summing the value of statistical life years (VSLY) lost.

Second, studies take a variety of approaches when describing the dose–response function itself, with two general approaches: some report changes in mortality as a function of absolute temperature change relative to some baseline (e.g., mortality at

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[5] In the context of developing an estimate of the SCC, where multiple dose–response functions are estimated for different types of damages, this is not necessarily a problem. For example, if adaptation costs are accounted for in other damage sectors (e.g., energy use and migration), including them in the "mortality" sector could lead to double-counting them.

0°C or 35°C relative to 20°C). Others report in relative terms (e.g., mortality at the 1st or 99th percentile of the temperature distribution relative to the optimal temperature). In addition, studies report outcomes using different temperature thresholds. While most report changes in mortality relative to the optimal temperature, others report changes relative to the average temperature or an arbitrary threshold, such as 60°F. Studies also vary in terms of their scope of coverage: some include the full distribution of temperatures, some focus exclusively on extremes, and some focus only on heat- or cold-related impacts.

Third, studies vary in their reporting of future impacts of climate change on mortality. Most report changes in mortality risk for a given emissions scenario (e.g., a high warming scenario, such as representative concentration pathway ([RCP] 8.5) relative to a historical baseline (e.g., McMichael et al. 2004; Hajat et al. 2014; Gasparrini et al. 2017). However, many of these studies do not report the levels of warming for these scenarios in terms of the physical climate driver (e.g., degrees Celsius), making it difficult to compare across studies, even when they use the same RCP scenarios.[6]

Finally, as noted earlier, few studies seek to monetize the mortality damages caused by climate change. These studies, carried out mostly by economists, typically do so by multiplying the number of excess deaths by a single VSL or an age-varying VSL. In the context of updating the SCC, this step is less important than in some other sectors (e.g., agriculture or sea level rise) because mortality damages can be monetized relatively simply by using a VSL or other metric within the framework of the Integrated Assessment Models (IAM) used to estimate the SCC.

1.5. Key components of an ideal temperature–mortality dose–response function

As the earlier discussion highlights, numerous challenges exist to developing a temperature-mortality dose–response function for updating the SCC, the ultimate purpose of this review. Here, I highlight several criteria that are particularly important when considering mortality damages:

- Is globally representative. An ideal dose–response function would develop temperature–mortality relationships for all global regions based on empirical methods.
- Accounts for future adaptation. An ideal dose–response function would include estimates for how populations in each region will respond to changing temperatures through technological, behavioral, and physiological pathways. The benefits of adaptation would be reflected in reduced mortality, whereas the costs could be accounted for directly as “mortality” damages or indirectly as damages in other sectors (e.g., additional energy costs).

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[6] Using a single RCP, changes in temperature and population exposure will vary between studies due to different climate and socioeconomic models employed by the researchers.

- Includes full age and socioeconomic distributions. Because heat- and cold-related mortality are more prevalent in some segments of the population (e.g., the elderly), an ideal dose–response function would capture how changing temperatures affect different groups, allowing future damages to reflect changing socioeconomic and demographic conditions.
- Includes the effects of heat and cold. A substantial number of studies have examined the effects of heat waves on human health (e.g., Anderson and Bell 2010) and estimate potential future exposure under a changing climate (e.g., Im, Pal, and Eltahir 2017; Anderson et al. 2018). This work provides important insight into future health risks, but—in isolation—is insufficient to develop a complete dose–response function because it excludes the effects of changes in moderate and cold temperatures.

2. Key methodological approaches

2.1. Epidemiological and economics approaches

There is one notable difference in the empirical approach between the economics and epidemiological literatures. Studies in the epidemiological literature typically estimate dose–response functions by performing linear or log-linear regression to years of data in a single location (such as a city) with mortality as the dependent variable, and independent variables that include daily temperatures, humidity, and air pollution, while controlling for confounding variables, such as day of the week and holidays. The regression is often fit to the daily data using multiple cubic splines, allowing for nonlinear relationships. With this analysis, researchers identify the temperature at which all-cause or cause-specific mortality is lowest (the optimal temperature), then sum the additional deaths resulting from deviations in temperature above and below the optimum.

In the economics literature, researchers tend to use panel data across multiple locations, allowing them to control for additional covariates, particularly city or regional fixed effects that may help explain variation across locations. They also tend to analyze effects by creating "bins" of temperature ranges (such as 0°C–5°C; 5°C–10°C, etc.), then assess the mortality effects of heat or cold relative to the optimum "bin" of temperatures. In addition, recent economics studies have taken a sophisticated approach to estimating the future effects of adaptation, as noted in Section 1.3.

As described by Deschênes (2014), both approaches can yield internally valid results describing the historical temperature–mortality relationship. However, external validity is a concern in the context of long-term climate change unfolding over decades and centuries. Although some studies include future adaptation, these estimates are also highly uncertain because future adaptive behavior could differ considerably from protective measures taken in the past.

Along with empirical studies, I include a selection of reviews to inform our assessments of the literature. A substantial number of literature reviews have recently been produced that survey public health studies, though these papers do not aggregate quantitative results. A number of these reviews include studies from multiple continents (Basu 2009; Huang et al. 2011; Hondula et al. 2015; Arbuthnott et al. 2016; Song et al. 2017), with others focused on specific regions, such as sub-Saharan Africa (Amegah, Rezza, and Jaakkola 2016).

Another crucial methodological element is the application of "process-based" analyses, deploying modeling tools to estimate the future effects of climate change. The most common type in this context are global climate models that simulate future climatic conditions under one or more scenarios. Many studies develop temperature–mortality dose–response functions, then use a process-based climate model to estimate future changes in mortality under these modeled future climates.

I also include all available meta-analyses that have global coverage, include the full age distribution, and incorporate the effects of heat and cold. This review covers 70 studies. Although it is not comprehensive (hundreds of additional studies are plausibly within scope), it captures all studies that—to my knowledge—meet or approach the key criteria outlined in Section 1.5.

Table 1 presents the 70 studies included in this review and indicates the following attributes: Column 1 indicates the author(s) and year of publication; Column 2 describes the geographic coverage; Column 3 describes the population examined (the elderly or all ages); Column 4 describes the temperature range examined (heat/cold/heat waves); Column 5 indicates whether the study estimates the effects of historical and/or future adaptation; Column 6 indicates the years in which data were collected and the years for which climate effects were estimated; and the final column summarizes key results.

3. Studies

Table 1. Studies included in this review

Author/year	Region(s)	Method	Pop.	Temp.	Adaptation?	Period(s) examined	Key results
Ahmadalipour & Moradkhani (2018)	Middle East, Med., most of Africa	Process-based	Elderly (>65)	H	Historical (assumed)	1951–2005, 2006–2100	Compared to historical baseline, relative risk ratio is 3–7 times higher for RCP 4.5 and 8–20 for RCP 8.5 across the region. Greatest effects, but also greatest uncertainty, are found around 12°N in West and Central Africa.
Alahmad (2019)	Kuwait	Empirical	All	H, C	Historical (assumed)	2010–2016	Mortality-minimizing temp. was 34.7C (66th percentile). Relative to this minimum, the relative risk of mortality was 1.65 at the 99th percentile (heat) and 1.67 for the 1st percentile (cold). Both effects were strongest in their first day but persisted for 7 days or more. Accounting for PM2.5 and ozone did not affect results.
Amegah et al. (2016)	Sub-Saharan Africa	Lit. review	Various	H, C	No	Various	n/a
Anderson & Bell (2009)	United States	Empirical	All	H, C, HW	No	1987–2000	Increasing temp. from 90th to 99th percentile of local distribution and from the 10th to 1st percentile increases risk rate by 3.0% and 4.2% respectively. Moving from 60°F to 40°F and 60°F to 80°F increases risk rate by 5.2% and 4.9%, respectively. Wide regional variation.
Anderson & Bell (2010)	United States	Empirical	All	HW	No	1987–2005	Mortality risk increased by 2.49% for every 1°F increase in heat wave intensity (4.39% in the Northeast and 3.22% in the Midwest, lower in South and West) and by 0.38% per additional day of heat wave (2.5% in the Northeast). Impacts were more acute during the first heat wave of each summer.
Anderson et al. (2018)	United States	Empirical, process-based	All	HW	Yes (quantitative)	1981–2005, 2061–2080	From 2061 to 2080 with no adaptation, high-mortality heat waves increase from ~0.25 per year (1981–2005) to 1.8–2.4 per year (RCP 4.5) and 2.2–3.8 per year (RCP 8.5). Human exposure increases from 2 million person-days per year (mpd/y) to 25–53 mpd/y (RCP 4.5) and 46–122 mpd/y. Adaptation can dramatically reduce exposure.
Arbuthnott et al. (2016)	Global	Lit. review	All	H, C, HW	Yes (qualitative)	Various	n/a

Author/year	Region(s)	Method	Pop.	Temp.	Adaptation?	Period(s) examined	Key results
Armstrong et al. (2019)	Global	Empirical	All	H	Historical (assumed)	1972–2015	This study was focused on determining whether humidity levels affected heat-related mortality. For 445 cities in 24 countries, a 23% increase in relative humidity (which is the 99th percentile of anomalies) decreased mortality by 1.1%. But the authors note that this result should be treated with caution, as different lag times produced different results (increased mortality for lag = 0 and decreased for lag = 1–3 days).
Åström et al. (2013)	Sweden	Empirical	All	H, C	Historical (assumed)	1900–1929, 1980–2009	Extreme cold/heat, compared with normal winter/summer days, increased mortality risk by 5.6% and 4.6%, respectively. In the more recent period in Stockholm, there were 31 more cold extremes, leading to 75 lives lost, and 158 more heat extremes, leading to 288 additional lives lost.
Åström et al. (2011)	Global	Lit. review	Elderly	HW	No	Various	n/a
Barreca (2012)	United States	Empirical, process-based	All	H, C	Yes (quantitative)	1973–2000, 2010–2100	Humidity and temperature both contribute to excess mortality. In 2070–2099 under SRES A1FI, without accounting for humidity, mortality rates decline by 0.9%. When accounting for humidity, mortality rates decline by 0.1%, but the result is not statistically different from zero. Net valuation of impact is +$5B per year.
Barreca et al. (2016)	United States	Empirical	All	H, C	Yes (quantitative)	1900–2004	For days of 90°F or higher, each 10% increase in residential AC reduces mortality rate by 0.0021 log points. Mortality effect of days hotter than 80°F has declined by roughly 75%, reducing annual mortality by ~20,000. Almost all of this effect is due to AC adoption. AC adoption increases electricity use by ~11% but results in annual net consumer surplus of $112–$225 per household due to health benefits.
Basu (2009)	Global	Lit. review	All	H	No	Various	n/a
Bunker et al. (2016)	Global	Meta-analysis	Elderly	H, C	No	Various	Effects of a 1°C temperature increase on cardiovascular, respiratory, and cerebrovascular mortality are 3.44%, 3.6%, and 1.4%, respectively. Effects of a 1°C temperature decrease on cardiovascular, respiratory, and cerebrovascular mortality are 1.7%, 2.9%, and 1.1%, respectively.
Burgess et al. (2017)	India, United States	Empirical, process-based	All	H, C	No	1957–2000, 2015–2099	Each day with temperatures above 95°F increases mortality rate in India by 0.7% and in the United States by 0.03%. Impacts in India are driven by rural agricultural regions experiencing heat during the growing season. Access to banking reduces these impacts. For children born in 2075–2099 under SRES A1FI, life expectancy in India and the United States decreases by 10.4 and 2.8 years, respectively.

Author/year	Region(s)	Method	Pop.	Temp.	Adaptation?	Period(s) examined	Key results
Burke et al. (2018)	Mexico, United States	Empirical, process-based	All	H, C	No	1968–2004 (United States), 1990–2010 (Mexico), 2000–2050	A 1°C increase in monthly average temperature increases suicide rates during that month by 0.7% and 2.1% in the United States and Mexico, respectively. Controlling for temporal displacement lowers, but does not eliminate, this increase to 0.4% and 1.0% in the United States and Mexico, respectively. Under RCP 8.5 in 2050, accounting for displacement and assuming recent (1990–2004) US trends of higher suicide rates, the number of suicides would be 14,020 (United States) and 7,460 (Mexico) higher than in year 2000.
Carleton (2017)	India	Empirical	All	H, C	Yes (historical)	1967–2013	For each day during agricultural growing season with a 1°C increase above 20°C, suicide rates increase by 0.008 per 100,000, equivalent to an additional 67 deaths. No effect is found during the nongrowing season. Higher levels of precipitation during growing season increases crop yields and lowers suicide rates.
Carleton et al. (2020)	Global (all countries)	Empirical, process-based	All	H, C	Yes (quantitative)	Varies by country, 1968–2014. Projections to 2100	Each additional day at 35°C (-5°C) relative to a 20°C day raises mortality rates by 0.4 (0.3) deaths per 100,000. Impacts are driven by people age >64, with lower-income populations and those in currently hot regions more vulnerable. Dose–response functions are mostly J-shaped, particularly in cooler regions. Including adaptation under RCPs 4.5 and 8.5 (with SSP 3), mean damages are 0.6% and 3.2% of global GDP by 2100, respectively, with 86% of costs from deaths (rather than adaptation) under RCP 8.5. Results add $17 (IQR: -$25 to +$54) and $37 (-$8 to +$73) per ton to the SCC under RCPs 4.5 and 8.5, respectively.
Cass (2018)	United States	Lit. review	All	H, C	Yes (qualitative)	Various	n/a
Chen et al. (2017)	China (Jiangsu province)	Empirical, process-based	All	H	No	1980–2005, 2011–2070	Assuming no population change in 2041–2065 with 2.0°C and 2.7°C of warming, there would be 7,992 (C.I. 7,542–8,454) and 13,069 (12,265–9,652) additional deaths due to heat-related illnesses each year, respectively. Total population would be 77 million. Impacts are more acute in rural regions.
Cheng et al. (2019)	Global	Lit. review	All	H, C, HW	Historical (assumed)	Various	The authors report that most studies are from high-income regions and that more deaths are attributable to cold than to heat. They note that climate impacts are likely to increase heat-related mortality and decrease cold-related mortality but with substantial uncertainties, particularly regarding adaptation and the shape of the dose–response function.
Ciscar et al. (2011)	Europe	Empirical, process-based	All	H, C	No	Various	Compared with a no climate change scenario and assuming no adaptation with 2.5°C to 5.4°C of warming by 2100, heat-related mortality increases across Europe by 60,000–165,000 and cold-related mortality decreases by 60,000–250,000. For reference, Europe's population in 2016 was roughly 740 million.

Author/year	Region(s)	Method	Pop.	Temp.	Adaptation?	Period(s) examined	Key results
Curriero et al. (2002)	United States	Empirical	All	H, C	Historical (assumed)	1973–1994	Risk of cold- and heat-related mortality increased by 3–7% and 0–7%, respectively, per 1°C below and above optimum local temperature. Effects of heat were more pronounced in northern cities, and effects of cold were more pronounced in southern cities. Age largely explains cold effects, and heat effects are explained by AC use and socioeconomic status.
Deschênes (2014)	Global	Lit. review	All	H, C	Yes (qualitative)	Various	n/a
Deschênes & Greenstone (2011)	United States	Empirical, process-based	All	H, C	Yes (quantitative)	1968–2002, 2015–2099	Each day with temperatures >90°F and <20°F increases annual age-adjusted mortality rate by 0.11% and 0.07–0.08%, respectively. By 2100 under SRES A1FI, climate change increases age-adjusted mortality rate by 3%, though this estimate does not account for long-term adaptation. Combining mortality and energy damages, impacts range from 0.1–0.6% of GDP/year.
Deschênes & Moretti (2009)	United States	Empirical	All	H, C	No	1972–1988	Extreme heat (>80°F) increases immediate mortality but without a long-term increase, due to the "harvesting" effect. Extreme cold (<30°F) increases the long-term daily mortality rate by up to 10%. Population shifts to warmer US regions account for 3–7% of the overall increase in the population's longevity.
Deschênes et al. (2009)	United States	Empirical, process-based	All	H, C	No	1972–1988, 2070–2099	By 2070–2099 under SRES A2, exposure to heat extremes reduces mean birthweight for whites and blacks* by 0.22% (7.5 grams) and 0.36 (11.5 grams), respectively. The likelihood of low birthweight (<2,500 grams) increases by 5.9% for whites and 5.0% for blacks*, respectively. Ninety-five percent of impacts are due to exposure during second and third trimester.
El-Zein et al. (2004)†	Beirut	Empirical	All	H, C	Yes (quantitative)	1997–1999	An annual average increase in 1°C above the optimal temperature (27.5°C) increase heat-related mortality by 12.3% (5.7–19.4%) and reduced cold-related mortality by 2.9% (2–3.7%).
Gasparrini et al. (2015)	Global (13 countries)	Empirical	All	H, C	No	1985–2012	Moderate and extreme cold (heat) is responsible for 7.3% (0.4%) of all deaths. Results vary widely by region, with 10.4% of deaths coming from cold in China and 2.6% in Thailand. Most cold-related deaths were caused by moderate rather than extreme cold. Heat-related-deaths range from 0.2% (Sweden) to 1.6% (Italy).
Gasparrini et al. (2017)	Global (23 countries)	Empirical, process-based	All	H, C	No	1984–2015, 2010–2099	In 2090–2099 relative to 2010–2019 under RCP 2.6, net mortality changes from -0.6% (C America) to +0.4% (SE Asia). Median is 0% change. Under RCP 8.5, net mortality changes from -1.2% (Australia) to +12.7% (SE Asia). Median is 3.0%.

Author/year	Region(s)	Method	Pop.	Temp.	Adaptation?	Period(s) examined	Key results
Gosling et al. (2009)	United States, EU, AUS	Empirical, process-based	Not specified	H	Yes (quantitative)	1961–1990, 2070–2099	Mortality in some regions increases dramatically under climate change due to both increased mean temperatures and enhanced variability. Under SRES A2, mortality increases per 100,000 in Boston (2–140), Budapest (5–68), Dallas (19–126), Lisbon (328–7,310), London (0.3–6.7), and Sydney (2.5–7.4).
Compeán (2013)	Mexico	Empirical	All	H, C	No	1980–2010	One day with temperatures above 30°C increases mortality rate by 0.15% relative to a day at 16–18°C.
Guo et al. (2014)	Global (12 countries)	Empirical	All	H, C	No	Various	At cold extremes (first percent of the temperature distribution), mortality risk ratio increases relative to the optimum temperature by between 10% (Canada) and 35% (Taiwan). At heat extremes (99th percent of the distribution), mortality risk ratio increases by between 6% (Australia) and 30% (Italy).
Guo et al. (2018)	Global (20 countries)	Empirical, process based	All	HW	Yes (hypothetical future)	1984–2015, 1971–2099	The authors examine data from 20 countries to develop dose–response functions from heat waves, then estimate future climate impacts based on multiple scenarios, including an adaptation scenario. Results vary widely across countries, with more severe impacts under high emissions, high population, and no adaptation scenarios.
Hajat & Kosatsky (2010)	Global	Meta-analysis	All	H	No	Various	Hotter regions have higher temperature thresholds above which mortality begins to increase, suggesting some level of adaptation and/or acclimatization. Risk was heightened among for older, less wealthy, and more dense urban populations. Mortality increase due to a 1°C rise above local heat threshold was 0%–19%.
Hajat et al. (2005)	Delhi, São Paulo, London	Empirical	All	H	No	1991–1994	This paper focuses on identifying the "harvesting" effect. With 28 days of lag, the change in net risk per 1°C increase above the local optimum temperatures in Delhi, São Paulo, and London was +2.4%, +0.8%, and -1.6%, respectively. This indicates that the "harvesting" effect was present in London but not in the other two cities.
Hajat et al. (2014)	United Kingdom	Empirical, process-based	All	H, C	No	1993–2006, 2020–2089	Historically and in projections, cold-related deaths outnumber heat-related deaths. However, under SRES A1B in the 2080s, relative to the 2000s, heat-related deaths increase by 10,500 and cold-related deaths increase by 4,900, for a net increase of 5,600 deaths.
Hashizume et al. (2009)	Bangladesh	Empirical	All	H, C	No	1994–2002	Every 1°C decrease in daily mean temperature is associated with a 3.2% increase in all-cause mortality. Below 21°C, a 1°C decrease is associated with a 30% increase in perinatal mortality. No heat effect is identified.

Author/year	Region(s)	Method	Pop.	Temp.	Adaptation?	Period(s) examined	Key results
Heutel et al. (2020)	United States	Empirical, process-based	Elderly	H, C	Yes (quantitative)	1992–2013, 2080–2100	Cool (warm) regions show more susceptibility to hot (cold) days. AC adoption explains reduced effects of heat in warm regions. In 2080–2100 under RCP 8.5, relative to 1992–2013, failure to account for this heterogeneity and likely adaptation changes national results from a +2.15% to a -0.53% change in overall mortality for the elderly.
Honda et al. (2014)	Global	Empirical, process-based	Elderly, all (some nations)	H	Yes (quantitative)	1972–2008, 2030–2050	Compared with 1961–1990 under SRES A1B, global excess mortality in 2050 is 192,000 assuming no adaptation and 124,000 assuming 50% adaptation. Global population in 2050 is ~9.3 billion.
Honda et al. (2014)	Global	Process-based	Elderly	H	Yes (quantitative)	1961-1990, 2030, 2050	Compared with 1961–1990 under SRES A1B, global excess mortality in 2050 is 192,000 assuming no adaptation and 124,000 assuming 50% adaptation. Global population in 2050 is ~9.3 billion.
Hondula et al. (2015)	Global, mostly United States & EU	Lit. review	All	H	Yes (qualitative)	Various	n/a
Huang et al. (2011)	United States	Empirical, process-based	All	H, C	No	1960–2004, 2020–2099	On average, each additional 1°C of warming increases net mortality by 5 to 6 per 100,000 population. Compared with 2010 under RCPs 8.5, 4.5, and 2.6, central estimates in 2080–2099 show annual mortality increases by 10 (C.I. 1–36), 2 (-5–12), and 1 (-4–5) per 100,000. Results vary widely by region, with reduced mortality in the north and increased mortality in the south.
Huang et al. (2011)	Global	Lit. review	All	H	Yes (qualitative)	Various	n/a
Huber et al. (2017)	17 countries	Empirical	All	H, C	No	See Martens (1998)	Mortality damages parameters specified in FUND are critiqued and updated. The authors find 1°C of warming leads to a global net increase in cardiovascular-related mortality of 150,000, unlike existing estimates under FUND, which project a net decrease of 380,000.
Khanjani & Bahrampour (2013)	Iran	Empirical	All	H, C	No	2004–2008	For each 1°C decrease in temperature, respiratory, and cardiovascular mortality increased by 2.5% and 0.6%, respectively.
Khanjani & Bahrampour (2013)	Iran	Empirical	All	H, C	No	2004–2008	For each 1°C decrease in temperature, respiratory, and cardiovascular mortality increased by 2.5% and 0.6%, respectively.

Author/year	Region(s)	Method	Pop.	Temp.	Adaptation?	Period(s) examined	Key results
Lee et al. (2019)	Global (28 countries)	Empirical, process-based	All	H, C	No	1984–2015, 2010–2099	This analysis builds on Gasparrini et al. (2017) and estimates changes in excess mortality under 4 RCPs through 2100. They report results by RCP and also as a function of temperature change (% change in mortality per 1C) and CO2 concentrations (% change in mortality per 100ppm). Results range from an increase in mortality for each 1C increase of 8–10% for the Philippines and Vietnam to a decrease of 0.9 percent in Ireland.
Longden (2018)	Australia	Empirical	All	H, C	Historical (assumed)	2001–2015	This analysis argues that other work (e.g., Gasparrini et al. 2017) has underestimated heat-related risks and overestimated cold-related risks in Australia. It uses data from five large cities and estimates modest effects of cold temperatures and large effects from heat waves, then argues that future excess deaths from heat will likely outweigh future reductions in cold-related mortality.
Longden (2019)	Australia	Empirical	All	H, C	Historical (assumed)	2006–2017	This work uses a method similar to Gasparrini et al. (2017) but incorporates truly national data (rather than data from specific cities) and makes different estimates for different climate zones. A key finding is that the selection of a "reference" temperature (mortality-minimizing temperature) has a large effect on the ultimate estimates of heat- and cold-related mortality.
Ma et al. (2014)	China (17 cities)	Empirical	All	H, C	Historical (assumed)	1996–2008	For each 1°C decrease below the 25th percentile of temperatures, total mortality increases by 1.7% on average. For each 1°C increase above the 75th percentile, total mortality increases by 2.8% on average. Effects vary widely by region, with warm regions more susceptible to cold and vice versa.
Ma et al. (2015)	China (66 communities)	Empirical	All	H, C	Historical (assumed)	2006–2011	On average, relative risk of mortality increases above the mortality-minimizing temperature by 61% and 21% for temperatures in the 1st and 99th percentiles, respectively, of the local distribution. Effects vary widely by region, with warm regions more susceptible to cold and vice versa.
Martens (1998)	Global	Meta-analysis	All, Elderly	H, C	No	Various	With 1.2°C of temperature rise, declines in cold-related mortality outweigh increases in heat-related mortality in most regions. Results range from mortality increase of 3 (Singapore and Venezuela) to decrease of 49 (Hungary) per 100,000 population. Median is decrease of 10 per 100,000 (Argentina).
McMichael (2013)	Global	Lit. review	All	H, C, HW	Yes (qualitative)	Various	n/a
McMichael et al. (2008)	Global (12 global cities)	Empirical	All	H, C	Historical (assumed)	1989–1999	For each 1°C decrease below the local cold threshold, which varies from 15°C to 29°C, mortality changes by -12.8% (Salvador) to +84% (Chiang Mai). Median change is +2.6% (Delhi and São Paulo). For each 1°C increase above the local heat threshold, which varies from 16°C to 31°C, mortality increases by 0.5% (Cape Town) to 19% (Monterrey). Median increase is 3% (Sofia and Ljubljana).

Author/year	Region(s)	Method	Pop.	Temp.	Adaptation?	Period(s) examined	Key results
McMichael et al. (2004)	Global	Meta-analysis	All	H, C	Yes (quantitative)	1961–1990, 2005–2030	By 2030 under an unmitigated climate scenario (IPCC IS92a) with "medium" adaptation, direct heat and cold effects of climate change cause risk ratios to increase in most regions relative to baseline levels, ranging from a decrease of 0.2% (Central Europe) to an increase of 0.7% (India, South Asia, low-income Africa). Median is an increase of 0.3% (Middle East). Without adaptation, range varies from +1.4% to -0.3%.
Mills et al. (2015)	United States	Empirical, process-based	All	H, C	Yes (quantitative)	1980–2009, 2000–2100	Under a Reference case (10 W/m2 in 2100) and a Policy case (3.7W/m2), net heat + cold mortality increases by 7,551 and 433, respectively. This estimate assumes a constant population. Baseline heat + cold mortality in year 2000 is 622. Using the "analogue cities" approach to estimate adaptation, net mortality increases under the Reference and Policy cases by 5,915 and 1,888, respectively.
Nordio et al. (2015)	United States	Empirical	All	H, C	No	1962–2006	Relative to a day of temperature at 15.6°C, risk rate of a day at 27°C ranges from +4% to +14%. From 1962 to 2006, excess mortality from one day at 27°C decreased from 11% to 1%. Little change was observed for cold temperatures.
Paci (2014)	Europe	Empirical, process-based	All	H, HW	Yes (quantitative)	Various	In 2070–2099, aggregate climate-induced mortality from heat, heat waves, and food- and water-borne illnesses increases under a 2°C case and a Reference case by 60,000 and 100,000, respectively. These damages are valued annually at €9 billion (using VSLY) or €124 billion (using VSL) in the 2°C case and €12 billion (VSLY) or €160 billion (VSL).
Pattenden et al. (2003)	Bulgaria, United Kingdom	Empirical	All	H, C	No	1993–1996 (UK), 1996–1999 (Bulgaria)	For each 1°C decrease below the 10th percentile of local temperatures, mortality increased by 1.8% in Bulgaria and 4.2% in the United Kingdom. For each 1°C increase above the 95th percentile of local temperatures, mortality increased by 3.5% in Bulgaria and 1.9% in the United Kingdom.
Patz et al. (2014)	United States	Empirical, Lit. review	All	HW	Not specified	1960–1999, 2045–2065	With 2.8°C of warming, frequency of extreme heat days (>32°C) increases in numerous cities, roughly tripling in New York and Milwaukee. Increased heat also exacerbates ozone levels. Health impacts of these changes are not presented.
Rohat et al. (2019)	Africa (43 countries)	Process-based	All	H	No	1985–2005, 2080–2100	This work estimates urban population growth and future temperature to estimate future exposure to extreme heat. They do not estimate the health effects of exposure. They estimate that by 2100, there will be a 20–52fold increase in the number of person-days exposed to extreme heat. Urban population accounts for a 4–9fold increase in exposure, and temperature effects account for the rest.

Author/year	Region(s)	Method	Pop.	Temp.	Adaptation?	Period(s) examined	Key results
Schwartz et al. (2015)	United States	Empirical, process-based	All	H, C	No	1997–2006, 1990–2100	Under RCP 6.0 in 2100, net mortality increases by 16.1–50.9 per million residents relative to 1997–2006 baseline. Results vary by region, ranging from a decrease of 51 (southern Florida and southern Texas) to an increase of 114 (coastal Northeast) per million residents.
Song et al. (2017)	Global	Lit. review	All	H, C, HW	Not specified	Various	n/a
Staddon et al. (2014)	United Kingdom	Empirical	Elderly	C	No	1950–2011	From 1950 to 1990, cold temperatures (<5°C) increased mortality. But from 1991 to 2011, cold days did not increase mortality due to better housing quality, improved health care, increased incomes, and greater public awareness. Influenza continues to increase winter mortality.
Vardoulakis et al. (2014)	United Kingdom, Australia	Empirical	All	H, C	No	1990–2006	Historically, cold increases mortality by more than an order of magnitude more than heat does. Under SRES A1B in 2080, cold-related mortality decreases in Australia and the United Kingdom by 14 and 19 per 100,000 residents, respectively. Heat-related mortality increases in both countries by 6 per 100,000.
Vicedo-Cabrera et al. (2018)	Global	Empirical, process-based	All	H, C	No	1984–2015, 1990–2100	The difference between increasing temperatures from 1.5°C to 2°C is net mortality increase in most regions, but the results are not statistically significant for most regions. The difference of 1.5°C to 4°C is a greater increase in net mortality, with more regions showing statistically significant results. Warmer regions show consistently higher net mortality impacts, whereas cooler regions often show small increases or even net decreases in mortality.
Watts et al. (2015)	Global	Process-based	Elderly	H, HW	Not specified	1986–2005, 2005–2090	Assuming no demographic changes under RCP 8.5, roughly 800 million more seniors (>65 years) are exposed to heat wave conditions in 2090 relative to 2020. With demographic changes, the number is closer to 3.5 billion. Direct health impacts are not estimated.
Yin et al. (2019)	Global	Meta-analysis, process based	All	H, C	Yes. (quantitative)	2010s, 2050s	The minimum mortality temperature (MMT) is roughly equal to the most frequent temperature (MFT), implying that humans have acclimatized and adapted over time. The authors project future MMTs through 2050 with the assumption that future MMTs will continue to equal future MFTs, implying considerable future adaptation to warmer temperatures.
Yu et al. (2012)	Global, mostly United States and EU	Meta-analysis	Elderly	H, C	No	Various	Increase of 1°C above local heat threshold leads to a 2–5% increase in mortality. Decrease of 1°C below local cold threshold leads to 1–2% increase in mortality.

*This is the term used by the authors.

4. Discussion and synthesis

This section seeks to draw insights from the 70 studies presented in Table 1: 49 with empirical methods to estimate mortality damages due to heat and/or cold, 25 with a process-based modeling approach (typically to project future climate impacts), 11 literature reviews, and 6 meta-analyses.[7]

Because our primary interest is applying study results to inform the SCC, the remainder of this section focuses only on studies that use empirical methods or meta-analyses to estimate dose–response functions and then use process-based modeling tools to project the effects of climate change on heat- and cold-related mortality. I restrict the analysis to studies that describe the net impacts of climate change; that is, I exclude studies that focus only on heat or cold effects (Section 1.5). These restrictions leave us with 17 studies.

4.1. Regional coverage

Because the effects of heat and cold vary widely across regions and populations, it is important to capture differences in regional effects. However, studies have focused more on some regions than others. This is largely the result of data availability, as reliable temperature and mortality data are not available for some nations or regions. Of the 17 studies that I focus on, only three cover every populated continent (A. McMichael et al. 2004; Yin et al. 2019; T. A. Carleton et al. 2020).

The most heavily studied regions are North America (particularly the United States), Europe, and Asia (particularly China and East Asia). Fewer studies directly estimate effects for lower-income regions, particularly Africa or India. This is a substantial limitation because the hundreds of millions of low-income households in these regions will tend to be less able to adapt to a changing climate by, for example, adopting air conditioning or relocating. Table 2 summarizes the regions examined in our 17 studies (note that some studies examine multiple regions).

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[7] The sum exceeds 70 because some studies used multiple methods.

Table 2. Regions examined

Region	Number of studies
Africa	7
Asia	11
Australia	8
Europe	11
Middle East	4
North America	17
South America	10

4.2. Net effects of climate change

Most studies find that climate change will increase heat-related mortality and reduce cold-related mortality, with the net effect of higher temperature-related mortality for most regions. However, results vary considerably across regions, studies, and levels of warming. Figure 2 illustrates these variations, showing the central estimates for number of additional deaths projected under different levels of future warming in four regions across nine studies. The figure shows results from studies that provide adequate data to estimate deaths per 100,000 population in a given region, and in some cases, study authors provided additional information to compute this metric.[8] It emphasizes results from two studies in dark blue (Gasparrini et al. 2017) and green (Vicedo-Cabrera et al. 2018) because, as we discuss in Section 5, these studies are particularly strong candidates for use in updating the SCC.

Although confidence intervals are not shown to enable easier interpretation of central results, it is important to recognize that many of these estimates come with large uncertainty ranges, with 95% confidence intervals for many regions extending into both positive and negative territory.

For context, note that in the United States, the 2019 mortality rate was roughly 147 per 100,000 for all cancers, 37 per 100,000 for all stroke, 30 per 100,000 for Alzheimer disease, and 14 per 100,000 for suicide (Centers for Disease Control and Prevention 2020).

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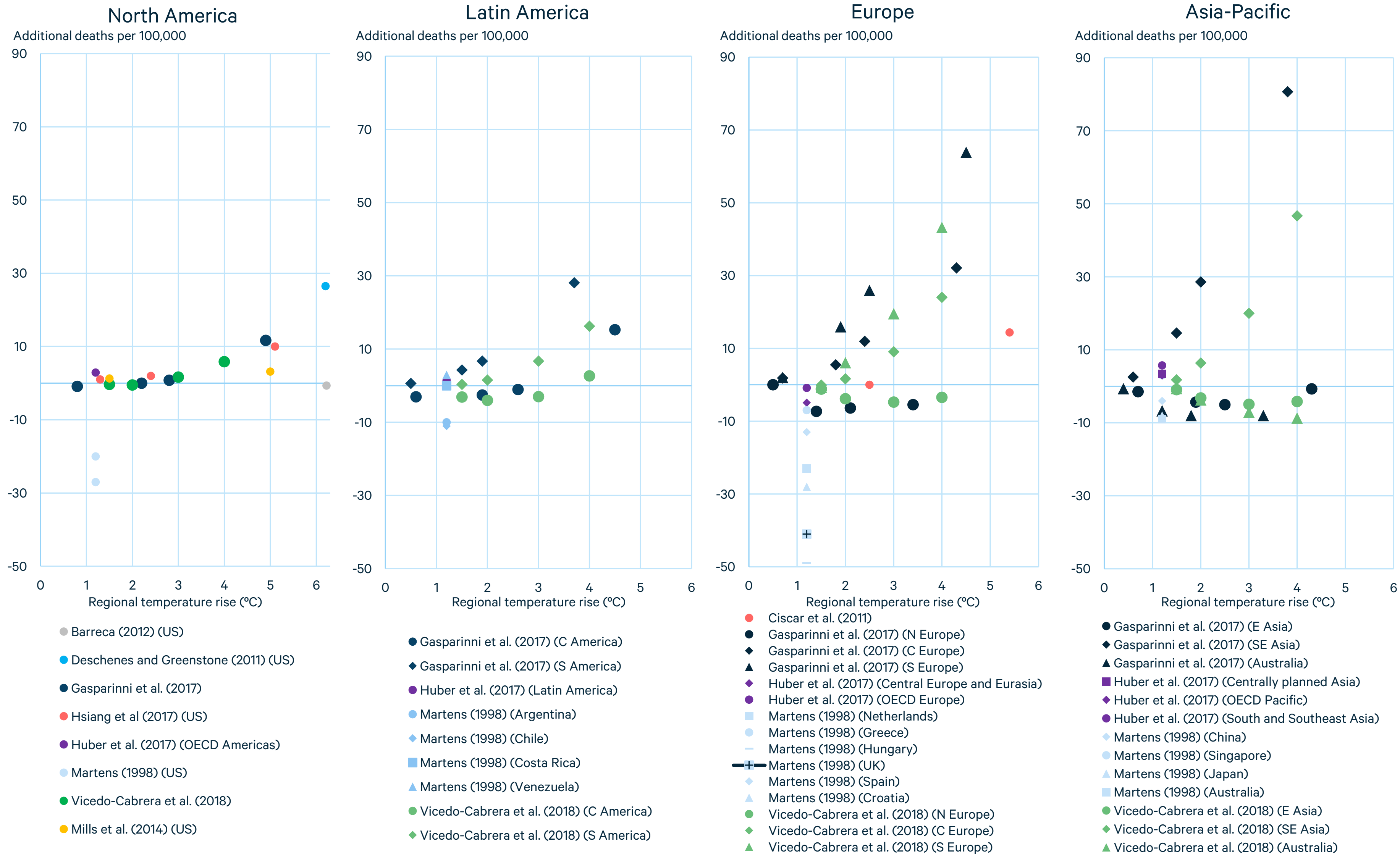
[8] The figure does not plot results from studies that only reported changes in relative risk ratios.

Figure 2. Net effects of climate change on heat- and cold-related mortality (central estimates only)



Note: Dark blue (Gasparrini et al. 2017) and green (Vicedo-Cabrera et al. 2018) markers are larger than others because we focus on these two studies as top candidates for use in updating the SCC.

With some exceptions, higher levels of warming lead to higher excess mortality in all regions. In North America, warming of 1°C to 3°C leads to relatively small changes in net mortality, with central estimates ranging from -1 to +3 additional deaths per 100,000. However, higher levels of warming lead to higher rates of excess mortality in more recent studies. Two notable outliers are Martens (1998) and Barreca (2012), which show decreases in net mortality under low- and high-warming scenarios, respectively.

In Latin America, low- to moderate-warming scenarios are associated with decreases in net mortality in Central America, whereas mortality increases by up to seven additional deaths per 100,000 with 3°C of warming in South America (again, Martens (1998) is an outlier). At warming greater than 3°C, central estimates show net negative effects for all studies across Latin America, reaching as high as 28 additional deaths per 100,000 in South America with 3.7°C of warming.

In Europe, where a relatively large number of studies have examined multiple climatic zones, results vary considerably. As in other regions, Martens (1998) is an outlier, showing large decreases in net mortality for most locations. In Northern Europe, central estimates from other studies agree that warming will reduce net mortality across scenarios. In Central Europe, relatively small mortality effects occur at low levels of warming, but these grow considerably as temperature rises, reaching as high as 32 additional deaths per 100,000 with 4.3°C of warming. The effects are most pronounced in Southern Europe, where central estimates show net mortality increasing by as much as 64 additional deaths per 100,000 with 4.5°C of warming. One Europe-wide study (Ciscar et al. 2011) estimates no net change in mortality with 2.5°C of warming and an increase of 14 per 100,000 at 5.4°C.

Effects also vary widely across different parts of the Asia-Pacific region. In Australia and East Asia (which includes China), central estimates from most studies show declining mortality at all levels of warming, though this trend begins to reverse in East Asia with the highest levels of warming. For example, Gasparinni et al. (2017) estimates a reduction of 5.1 deaths per 100,000 at 2.5°C but a reduction of just 0.7 at 4.3°C in East Asia. By contrast, central estimates from most studies (again with the exception of Martens (1998)) show large increases in mortality in Southeast Asia, with additional mortality of roughly 50–80 additional deaths per 100,000 at roughly 4°C of warming.

Only one study examining Africa, the Middle East, or India reports results in comparable units to the plot in Figure 1. This is Huber et al. (2017), who estimate that 1.2°C of warming would result in 2.7 and 0.5 additional cardiovascular-related deaths per 100,000 in Africa and the Middle East, respectively. Other studies examining these regions report their outcomes in different units but generally indicate that warming will lead to higher net mortality. McMichael (2004) estimates that by 2030, under an unmitigated warming scenario, the mortality risk ratio from cardiovascular disease would increase by 0.7 percent in India, South Asia, and low-income nations in Africa and by 0.3 percent in the Middle East. In India, Burgess et al. (2017) estimate that a high warming scenario would reduce life expectancy by roughly 10 years, driven by impacts in rural agricultural regions. A related working paper from Geruso and Spears (2018) examines infant mortality in low-income countries in Africa, Asia, and Latin America, finding that hot and humid days increase infant mortality in the first month of life by 700 per 100,000 births.

I do not present global results in the figures above because only one study that I am aware of (T. A. Carleton et al. 2020) provides truly global estimates of mortality damages (other studies, such as Gasparrini et al. (2017) and Vicedo-Cabrera et al. (2018), cover many regions but exclude Africa, India, and others). Because Carleton et al. (2020) has not yet been published in a peer-reviewed journal, its full results are not publicly available at the time of writing.

4.3. Key studies with wide geographic coverage

To inform the SCC, it would be useful to identify a single study that satisfied each of the criteria discussed in Section 1.5. In this section, I provide details on the limited number of studies that meet or approach these criteria. Building on the earlier discussion, I focus on studies that (1) apply empirically derived dose–response functions to estimate future climate damages, (2) include the effects of heat and cold, (3) include effects for the full range of population, and (4) have global (or close to global) coverage. Ideally, studies would also account for future adaptation, but because so few studies take this additional step, I do not exclude studies that fail to do so.

4.3.1. Meta-analyses

Despite the large body of literature in this area, a relatively small number of meta-analyses are available and include the information necessary to be applied to an SCC calculation. Some meta-analyses are roughly 20 years old and do not reflect the most current research (e.g., Martens, Jetten, and Focks 1997; Martens 1998), and others focus exclusively on the elderly (e.g., Bunker et al. 2016; Yu et al. 2012).

One wide-ranging meta-analysis (McMichael et al. 2004) produces low, medium, and high estimates on the mortality effects of climate change covering multiple health damages, including direct heat and cold effects, diarrhea, malnutrition, and vector-borne diseases. By including each of these impact pathways and applying them to every global region, this study captures the largest number of potential impacts. The approach applies dose–response functions from studies carried out in specific locations to wide geographic regions based on climatic conditions. For example, it applies one function from Delhi to represent all “hot/dry” regions and one from Amsterdam to represent all “temperate” regions.

Results are reported in terms of changes in risk ratio. In this case, the authors compare the risk of future populations experiencing climate change with a baseline group that experienced climatic conditions from 1961 to 1990. They estimate that the largest increase in risk occurs in Africa, India, and South Asia, which—under a scenario of 1.2°C warming and no adaptation—see increased risks of 1.3%–1.4% by 2030. The Middle East and low-income nations in the Americas see risk ratios grow by 0.7%–0.9% under this scenario, and Europe, Eurasia, East Asia, and high-income nations in the Americas experience no change or a small decrease in risk. For nations that experience increased risk, a “medium” adaptation scenario cuts these risks roughly in half.

Along with cardiovascular risks, the authors estimate the change in mortality risk from other events, including coastal floods, and find substantially higher increase in relative risk from these factors than the direct heat and cold effects that are the focus of this review.

4.3.2. Recent empirical studies

Four recent studies on the temperature-mortality relationship satisfy many of the criteria identified in Section 1.5 for updating the SCC. These studies are of particular interest because they are based on large sample sizes and provide regionally disaggregated results.

Three of these (Gasparrini et al. 2017; Vicedo-Cabrera et al. 2018; Lee et al. 2019) come from a group of researchers known as the Multi-Country Multi-City Collaborative Research Network. The first, from Gasparinni et al. (2017), builds on an earlier analysis from the same group (Gasparrini et al. 2015) that develops location-specific dose–response functions to estimate the historical mortality risk associated with heat and cold across five continents (Africa is not included). Gasparrini et al. (2017) use these dose–response functions to estimate future impacts of heat and cold across 23 countries under RCPs 2.6, 4.5, 6.0, and 8.5 through 2100.

In all regions and for all scenarios, cold-related mortality declines and heat-related mortality grows. However, the net effects vary considerably across regions and scenarios. By 2100 under RCP 2.6, net mortality increases modestly in four regions and decreases modestly in five. But under RCP 8.5, net mortality increases in six out of nine regions, and in some regions, the effects are very large. For example, excess mortality in Central America falls by 0.6% under RCP 2.6 but grows by 3.0% under RCP 8.5. Notably, these projections have considerable uncertainty, with 95% confidence intervals spanning zero for most regions and most scenarios.

The second paper from many of the same authors (Vicedo-Cabrera et al. 2018) uses similar methods and arrives at similar results. The authors estimate changes in excess mortality under GMST rises of 1.5°C, 2°C, 3°C, and 4°C. Again, they find wide variation across regions but conclude that limiting warming to 2°C would likely prevent a large number of additional deaths. At 2°C, central estimates show an increase in excess mortality for just four out of nine regions, whereas at 4°C, excess mortality increases in six out of nine regions, with some regions showing very large increases (see Figure 1). Their comparison of 1.5°C versus 2°C yields more ambiguous results.

Third, Lee et al. (2019) build upon the same data and methods as Gasparrini et al. (2017) to analyze 28 countries under the same four RCPs. Like the previous work, they find that net mortality changes are relatively modest under RCP 2.6 but grow considerably under higher levels of warming, particularly RCP 8.5. They develop three key indexes to describe results: (1) temperature increase per 100 ppm increase in CO_2 concentrations, (2) the percentage change in regional excess mortality per 1°C regional change in temperature, and (3) the percentage change in excess mortality per 100 ppm increase in atmospheric CO2. They report results at the national level and again find considerable variation across locations.

The largest net increases in excess mortality occur in Vietnam (7.6% per 100ppm) and the Philippines (5.7% per 100ppm), along with considerable increases in southern European nations. Several northern European nations, including Estonia and the United Kingdom, along with Australia, experience modest decreases in net mortality (ranging from -0.2% to -0.6% per 100ppm). The authors also explore some potential drivers of these varying effects, finding that higher health expenditures and higher levels of obesity are associated with lower and higher mortality rates, respectively.

For estimating the SCC, these analyses have several shortcomings. First, they do not attempt to account for adaptation. Second, they do not estimate damages for large parts of the world (including India, Africa, and large parts of the Middle East and Eurasia) due to lack of data. Third, much of the data used to develop dose–response functions comes from cities, where effects of heat and cold may differ from rural regions, even when controlling for income and other factors.

Finally, as noted earlier, Carleton et al. (2020) examine the mortality effects of climate change by developing dose–response functions and accounting for adaptation across more than 24,000 regions, the most comprehensive and geospatially resolved analysis identified in this review. The authors gather mortality and climate data from 44 countries, and where data are not available (Africa, Australia, Eurasia, and the Middle East have little to no data), they estimate effects by imputing results from regions with similar climatic and socioeconomic characteristics.

Globally, the authors' mean estimate is an additional 85 death-equivalents (73 deaths and 12 death-equivalents in adaptation costs) per 100,000 under RCP 8.5 and SSP 3 by 2100, with an interquartile range of 16 to 121 (without adaptation, they estimate 221 per 100,000). Under this scenario, mortality and adaptation costs equal roughly 3.2% (IQR: -5.4% to +9.1%) of global GDP using an age-varying VSL. Under RCP 4.5, the effects are considerably lower, with a mean of 14 additional death-equivalents per 100,000 and global damages equivalent to 0.6% of GDP (IQR: -3.9% to +4.6%). These effects are driven predominately by the elderly (aged 64 and up). In these two scenarios, the median result from an ensemble of climate models used by the authors shows GMST temperatures warming by roughly 3.5°C under RCP 8.5 and 1.75°C under RCP 4.5 by the end of the twenty-first century. [9]

Globally, 86% of damages are from increased mortality (14% are adaptation costs) with wide variation: in high-income regions, most costs are reflected in adaptation, whereas in lower-income regions, most costs are due to increased mortality. The most acute damages occur in Central and Northern Africa, the Middle East, and parts of South America, India, and Southeast Asia. With a 2% discount rate, these damages add $37 (IQR: -$8 to +$73) and $17 (-$25 to +$54) to the SCC under RCPs 8.5 and 4.5, respectively. With a 3% discount rate and an age-invariant VSL, these SCC values fall to $22 (-$6 to +$53) and $7 (-$16 to +$32).

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[9] Climate model results and interpretation were provided by the study authors.

5. Discussion

Looking broadly across the available literature, most studies estimate that climate change scenarios with high levels of warming will result in increased mortality in most regions, with the most acute effects in warmer and low-income regions. At the same time, numerous studies estimate that under lower levels of warming, higher income regions in cooler climatic zones will experience modest reductions in mortality.

The studies with the broadest geographical coverage and richest data (Gasparrini et al. 2017; Vicedo-Cabrera et al. 2018; Lee et al. 2019; Carleton et al. 2020) suggest that high levels of warming (i.e., >2°C) will increase net (including both heat- and cold-related) mortality globally. This result is explicitly stated in Carleton et al. (2020), the only analysis that provides truly global estimates and includes the effects of adaptation.

For the other three studies, it is reasonable to infer that global mortality will rise at higher levels of warming for two main reasons. First, the regional increases in excess mortality experienced at higher levels of warming are considerably larger (in absolute value terms) than the mortality declines seen in other regions. For the nine regions examined in Gasparrini et al. (2017) and Vicedo-Cabrera et al. (2018), the highest warming scenario (roughly 4°C GMST) leads to excess mortality of 15 and 7 deaths per 100,000, respectively.[10] At roughly 2°C of warming, the two studies estimate aggregate declines in excess mortality of 0.2 and 1.1 per 100,000, respectively. Second, these estimates exclude some of the regions that may be most negatively affected by a warming climate, particularly Africa, India, and much of the Middle East. These regions are generally warmer and lower income than the global average, with large inland populations, three traits that are associated with higher levels of excess mortality (Lee et al. 2019). In their analysis, Carleton et al. (2020) find some of the highest rates of mortality risk in these three regions.

Another key similarity between recent empirical analyses is that they all report wide ranges of uncertainty. Although their central estimates consistently show an increase in mortality under high levels of warming, they are unable to reject the possibility (using 95% confidence intervals) that climate change could reduce heat- and cold-related mortality in many regions, particularly under scenarios with lower levels of warming. Similarly, these wide confidence intervals indicate that damages could be far higher than the central estimates discussed above.

For the purposes of informing and updating estimates of the SCC, each of these studies could be valuable. As discussed earlier, Carleton et al. (2020) use their results to estimate a "partial" SCC that incorporates mortality damages and adaptation costs. However, to update the SCC in a conventional IAM framework, such as FUND, the

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[10] Lee et al. (2019) do not provide adequate data to estimate excess mortality in per capita terms.

incorporation of adaptation costs could pose challenges.[11] While Carleton et al. (2020) report mortality and adaptation damages in a single valuation (i.e., deaths and death-equivalents), estimating the SCC using FUND requires discrete estimates for damages from changes in mortality and energy use (one important component of adaptation in the Carleton et al. analysis). It would be necessary to disaggregate the results from Carleton et al. (2020) into discrete mortality and energy use damages (or identify another approach to avoid double-counting damages in both the "mortality" and "energy" categories) to apply it to the FUND framework.

Two more important themes emerge across all studies, including the key studies described in Section 4.3. The first is the challenge of estimating truly global damages, particularly for rural regions and large parts of the world, such Africa and the Middle East, where historical data are limited or unavailable. Because these regions, in many cases, may be most at risk due to low incomes and limited capacity for adaptation, it would be valuable to develop dose–response functions based on local data.

Due to these data limitations, researchers have taken several approaches, including (1) not attempting to estimate effects in regions with no data (e.g., Gasparrini et al. 2017; Lee et al. 2019); (2) applying dose–response functions developed in other parts of the world to those regions lacking data, matching the functions based on climatic and/or socioeconomic conditions (e.g., McMichael et al. 2004; Carleton et al. 2020); and (3) applying data collected in urban settings to rural areas (e.g., Martens 1998; Gasparrini et al. 2017).

A second challenge that applies across the literature is accounting for adaptation. As discussed in Section 1.3, some researchers attempt to account for adaptation, with particularly sophisticated treatments provided in recent econometric studies (Carleton et al. 2020; Heutel, Miller, and Molitor 2020). It would be valuable for other studies, particularly those from epidemiological researchers, to apply these or other techniques to estimate the mortality effects of different levels and types of adaptive behavior. In the context of updating the SCC, additional work will also be needed to avoid double-counting by calibrating assumptions about adaptive behavior that are built into IAMs such as FUND.

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[11] As discussed in the Appendix, it is unclear how evolving estimates of climate-mortality damages could be incorporated into other IAMs, such as DICE and PAGE. However, incorporating these estimates into all relevant IAMs will be critical to updating the SCC.

6. Conclusion

This paper reviews the recent literature on the effects of climate change on heat- and cold-related mortality with a focus on identifying studies that can be used to update the SCC. I describe key criteria that are useful to inform the SCC, such as global representation, accounting for future adaptation, and including heat and cold effects and groups across age and socioeconomic backgrounds. I identify studies that appear particularly promising for use in updating the SCC and discuss them in detail. In general terms, most studies estimate that climate change scenarios with high levels of warming will result in increased mortality globally, with the most acute effects in warmer and low-income regions. At the same time, numerous studies estimate that under lower levels of warming, higher-income regions in cooler climatic zones will experience modest reductions in mortality. However, all studies report large uncertainty ranges for future effects, including the possibility that climate-related mortality could be much higher than those shown in central estimates. Major challenges for the literature include estimating damages for parts of the world where data are limited or nonexistent and quantifying the effects of future adaptation.

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Appendix A: How mortality is treated in Integrated Assessment Models

Currently, FUND (Anthoff and Tol 2014) is the only Integrated Assessment Model (IAM) used by the US government to calculate the SCC that includes a specific dose–response function for heat- and cold-related mortality. FUND creates separate categories for cardiovascular and respiratory diseases, vector-borne disease, and diarrhea. While this disaggregation of impacts provides a more granular look at specific pathways, it may be preferable to create a single broader category that describes all mortality associated with changes in temperature (and other physical drivers).

FUND bases its estimates of cardiovascular and respiratory mortality responses to heat and cold on a meta-analysis published in 1998 (W. J. M. Martens 1998). That study employs a V-shaped dose–response function and estimates that, for 1.2°C of warming, most regions experience a net reduction in mortality, with reduced cold-related deaths outweighing an increase in heat-related deaths. However, the study is limited in several ways. First, the relatively low level of warming upon which these estimates are based does not capture nonlinear damages that could occur at higher levels of warming. Second, the underlying data come from a relatively small dataset (20 cities) and only cover urban areas. Huber et al. (2017) describe concerns with the study, particularly the application of mortality data from all ages to the elderly and a lack of control for seasonal effects. Huber et al. reanalyze the data focused solely on cardiovascular disease and find that most regions experience a net increase in mortality with 1.2°C of warming.

As noted earlier, the two other IAMs used by the federal government to estimate the SCC—the Dynamic Integrated Climate-Economy (DICE) and Policy Analysis of the Greenhouse Effect (PAGE) models—employ aggregate damage functions and do not explicitly represent mortality or other specific damage components. Ongoing research seeks to incorporate emerging estimates of the mortality and other effects of climate change into an integrated modeling framework to support updated estimates of the social cost of carbon and other greenhouse gases in accordance with NAS (2017).