Energy Economics 46 (2014) 606–619

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

Temperature, human health, and adaptation: A review of the empirical literature[☆]

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ARTICLE INFO

Article history:
Received 5 December 2012
Received in revised form 30 September 2013
Accepted 18 October 2013
Available online 16 November 2013

JEL classification:
I10
I12
I18
Q40
Q51
Q54

Keywords:
Climate change
Health
Adaptation
Extreme temperatures
Mortality
Air conditioning

ABSTRACT

This paper presents a survey of the empirical literature studying the relationship between health outcomes, temperature, and adaptation to temperature extremes. The objectives of the paper are to highlight the many remaining gaps in the empirical literature and to provide guidelines for improving the current Integrated Assessment Model (IAM) literature that seeks to incorporate human health and adaptation in its framework. I begin by presenting the conceptual and methodological issues associated with the measurement of the effect of temperature extremes on health, and the role of adaptation in possibly muting these effects. The main conclusion that emerges from the literature is that despite the wide variety of data sets and settings most studies find that temperature extremes lead to significant reductions in health, generally measured with excess mortality. Regarding the role of adaptation in mitigating the effects of extreme temperature on health, the available knowledge is limited, in part due to the few real-world data sets on adaptation behaviors. Finally, the paper discusses the implications of the currently available evidence for assessments of potential human health impacts of global climate change.

1. Introduction

The changes in the earth's climate that are predicted to result from greenhouse gas emissions are both varied and complex. As a result, the impact margins of climate change are wide and far-reaching. In particular, climate change is likely to affect human health in a number of ways: through its effect on the disease environment, through changes in the prevalence of extreme and destructive weather events, through changes in the average and the variability of temperature, through droughts, etc. Human health is now recognized as one of the most important impact margins of climate change, and thus is a global research priority (Lancet 2009). A vast literature – almost exclusively in public health and epidemiology – has emerged to document the excess morbidity and mortality associated with exposure to extreme temperatures, as well as the associated risk factors. (See International Panel on Climate Change (IPCC), 2007 and National Institutes of Environmental Health Science (NIEHS), 2010 for reviews.)

A critical aspect in assessing the human health threats posed by climate change is the degree to which 'adaptation' is possible. Adaptation, according to the IPCC, is defined as "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (IPCC, 2007). For the rest of this paper, the practical definition of adaptation will refer to the set of actions that are taken in order to reduce the health impacts of exposure to extreme weather events or changes in climate. [1] As such, adaptation measures can include individual or household-level actions as well as community-level actions. Further, some aspects of adaptation will be possible in the short-run and longer-run (e.g., air-conditioning usage, migration) while others will only be possible in the longer-run (e.g., urban space redesign). [2]

[☆] This paper was prepared for the Integrated Assessment Modeling Conference, May 17–18, 2012, in Cambridge MA. I thank the conference participants for helpful suggestions. Karin Donhowe, Ashwin Rode, and Corey White provided excellent research assistance.

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[1] Physical acclimatization could also be considered as a form of adaptation. However, since acclimatization occurs through medium-term changes in human physiology (i.e. increased physiological tolerance to extreme heat) as opposed to behavioral adaptation (such as air-conditioning usage), it does not fall under the scope of this paper. Nevertheless, if physical adaptation increases heat-tolerance in the population, then it will lead to similar effects as behavioral adaptation in the long-run, i.e. reduce the health impacts of exposure to extreme temperatures.

[2] Short-run forms of adaptation are also called defensive or avoidance behavior in environmental economics literature.

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http://dx.doi.org/10.1016/j.eneco.2013.10.013

The purpose of this paper is to review the existing empirical literature that specifically examines the determinants and effects of adaptation on human health in response to extreme weather and climate events. In order to narrow the scope of the analysis, I focus exclusively on health impacts and adaptation driven by exposure to extreme temperatures. It is important to note that the set of changes to the global climate system unquestionably goes far beyond rising temperatures (i.e. rising sea-levels, droughts, storms). As such, this review only offers a partial survey of the implications of global climate change on human health and adaptation.[3] However, the increased incidence of extreme temperature events and the prospects of increased heat-related morbidity and mortality are by far the most studied outcomes in empirical research.

I begin by presenting the conceptual and methodological issues associated with the measurement of the effect of temperature extremes on health, and the role of adaptation in possibly muting these effects. To proceed, I derive the implications of a simple version of the Becker–Grossman economic model of health production in the presence of 'adaptation'. The model highlights the tradeoff between health production and costly adaptation. A key implication is that in the extreme, it is possible that individuals can fully adapt such that extreme temperatures would have no detectable effects on measured health outcomes. In this case, an analysis that would only focus on the dose–response relationship between health outcomes and temperature would incorrectly conclude that the human health burden of climate change is negligible. An important finding in the review below is that virtually all studies outside of the economic literature do not explicitly model adaptation and so are subject to such incorrect inference.

In terms of methodological issues, the most salient are the measurement of health, temperature exposure, and adaptation, the research design underlying the study, and its external validity. At the conceptual level, the main limitation of the existing literature is that mortality and hospitalizations are the only health outcomes that have been exclusively studied, and so little is known about the potentially large "lower-level" effects of temperature extremes on chronic conditions and quality of life. A second key drawback is that only a handful of possible adaptations have been analyzed in context by the literature, namely energy consumption (or air-conditioning), geographical mobility, and indoor/outdoor time allocation. Finally, the empirical literature is based on research designs that exploit day-to-day or year-to-year fluctuations in daily temperature distributions. Since daily temperatures are determined independently of health conditional on time and location, these studies have generally reasonable degrees of internal validity. Whether or not these studies are externally valid to make projections of impacts due to permanent climate change is clearly more questionable. At the very least, economic theory suggests that these impacts derived from short-run fluctuations in temperatures are likely to overstate the impacts that would result under permanent climate change.

I then present a review of the literature published in economics journals and working papers, as well as in public health and epidemiology. Unfortunately, the lack of uniformity of the modeling of temperature effects across the wide range of studies makes it virtually impossible to convert the estimates into elasticities or other statistics that can be systematically compared across studies. In particular, the public health studies mostly report the estimates through figures, and do not consistently report point estimates and confidence intervals for the temperature–mortality gradients. My review of these studies is thus based on visual inspection of the relevant figures, and the conclusions stated by the authors.

The main points that emerge from this literature review are that despite the wide variety of data sets and settings most studies find that temperature extremes lead to significant reductions in health, generally measured with excess mortality. There is also some evidence of heterogeneity in the response across subpopulations and geographical areas, although that evidence is not as definitive. There is broad evidence of a dynamic relationship between temperature exposure and health, where heat impacts on mortality are more immediate, and to some extent reflect the influence of harvesting or forward displacement. On the other hand, cold temperature exposure leads to mortality impacts that tend to accumulate over time, indicative of delayed effects.

Regarding the role of adaptation in mitigating the effects of extreme temperature on health, the available knowledge is more limited, in part due to the fewer credible and large scale real-world data on measures of adaptation and associated research design. The best evidence available looks at the relationship between residential energy consumption and extreme temperatures and finds a nonlinear relationship where energy consumption increases significantly at the extremes of the temperature distribution. The response of residential energy consumption to extreme heat is four times as large as the mortality response (Deschenes and Greenstone, 2011). This is consistent with the hypothesis that the more muted mortality–temperature relationship is at least partially due to the self-protection provided by the cooling from increased energy consumption. Further, a recent study by Barreca et al. (2013) confirms and substantiates this finding by documenting that the diffusion of residential AC in the U.S. from the mid-1950s to the present substantially reduced the incidence of heat-related mortality in the U.S.

I conclude with a discussion of the remaining gaps in the empirical literature, the implications of the currently available evidence for assessments of the potential human health impacts of global climate change, and by providing guidelines for improving the current Integrated Assessment Model (IAM) literature that seeks to incorporate human health and adaptation in its framework.

2. Economic framework

This section presents a simple one-period Becker–Grossman health production model that highlights the role of adaptation in the context of the health impact of climate change. The presentation follows from Harrington and Portney (1987) and Deschenes and Greenstone (2011). In particular the model shows the important point that the health-related welfare impact of climate change goes beyond what is suggested by the statistical relationship between climate or weather extremes and health when individuals invest resources in adaptation or self-protection. Indeed, the model shows that the correct measurement of the willingness-to-pay (WTP) to avoid climate change requires knowledge of how temperature affects health outcomes like mortality and how it affects self-protection investments that maintain health. More generally, the correct WTP should consider all the monetized health impacts and the value of all self-protection investments caused by the climatic factors likely to change under global climate change.

To proceed, assume that the representative individual derives utility from consuming a single consumption good, X_C (whose price is normalized to 1), and from health, or more precisely from the survival rate S.[4] This can be represented by the following utility function:

$$U = U[X_C, S]. \tag{1}$$

The survival rate depends on ambient temperature T and on the consumption of a health-maintaining market good X_H (with price $= p_H$) that increases the probability of survival. Expenditures in X_H have also been labeled 'defensive' or 'averting' expenditures. Specifically, the production function for survival is expressed as follows:

$$S = S(X_H, T). \tag{2}$$

The consumption of X_H does not directly generate utility, it is only purchased to increase the survival probability and is defined such that

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[3] See IPCC (2007) and NIEHS (2010) for broad surveys of the full spectrum of potential health impacts of climate change.

[4] A more complete model would also include leisure. See Harrington and Portney (1987).

$\partial S/\partial X_H > 0$. For the purpose of this review, 'adaptation' is defined as the process by which individuals change their investments in X_H in response to climate change that operates through a change in T. As such, this variable allows for adaptation to alter the relationship between temperature and health. Temperature is treated as an exogenous variable in this model. In order to keep the exposition simple, we assume that higher temperatures are harmful for health so that $\partial S/\partial T < 0$. In reality, warmer winters can in principle lead to lower mortality rates.

The individual faces the standard budget constraint of the form:

$$X_C + p_H X_H = I, \tag{3}$$

where I is exogenous income. The individual's problem is to choose X_C, and X_H to maximize Eq. (1) subject to Eqs. (2) and (3). The first-order conditions associated with an interior optimum are:

$$\frac{\partial U}{\partial X_C} = \lambda \tag{4}$$

$$\frac{p_H}{\partial S/\partial X_H} = \frac{\partial U/\partial S}{\lambda}. \tag{5}$$

Condition (4) shows that the Lagrange multiplier λ equals the marginal utility of income. Condition (5) shows that purchases of the health-producing good X_H are made until their marginal cost p_H equals the monetized value of the health time it provides. Solving for the first-order conditions yields input demand equations for X_C and X_H that are functions of the exogenous variables prices, income, and temperature. Further, it reveals the indirect utility function, V, which is the maximum utility obtainable given p, I, and T.

The indirect utility function V(p, I, T) can be used to derive an expression for the welfare impact of climate change, holding constant utility (and prices). In particular, consider an increase in T as climate change is predicted to increase temperatures. In this case, it is evident that the consumer must be compensated for changes in T with changes in I when utility is held constant. Denote this function as $I*(T)$. The term $dI*(T) / dT$ is the change in income necessary to hold utility constant for a change in T. In other words, it measures willingness to pay (accept) for a decrease (an increase) in temperatures. In this stylized model that focuses on mortality and temperature alone, $dI*(T) / dT$ is the theoretically correct measure of the health-related welfare impact of climate change.

The challenge to derive this measure is that the indirect utility function is not observable and so we must derive an expression for $dI*(T) / dT$ in terms that can be measured with available data sets. Deschenes and Greenstone (2011) derive a practical expression for $dI*(T) / dT$ when utility depends only on S and X_C:

$$\frac{dI*(T)}{dT} = \left(p_H \frac{\partial X_H^*}{\partial T}\right) - \left(\frac{\partial U/\partial S}{\lambda}\frac{dS}{dT}\right). \tag{6}$$

Eq. (6) shows that the willingness to pay for/accept a change in temperature can be inferred from measured changes in S and X_H. The total derivative of the survival function with respect to temperature (dS / dT), or the dose–response function, is obtained through the estimation of epidemiological-style equations that do not control for X_H. The vast majority of the public health and economics literature reviewed here has used such an approach. The term $(\partial U / \partial S) / \lambda$ is the dollar value of the disutility of a change in the survival rate. This is known as the value of a statistical life (VSL) and empirical estimates are available. The first term is the partial derivative of X_H with respect to temperature multiplied by the price of X_H.

Since temperature increases in this model raise the effective price of survival, the theory predicts that $dS / dT \leq 0$ and $\partial X_H / \partial T \geq 0$. Further, it is possible that there will be a large change in the consumption of X_H (at the expense of consumption of X_C) and little change in S. The key point is that in this model the full welfare effect of the exogenous change in temperature is reflected in changes in the survival rate and in the consumption of the health-preserving good X_H. More generally, this simple model highlights the importance of adaptation in modifying the temperature–health relationship. Studies based on the epidemiological dose–response model alone (i.e. those that do not analyze adaptation as a separate endogenous variable) are likely to understate the health-related social cost of climate change.

It is important to highlight that this simple framework has some limitations. First, by focusing on mortality, it only offers a partial measure of the health-related welfare loss, because climate change may affect other health outcomes (e.g., morbidity rates, chronic disease, quality of life). Further, climate change may induce many forms of adaptation through investments in X_H (e.g., energy expenditures for temperature regulation (i.e. AC), substituting outdoor time for indoor time, geographic mobility).[5] As such, the data requirements to analyze the full set of adaptations are tremendous.

Finally, the simple static model presented here obscures an issue that may be especially relevant given that all empirical studies of the temperature–mortality relationship are based on short-term (i.e. day-to-day) or intermediate-term (i.e. year-to-year) fluctuations in temperature. An important issue that is discussed below is the extent to which studies identified by such fluctuations are externally valid to make meaningful statements about the health effects of permanent climate change. Short- to medium-term adaptations such as purchasing an air conditioner or increasing energy demand to use air conditioning are possible in response to temporary increases in temperature. In the longer-run, it may be possible to engage in other forms of adaptations that cannot be employed in response to seasonal or annual shocks. For example, permanent climate change may lead individuals to improve the heat protection and energy efficiency of their homes or perhaps even to migrate out of regions where the new climate is detrimental to health.

3. Methodological issues

There are several important methodological issues that require attention in assessing studies of the prospective effect of climate change on human health including: (A) What are the health outcomes analyzed? (B) How is exposure to temperature modeled? (C) What is the research design and how does it address the main statistical challenges? (D) What measures of adaptation are considered in the analysis? and (E) What is the external validity of the study regarding the possible impacts of climate change on health?

An important methodological issue that I leave aside for this review for reason of brevity is the dimension of climate or weather that is under study (e.g., change in temperature, precipitation, sea level, storms). As mentioned in the introduction, I will focus exclusively on health impacts and adaptation driven by extreme temperatures, noting that these studies represent the majority of the accumulated knowledge in this research area.

3.1. Health outcomes

The overwhelming majority of studies focus on mortality or hospitalization rates as the health outcome analyzed. All-cause and cause-specific mortality for causes of death that are thought to be impacted by temperature (cardiovascular disease and respiratory disease) are generally the main outcomes, as opposed to mortality directly coded as "heat-related". This is because only a few deaths are directly coded

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[5] Energy consumption may affect utility through other channels in addition to its role in self-protection. For example, high temperatures are uncomfortable. It would be straightforward to add comfort to the utility function and make comfort a function of temperature and energy consumption. In this case the observed change in energy consumption would reflect its role in self-protection and comfort.

on death certificates as being caused by heat. Premature mortality is clearly a key societal health outcome. Nevertheless, the strong focus on these outcomes as opposed to others (e.g., incidence of chronic conditions) also reflects the fact that vital statistics data on age and cause-specific mortality and administrative records from hospital admissions are available from a wide range of countries over relatively long periods of time.

A notable methodological difference exists between the studies in economics and the studies in public health. Economic studies generally estimate models for annual or monthly mortality rates using panel data methods, in particular fixed effects models. These fixed effects are used to control for permanent time-invariant differences in health across geographic areas (and possibly for differences by SES group and location) while also controlling for seasonality and trends in health over time. On the other hand, studies in public health typically are based on models for city-level daily mortality counts. These are analyzed in a Poisson regression framework and also allow for geographical and temporal heterogeneity. An advantage of using annual or monthly panel data on mortality rates is that those typically have greater geographical coverage and a longer time frame than daily-level data sets, which are often limited to a few months or years for a single city. The wider geographical and temporal frame allows for a richer variation in the weather outcomes studied. Further, studies leveraging variation in temperature at the annual or seasonal level are less likely to be confounded by near-term displacement or 'harvesting' than studies relying on daily variation due to the longer exposure window. On the other hand, a strength of the daily-level data approach is that it allows for a detailed characterization of the complicated dynamic relationship between temperature and health, provided a sufficiently rich distributed lag model is used.

Other health outcomes considered include measures of infant neonatal health (see e.g., Deschenes et al., 2009). These are especially important given that exposure to extreme weather events during the perinatal and postnatal periods may lead to significant long-term reductions in health and quality of life. Therefore, the key implication of this is that the available empirical estimates can only characterize a partial measure of the health-related welfare loss, because climate change may affect other health outcomes (e.g., morbidity rates, chronic respiratory conditions, quality of life) and those have not been extensively studied. An important direction for future research is to expand upon these health outcomes.

A key challenge for studies of the impact of extreme temperatures on health that seeks to inform about substantive changes in life expectancy is to develop estimates that are based on the long-term impact of such shocks on life expectancy. This information cannot be obtained from studies that correlate day-to-day changes in temperature with day-to-day changes in mortality in the presence of delayed effects and/or 'harvesting'. "Harvesting" or short-term mortality displacement refers to the temporal advancement of death among persons who are already ill or at high risk of dying. On the other hand, delayed effects refer to the case when the effect of temperature shocks on health takes several days or weeks to manifest themselves. The solution to this problem is to design studies that examine intermediate- and long-term effects, rather than only short-term effects, either through appropriate time aggregation of the data (as in Deschenes and Greenstone, 2011) or through the use of distributed lag models (as in Braga et al., 2001 and Deschenes and Moretti, 2009).[6]

3.2. Temperature exposure

Heat (and cold)-related mortality is the result of excessive temperature-related stress experienced by the human body. The body's heat regulatory function enables us to cope with exposure to high and low temperatures, but this coping increases the stress on many functions, primarily the cardiovascular circulation. Most studies therefore focus on ambient temperature, measuring a single or group of weather stations near cities or county centers, as an indicator of heat stress. This invariably leads to some measurement error since the actual heat stress experienced by the population is not systematically recorded. This is an issue if individuals modify their behavior to change exposure to ambient and if this behavioral response is not measured in the data. However, if the only goal of a study is to inform debates regarding climate change policy (that lead to changes in ambient temperatures), then the ambient temperature is the key predictor of health that should be considered.

The majority of studies focus on daily average temperature, and some also use daily minimum and maximum temperatures to capture differences in daytime and nighttime exposure. Additionally, some studies control for measures of relative humidity or dew temperature, or calculate measures of apparent temperature such as the heat index. Generally, these additional considerations do not lead to meaningful changes in the model estimates (compared to models that only control for temperatures).

The key modeling issue with temperature is the fact that nonlinearities and threshold effects need to be accounted for. Credible studies of the effect of temperature on mortality generally detect significant effects only at the upper and lower extremes of the temperature distribution. Empirically, this is accomplished by modeling temperature through splines, threshold indicators, or temperature-day bins. This latter approach discretizes the daily temperature distribution in a set of ranges or 'bins' and then allows each temperature range (up to a reference category) to have a potentially differential impact on the health outcome. The temperature-day bins approach is used in most economics papers in this literature, whereas in public health the spline approach is most common.

3.3. Research design

For obvious reasons the effect of temperature on human health has not been studied under the protocol of randomized control trials. All studies, both in the economics and public health/epidemiological literatures are based on observational data, generally from vital statistics registries. Nevertheless, due to the unpredictability of weather conditional on time and location, these studies are identified through presumably exogenous shocks to local weather distributions across days or years. As such these are quasi-experimental studies with a reasonable degree of internal validity.

In the public health literature, the standard approach, known as the 'time-series approach,' is to relate daily mortality rates or counts measured across geographic areas (typically at the city level) to the temperature exposure variables. [7] This is done through a Poisson regression model, so the resulting estimates are interpreted in relative risk. The effect of seasonality and other secular time trends are controlled for by including smooth splines in season and time, as well as day of the week indicators. When applicable, models also include covariates to control for other predictors of health, such as ambient pollution. These models are estimated separately by city, and the set of parameters of interest – i.e. the city-specific temperature–mortality gradients – can be averaged across cities using various statistical techniques, for example a hierarchical model.

There are a few differences compared to the approach used in economics. The key difference is that a single set of temperature–mortality gradients is estimated, or at the very least, it is not estimated for each observed geographical area.[8] This allows the inclusion of county or city fixed effects, which can also be included in the 'time-series approach'

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[6] Studies that focus on isolated heat waves are particularly sensitive to the problem of short-term mortality displacement.

[7] The public health/epidemiological literature also reports 'descriptive studies' or 'heat wave studies' which are not reviewed in this paper. These studies focus on mortality (or other measures of health) in isolated heat wave events and compare mortality during the heat wave to baseline mortality for the same city in the years prior to the heat wave.

[8] Some studies also estimate the temperature–mortality gradients by region or census division (e.g., Deschenes and Greenstone, 2011).

used in epidemiology since the constant term from each city-specific regression is equivalent to a city fixed effect. These variables play a key role in the analysis as they absorb all unobserved county- or city-specific-time invariant determinants of the mortality rate. So, for example, differences in the overall healthiness of the local population will not confound the analysis. A second difference is that the influence of seasonality and other time trends is controlled for by year, or year-by-geographic area, and season fixed effects. The inclusion of time fixed effects that vary geographically is also important since they control for time-varying differences that are common within a geographic area and that affect health (e.g., changes in state Medicare policies).

3.4. Measures of adaptation

The broad policy literature (e.g., IPCC, 2007; NIEHS, 2010) strongly emphasizes adaptation and its role in reducing the health impacts of climate change. The words “adaptation” and “adaptive” appear 56 and 96 times in IPCC (2007) and NIEHS (2010), respectively. The reviews list several possible adaptation strategies in response to global warming and increased incidence of extreme temperature events. These can be categorized as household (or individual) level actions, or community (possibly national) level actions as follows:

Household level adaptations:	Community level adaptations:
• Air conditioning	• Early warning systems and other health communication (media, internet, etc.)
• Change in outdoor/indoor time allocation	• Public outreach systems
• Wearing sun-protective clothing	• Establishment of local cooling centers
• Building design	• Fan distribution
• Geographical mobility	• Increased access to quality water

This strong focus on adaptation is explained by the fact that it is likely to be one of the most important components of the global strategy to address climate change in light of the difficulties in reaching a global agreement to reduce the emission of greenhouse gases, especially in the short run. Despite this strong focus little is directly known about the effectiveness of particular adaptation strategies in reducing the health impairments caused by exposure to temperature extremes. Empirical evidence on the ability to adapt to large-scale climate or environmental change remains limited due to the few credible opportunities to combine large scale real-world data on adaptive behaviors with data on health outcomes for long periods of time. One exception is the recent study by Barreca et al. (2013) which is discussed in more detail below.

Studies in public health and epidemiology generally do not directly measure and analyze any of the adaptation strategies listed above. Some studies residually associate reductions over time in heat-related mortality during successive heat waves to better preparation and adaptation (e.g., Fouillet et al., 2008). A few other studies relate city-specific estimates of mortality–temperature gradients to city-level penetration rates of air-conditioning (e.g., Curriero et al., 2002). This literature does not appear to have directly analyzed the relationship between measures of adaptation (say, AC usage) and temperature. Further, it has not examined whether AC usage dampens the relationship between mortality and temperature.

In economics, five of the six papers considered in this review do explicitly analyze the relationship between some form of adaptation (AC/energy consumption, outdoor time use, geographical mobility) and measures of temperature extremes. So the economics literature is more advanced in this area. Nevertheless, these measures of adaptation have generally been analyzed as dependent variables only in models that complement similar models where measures of health are outcomes. The single exception is a recent study by Barreca et al. (2013) that presents the first empirical study of adaptation to extreme temperatures by reporting direct estimates of the protective effect of residential AC on heat-related mortality. The study combines century-long data on U.S. mortality rates (measured at the state-year-month level) with measures of temperatures and AC penetration rates from the U.S. census. As such, the study design allows for regression models that control for the main effect of temperature on mortality and for the interaction effects between the measure of adaptation (residential AC in this case) and temperature, conditional on geographical and time effects.[9]

Despite this progress, more research is needed to further quantify the extent to which any of the adaptations listed in the table above modify the relationship between health and temperature. Acquiring the necessary data files and performing analyses similar to the one in Barreca et al. (2013) is an important goal for future research.

3.5. External validity and projected health impacts of climate change

Are studies based on historical variation in temperature and mortality externally valid to assess the health impacts of global climate change? This is an extremely important question that has received little attention outside of economics. The key problem, as explained in Deschenes and Greenstone (2011), is that all empirical studies are identified by historical variation in temperature, rather than a permanent change in climate. It is an open and debatable question if the estimates of the temperature–mortality relationship estimated from the observed historical variation are externally valid to the new ‘environment’ after permanent climate change.[10]

In the absence of a random assignment of climates across population, there is no research design that can fully address this point. At the very least, economic theory suggests that this approach leads to an overstatement of the projected human health costs of climate change. This is because the set of health-preserving adaptations that are available to respond to a temperature shock that occurs in the short-run are constrained relative to the set of health-preserving adaptations that are likely to be available in the longer-run. One implication of this, it appears, is that studies in economics that leverage year-to-year shocks to temperature distributions are more likely to have a higher degree of external validity than studies in public health that rely primarily on day-to-day shocks to ambient temperature.

A second and related question is what are the predicted impacts of climate change on health, notwithstanding the issue of external validity? Again, few studies outside of economics have tackled this question. This task requires the preparation of data files with predicted changes in the temperature exposure variables (and in any other weather/climate variables included in the statistical models) over various time horizons, at the local level.

To this end, Deschenes and Greenstone (2011) use future climate predictions from the Hadley Centre's 3rd Coupled Ocean–Atmosphere General Circulation Model and from National Center for Atmospheric Research's Community Climate System Model (CCSM) 3. These daily data are available in model-gridded format for the entire United States, and thereby allow the derivation of future climate predictions that vary geographically across areas of the country. Calculating the actual magnitude and the geographical difference in the predicted impacts of climate change on health should be an important component of future research as well.

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[9] It should be noted that while the identification of the main effect of temperature on mortality is based on exogenous monthly shocks to the temperature distribution, identification of the interaction effect relies on non-experimental variation in the measures of adaptation. Thus it is important to rule out possible confounders by including a rich set of geographical and time effects, and by performing specification analysis. See Barreca et al. (2013) for details.

[10] On the other hand, studies directly analyzing the relationship between climate (e.g., the long-run average of temperature and health) are subject to the standard cross-sectional bias. Since climate is time-invariant (at least in periods where health status is comparable), it will be impossible to separately identify the effect of climate on health from the effect of unobserved determinants of health that are correlated with climate. Perhaps for this reason no such study appears in the reviews by IPCC (2007) and NIEHS (2010).

Table 1
Recent studies of health, temperature extremes, and adaptation in economics literature.

Study	Data source and sample	Measure of temperature	Measure of adaptation	Methodology and comments	Main findings
1. Deschenes and Moretti (2009)	1972–1988 daily mortality rate data at U.S. county level, from Multiple Cause of Death Files (NCHS). DV = daily mortality rate.	Indicator variables for days with mean temperature below 30 °F and above 80 °F	Geographical mobility, air-conditioning (interaction of temperature and county-level average AC coverage)	Estimates based on panel fixed effect regression for daily mortality rates. Models include county × year × month fixed effects and up to 30 days in lags.	Heat-related mortality (80 °F) mostly associated with short-term displacement. Cold-related (30 °F) excess mortality larger in magnitude and persistent up to 30 days after temperature event. Geographical mobility from Northeast to Southwest has contributed to increased longevity in the U.S.
2. Deschenes et al. (2009)	1972–1988 daily natality data at U.S. county level, from Natality Detail Files (NCHS). DV = infant birth weight, indicators for low birth weight.	Temperature-day bins (daily mean temperature), by gestational trimester	None	Estimates based on individual-level regression and include controls for maternal characteristics, smooth profile in day of the year, and county × year × race fixed effects.	Exposure to temperature extremes (<25 °F and >85 °F) in utero associated with lower birth weight, especially in the 2nd and 3rd gestational trimesters. Climate change (under predictions from CCSM 3 A2) predicted to increase incidence of low birth weight.
3. Graff-Zivin and Neidell (2010)	2003–2006 American Time Use Surveys (ATUS). DV = time spent inside and outside	Temperature-day bins (daily maximum temperature)	Indoor time use	Estimates based on individual-level regression and include controls for other weather variables, individual characteristics, day of the week fixed effects, year ∗ month fixed effects and county fixed effects.	Time spent indoors significantly increase when maximum temperature exceeds 100 °F or is below 65 °F
4. Deschenes and Greenstone (2011)	1968–2002 annual mortality rate data at U.S. county level, from Compressed Mortality Files (NCHS). DV = annual mortality rate	Temperature-day bins (daily mean temperature)	Residential energy consumption (cooling and heating)	Estimates based on panel fixed effect regression for annual mortality rates. Models include county and state × year fixed effects. Model for residential energy consumption estimated on state ∗ year panel.	Temperature-days above 90 °F and below 40 ° F associated with increased mortality. Temperature-days above 80 °F and below 40 ° F associated with increased residential energy consumption. Residential energy consumption effect proportionally larger than mortality effect. Climate change (under predictions from Hadley 3 A1FI corrected) predicted to increase mortality rate by 3% by end of century.
5. Barreca (2012)	1973–2002 monthly mortality rate data at U.S. county level, from Multiple Cause of Death Files (NCHS). DV = monthly mortality rate	Temperature-day bins (daily mean temperature)	Residential energy consumption (cooling and heating)	Same specification as Deschenes and Greenstone (2011), except mortality data is at county-month level. Only the largest 373 counties are included. Models include also measures of humidity.	Temperature-days above 90 °F associated with increased mortality. High-temperature result unchanged by inclusion of humidity control. Interactions between high temperatures and humidity insignificant. No systematic relationship between residential energy consumption and humidity.
Barreca et al. (2013)	1900–2004 monthly mortality rate data at U.S. state level, from Multiple Cause of Death Files (NCHS) and Published Annual U.S. Vital Statistics (NCHS). DV = log monthly mortality rate	Temperature-day bins (daily mean temperature)	Residential air-conditioning (share of households with residential air conditioning in state)	Estimates based on panel fixed effect regression for state–year–month mortality rates. Models include year × month fixed effects, state × month fixed effects, and state × month quadratic time trends.	The diffusion of residential air-conditioning alone explains close to 90% of the decline in extreme heat's effect (temperature-days above 90 °F) on mortality from 1960 to 2004.

4. Review of the evidence

Tables 1 and 2 summarize the recent empirical studies of the impact of ambient temperature on health. For studies in economics, I derived the set of studies by searching Econlit, the NBER Working Paper Series, and by examining citations in published papers. Book chapters, review articles, and dissertation chapters were excluded. A first key point for this review is that the set of empirical studies in economics that analyze health, temperature, and possibly adaptation is small.[11] Only six articles: Deschenes and Moretti (2009), Deschenes et al. (2009), Graff-Zivin and Neidell (2010), Deschenes and Greenstone (2011), Barreca (2012), and Barreca et al. (2013) fit these requirements.[12] Of those, five articles analyze adaptation measures that include air-conditioning (energy consumption), outdoor time use, and geographical mobility. Barreca et al. (2013) present the only direct evidence on how adaptation (represented by residential AC adoption rates) reduces heat-related mortality.

The literature outside of economics (e.g., public health, epidemiology) is much wider. In order to limit the set of studies included, I derived

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[11] Studies derived from IAM, CGE or calibrated models are excluded.

[12] The Barreca study is very similar to Deschenes and Greenstone (2011). The only difference is that the former includes controls for humidity in the regression models and analyzed monthly mortality as opposed to annual mortality. Both control for precipitations, so the measured effects of cold temperature are not directly due to snowfall.

Table 2
Recent studies of health, temperature extremes, and adaptation in public health/epidemiology literature.

Study	Data source and sample	Measure of temperature	Mention of adaptation in text?	Measure of adaptation	Methodology and comments	Main findings
1. Kalkstein and Greene (1997)	Daily mortality counts from 44 U.S. MSAs, 1964–1990 (NCHS). Age-adjusted mortality count deviated from baseline level	Days with either 'hot and dry' or 'moist tropical' as per Spatial Synoptic Classification	Yes	None	Estimates based on stepwise regression.	Oppressive air masses associated with increased excess mortality. Relationship is stronger in the Eastern U.S. than in the Southern U.S.
2. Chestnut et al. (1998)	Same as Kalkstein and Greene (1997)	Variability in daily minimum summer temperature, days with "moist tropical 1" (MT1) air mass.	Yes	Fraction of houses with AC in MSA (from 1980 census)	Estimation sample is set of 44 MSA-specific excess heat-related mortality estimates from Kalkstein and Greene (1997).	Variability in daily minimum summer temperature and number of days with MT1 air mass associated with higher heat-related mortality even after controlling for across MSA differences in average AC rates.
3. Piver et al. (1999)	Daily records from Tokyo, Japan, for months of July and August, 1980–1995, population aged 65+. DV = hospital emergency transports for heat stroke	Daily maximum temperature, modeled linearly	No	None	Models include up to 4 lags and also control for ambient pollution. Final estimates based on stepwise regression procedure.	Daily maximum temperature and NO_2 are associated with increased hospital emergency transport for heat stroke.
4. Ye et al. (2001)	Same as Piver et al. (1999). DV = hospital emergency transports for CVD and RD	Daily maximum temperature, modeled linearly	No	None	Models include up to 4 lags and also control for ambient pollution. Final estimates based on stepwise regression procedure.	Daily maximum temperature not associated with increased hospital emergency transport for CVD and RD.
5. Braga et al. (2001)	Daily mortality counts from 12 U.S. cities, 1986–1993 (NCHS). DV = mortality count	Daily mean temperature, modeled with splines	Yes	City-level fraction of houses with AC	Estimation based on city-specific Poisson model. Model includes up to 21 days in lags, and controls for season, day of the week, humidity, and barometric pressure	Hot and cold temperature exposure associated with excess mortality. Effect of cold and heat on mortality varies across cities. Cold-related mortality effect persistent. Most of the heat-related mortality caused by harvesting. Variability of summer temperature explains larger share of across-city difference in heat-related mortality than AC.
6. Curriero et al. (2002)	Daily mortality counts for 11 Eastern U.S. cities, 1973–1994 (NCHS). DV = mortality count	Daily mean temperature, modeled with splines	Yes	City-level fraction of houses with AC and heating	Estimation based on city-specific Poisson model. Model includes up to 7 days in lags, and controls for dew point temperature, and smooth polynomial time trend.	Hot and cold temperature exposure associated with excess mortality. Effect of cold and heat on mortality varies across cities. Effect of temperature on mortality strongest in same-day or lags 1–3. High temperature mortality gradient reduced by city-level average AC coverage.
			Yes	None		

Table 2 (*continued*)

Study	Data source and sample	Measure of temperature	Mention of adaptation in text?	Measure of adaptation	Methodology and comments	Main findings
7. Gouveia et al. (2003)	Daily mortality counts from Sao Paulo, Brazil, 1991–1994. DV = mortality count	Daily mean temperature, modeled with splines			Data available at city district level. Estimates based on SES-specific Poisson model. Model includes up to 21 days in lags, and controls for ambient pollution, humidity, day of the week, and smooth polynomial time trend.	Hot and cold temperature exposure associated with excess mortality. No differences in mortality effects by socioeconomic status.
8. Ebi et al. (2004)	Hospital admission records from three California 'regions' (Los Angeles, San Francisco, Sacramento), for age 55+ persons, 1983–1998. DV = hospitalizations for various heart diseases (AMI, stroke, etc.)	Relative daily temperature, precipitation, extreme heat days, El Nino events	Yes	None	Estimation based on Poisson model. Model includes up to 7 days in lags, and linear time trend.	3 °C increase in maximum temperature or 3 °C decrease in minimum temperature increased hospitalizations for age 70+ population in San Francisco and Sacramento. No significant effect for Los Angeles.
9. Schwartz et al. (2004)	Daily hospital admission records from 12 U.S. cities, 1986–1994 (Medicare patients, from HCFA). DV = hospitalizations for CVD for age 65+ population	Daily mean temperature, modeled with polynomials	Yes	None	Estimation based on city-specific Poisson model. Model includes up to 21 days in lags, and controls for season, day of the week, humidity, and barometric pressure	Hospital admissions increased monotonically with temperature. Effects similar across cities. Effect of high temperature on hospital admissions driven primarily by short-term displacement ('harvesting'). No effect of humidity.
10. Hajat et al. (2005)	Daily counts of all-cause mortality from Delhi, Sao Paulo, and London, for 1991–1994, by age group. DV = mortality count	Daily mean temperature, modeled with splines	No	None	Estimation based on city-specific Poisson model. Model includes up to 34 days in lags, and controls for season, relative humidity, rainfall, ambient air pollution, day of the week, public holidays, and smooth polynomial time trend.	Temperatures greater than 20 °C associated with excess mortality in each city. Largest effect in Delhi, smallest in London. In Delhi, excess mortality detected 3 weeks after exposure. In London excess mortality offset after 2 days.
11. Hajat et al. (2006)	Daily counts of all-age mortality in London (1976–2003), Budapest (1970–2000) and Milan (1985–2002). DV = mortality count	Daily mean temperature with threshold (temperature above threshold modeled linearly or with splines). Also include "heat wave" indicators for sequences of temperature-days at	No	None	Models fitted only to observations from June to September. Estimation based on city-specific Poisson model. Model includes up to 2 days in lags, and controls for season, day of the year, humidity, and ambient pollution.	Controlling for daily temperature, "heat wave" indicators raise daily mortality by additional 5.5–12.5%. Effects smaller in distributed lag and nonlinear models. Heat wave effect small relative to

(*continued on next page*)

the set of empirical studies by examining the citation in two prominent and broad policy surveys: A Human Health Perspective on Climate Change (NIEHS, 2010), and the chapter 'Human Health' in Climate Change 2007 (IPCC, 2007).[13] Further, I also examine the citations in the papers listed in IPCC (2007) and NIEHS (2010). Based on this, there are 14 studies to be reviewed. These selected studies are among the most cited in this area and representative of the research conducted. Nevertheless, it is possible that important studies are ignored by this selection approach. For the rest of this review I will refer to these studies as the "public health" studies.

4.1. Cold and heat-related mortality

Although the studies use a variety of data sets, time periods, populations, temperature exposure variables, control variables, and statistical

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[13] Studies that do not include an empirical analysis such as review articles and studies that only include data tabulations are excluded.

Table 2 (*continued*)

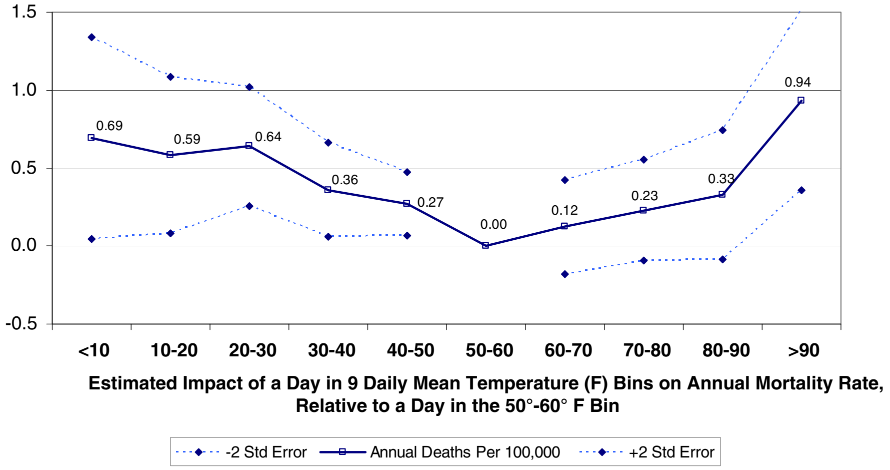
Study	Data source and sample	Measure of temperature	Mention of adaptation in text?	Measure of adaptation	Methodology and comments	Main findings
		or above 98th or 99th percentile				excess summer mortality.
12. Morabito et al. (2005)	Hospital discharge data from large hospital in Florence, Italy, 1998–2002. DV = hospital admissions for AMI	Daily mean temperature. Various biometeorological indices for apparent temperature	No	None	Models estimated by linear regression.	Strong association between cold ambient temperature and hospital admissions. No association with high ambient temperature. At least 9 h per day of severely hot weather (based on apparent temperature) leads to increase in admissions.
13. Barnett (2007)	Daily CVD mortality counts for 107 U.S. cities, 1987–2000 (National Morbidity and Mortality Air Pollution Study). DV = CVD mortality count	Daily mean temperature	Yes	None	Models estimated by city-specific random effect regression and then averaged to single estimate using Bayesian hierarchical model. Models also control for dew temperature and day of the week indicators.	Excess summer CVD mortality due to high temperature disappears between 1987 and 2000.
14. Fouillet et al. (2008)	Mortality records from France, 1975–2006 (only for June 1–Sept. 30). DV = mortality count	Daily minimum and maximum temperatures, modeled with interactions and cumulative maximum temperature	Yes	None	Estimates based on Poisson model that includes seasonal controls.	Observed mortality during the 2006 heat wave 32% smaller than predicted mortality based on model fitted to 1975–2003 data. This is attributed to better preparation and adaptation after the 2003 heat wave.

models, most do find that temperature extremes lead to significant reductions in health, generally measured with excess mortality. This point is illustrated in Fig. 1 that is taken from Deschenes and Greenstone (2011). It shows the temperature–mortality response function estimated from daily temperature and annual county-level mortality data for the U.S. between 1968 and 2002. The key finding is that days with mean temperature above 90 °F and below 40 °F are associated with statistically significant increases in the annual mortality rate in the U.S. The estimates indicate that each day where the average temperature exceeds 90 °F leads to an increase in the annual mortality rate by 0.1%, while days where the average temperature lies between 80 °F and 90 °F do not lead to significant changes in the mortality rate. It is also evident that cold-related mortality is important, at least in the United States. Days where the average temperature is below 40 °F are associated with excess mortality, although the magnitude is smaller than the heat-related excess mortality of the >90 °F days. This suggests that the overall impact of climate change that leads to a right shift in the daily temperature distribution is a priori ambiguous, as it might lead to a reduction in cold-related mortality and an increase in heat-related mortality. Barreca et al. (2013) report similar estimated temperature–mortality relationships. Notably, this relationship is significantly more pronounced in the first part of the 20th century (i.e. prior to 1960).

The differences in the estimated effect of temperature on mortality across the temperature distribution suggest that the relationship is indeed nonlinear. Importantly, most of the reviewed studies use a statistical model that allows for nonlinear relationships or threshold effects. Unfortunately, the lack of uniformity of the modeling of temperature effects across the wide range studies makes it virtually impossible to convert the estimates into elasticities or other statistics that can be compared across studies. In addition, the public health studies mostly report the estimates through figures, and do not consistently report point estimates and confidence intervals for the temperature gradients. As such it is difficult to interpret the estimates beyond the textual summaries provided in these papers.

Some other results on the effect of temperature on health are worth emphasizing. Not all causes of death are equally impacted by temperature fluctuations. Cardiovascular and respiratory diseases are two causes whose risk is elevated by cold and heat exposure, while neoplasms are not. Not surprisingly, the impact of temperature on health and mortality varies across the age distribution, with the older population (e.g., 65+ or 75+) being the groups with the greatest risk. Many studies have also examined whether the relationship between temperatures and mortality varies geographically. Such variation could reflect differences in acclimatization, as the population that is least exposed to high temperatures may be more likely to be impacted by heat waves and extreme events. Similarly, differences in housing stocks' abilities to face extreme temperatures by having central AC, as well as differences in SES and state-level public health preparation, may also explain why the effect of temperature on mortality could vary across geography or climatic baselines.

The evidence is generally suggestive of geographical differences in the effect of high temperatures on mortality. However, the areas where the mortality impacts are more pronounced tend to differ. For example, Deschenes and Greenstone (2011) and Barreca (2012) find that the responses are the highest in the South Atlantic and East South Central divisions, whereas Curriero et al. (2002) conclude that colder temperatures have larger effects on mortality risk in southern cities and warmer temperatures have larger effects on mortality risk in northern



Notes: Takenfrom Deschenes and Greenstone (2011). Figure 1 plots the aggregate response function between annual mortality rate (per 100,000) and average daily temperatures, based on a sample of 107,590 county-year observations. The response function is normalized with the 50°-60° F category set equal to zero soeach of the 9 estimated coefficients corresponds to the estimated impact of an additional day in bin j on the annual age-adjusted mortality rate (i.e.,deaths per 100,000) relative to the mortality rate associated with a day where the temperature is between 50°-60° F. The figure also shows the 95% confidence interval.

Fig. 1. Estimated relationship between annual age-adjusted mortality rate per 100,000 and average daily temperature in the United States, 1968–2002. Notes: Taken from Deschenes and Greenstone (2011). This figure plots the aggregate response function between annual mortality rate (per 100,000) and average daily temperatures, based on a sample of 107,590 county-year observations. The response function is normalized with the 50°–60 °F category set equal to zero so each of the 9 estimated coefficients corresponds to the estimated impact of an additional day in bin j on the annual age-adjusted mortality rate (i.e., deaths per 100,000) relative to the mortality rate associated with a day where the temperature is between 50° and 60 °F. The figure also shows the 95% confidence interval.

cities. The paper fails to report standard errors so it is impossible to assess the significance of such a finding.[14] Deschenes and Greenstone (2011) try to test whether the difference in response functions across divisions is due to better heat-(cold) related adaptation in warmer (colder) places. These tests, based on U.S. census division specific estimates of the temperature–mortality relationship (which contain just nine data points per temperature bin), fail to produce empirical support for the hypothesis that differential adaptation to hot and cold temperatures explains the differences across divisions in the effects of hot and cold temperatures. This sort of hypothesis should be investigated more thoroughly in future research.

Other possible sources of heterogeneity in the temperature–mortality response include differences across age groups and sex. Deschenes and Greenstone (2011) report estimates of heat-related mortality that grow in magnitude with age along with the overall mortality rate. As a result, impacts in proportion to overall mortality are similar across age groups. Nevertheless, it is generally believed that the elderly and infants are the most vulnerable age groups due to their reduced capacity for physiological heat regulation function. Similarly, individuals from lower socioeconomic groups and those with prior histories of cardiovascular disease are also thought to be more at risk for heat-related mortality. Deschenes and Greenstone (2011) also report estimated temperature–mortality effects that are similar for males and females. Ebi et al. (2004) also examine male–female difference in the effect of temperature on hospital admissions in California. It is impossible to assess the male–female differential effect with the information reported in the paper.

Another important concern is the possibility of bias in the estimates of the temperature–mortality relationship due to the exclusion of confounders such as ambient pollution or humidity. Adding controls for humidity or dew temperature in order to better approximate apparent temperature generally does not lead to meaningful changes in the effect of heat on mortality, but does reduce the measured effect of cold temperature (Barreca, 2012). Studies in public health have also investigated whether ambient pollution modifies the temperature–mortality relationship. This is important because the concentrations of some pollutants are strongly associated with temperature (e.g., ground-level ozone). The literature has not reached a definitive conclusion on whether failure to control for ambient pollution confounds the temperature–mortality relationship.

Finally, it is important to consider whether the received evidence is robust to the harvesting and other dynamic effects that were discussed in Section 3.1 (Health outcomes). Indeed, most of the reviewed studies allow for a dynamic relationship between temperature and mortality. Studies based on daily data tend to address the issue by including distributed lags in temperature and computing cumulative effects (e.g., Curriero et al. (2002), Deschenes and Moretti (2009)). Studies based on monthly or annual data instead focus on time-aggregating the daily temperature data in a manner that allows for sufficient post temperature shock mean-reversion thereby reducing concerns about near term displacement (e.g., Barreca et al., 2013, Deschenes and Greenstone, 2011).

Regarding the dynamic relationship between temperature and mortality, the key finding throughout the literature is that extreme heat is associated with some mortality displacement in that contemporaneous (or “day 0”) impacts are larger than cumulative impacts that account for exposure over periods of days or weeks prior to the mortality event. In other words, heat effects on mortality are more immediate, and to some extent reflect the influence of harvesting or forward displacement. In the case of cold temperature exposure, mortality impacts tend to accumulate over time, at least for certain causes of death, indicative of delayed effects (see e.g., Braga et al., 2001 and Deschenes and Moretti, 2009). The implication of both results is that the substantive long-term impact of a given day's temperature on longevity may take several days before it impacts observable health.

Hajat et al. (2005) also report differences in the estimated displacement effect of high temperature on mortality across countries (India, Hungary, England). Impacts of high temperature shocks in Delhi, India on mortality last for up to four weeks, whereas in London, England, the impact disappears after two days. Interestingly, the contemporaneous effect (i.e. the lag 0 effect) for all three countries falls within the same confidence interval. An important component of future research is to better ascertain the differences in the temperature–mortality

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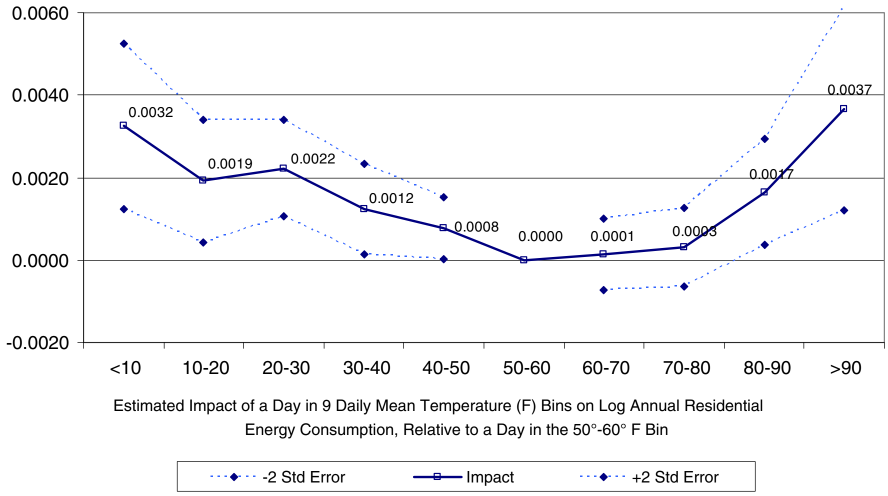
[14] Deschenes and Greenstone (2011) find that the effect of 90 °F + temperature-days is the largest in the New England division, however, the estimate is statistically insignificant (p-value = 0.24).



Notes: Taken from Deschenes and Greenstone (2011). Figure 2 plots the estimated response function between log annual residential energy consumption and daily mean temperatures, based on a sample of 1, 715 state-year observations. The response function is normalized with the 50°-60°F category so each of the 9 estimated coefficients corresponds to the estimated impact of an additional day in bin j on residential QBTU relative to the log residential energy QBTU associated with a day where the temperature is between 50°-60° F. The figure also shows the 95% confidence interval.

Fig. 2. Estimated relationship between log residential energy consumption and average daily temperature, 1968–2002. Notes: Taken from Deschenes and Greenstone (2011). This figure plots the estimated response function between log annual residential energy consumption and daily mean temperatures, based on a sample of 1715 state-year observations. The response function is normalized with the 50°–60 °F category so each of the 9 estimated coefficients corresponds to the estimated impact of an additional day in bin j on residential QBTU relative to the log residential energy QBTU associated with a day where the temperature is between 50° and 60 °F. The figure also shows the 95% confidence interval.

response across countries, especially the difference between developed and less developed countries as well as differences within countries (e.g. rural vs. urban).

4.2. Adaptation

Most studies in public health do not directly measure and analyze adaptive behaviors in response to temperature extremes, although some do consider adaptation as a residual explanation for changes observed in mortality effects over time (see Table 2). In contrast, five out of the six recent studies published in economics journals and working papers include adaptation measures as part of their empirical analysis (see Table 1).[15] Air-conditioning is the form of adaptation to climate change that is by far the most cited in both the broad policy and academic literatures. The reasons behind this are obvious since air-conditioning can regulate ambient indoor temperatures and lower the heat stress imposed on the human thermoregulatory function. One issue with studying air-conditioning, however, is that data on air-conditioning usage is not available in any large-scale survey. Moreover, information on air-conditioning ownership is limited to decadal information in the U.S. Census of Population and in the smaller scale American Housing Survey, which is conducted every six years and difficult to link to county-level measures of health in a systematic way.

Instead of focusing directly on air-conditioning and its potential effect on reducing heat-related mortality, Deschenes and Greenstone (2011) and Barreca (2012) rely on residential energy consumption. Data on annual residential energy consumption is available from the EIA since at least the late 1960s and so it can be used in a rich panel data analysis.[16] In addition, residential energy consumption has the advantage of embodying the adaptive actions taken in response to extreme cold and extreme heat. As a result it is straightforward to use a temperature-residential energy consumption response function to assess the impact of climate change on this form of adaptation.

Deschenes and Greenstone (2011) find a nonlinear relationship between annual energy consumption and daily temperature, where energy consumption is elevated in response to temperature-days at the two extremes of the distribution. This is illustrated in Fig. 2 which shows the temperature-residential energy consumption response function estimated from daily temperature and annual state-level energy consumption data for the U.S. between 1968 and 2002. Another important finding is that the residential energy consumption response curve is more pronounced than the mortality response curve: for example, each additional temperature-day exceeding 90 °F increase annual energy consumption by 0.4%, relative to the baseline temperature-day. The corresponding impact in Fig. 1 for annual mortality is 0.1%, so the residential energy response to this given temperature shock is four times as large as the mortality response.

Even though the data sets available in Deschenes and Greenstone (2011) do not allow us to directly test the hypothesis that access to ambient temperature regulation contributed to reduce heat and cold-related mortality, it seems plausible to conclude that the weaker temperature–mortality relationship is at least partially due to the self-protection provided by the cooling from increased energy consumption.

Barecca et al. (2013) present the first empirical study to directly measure the protecting effect of air conditioning on health. Specifically they estimate panel data models for mortality rates and temperature bins (as in Deschenes and Greenstone, 2011) where the temperature bins enter as main effects, and also through an interaction with the AC ownership rate at the state-year level for 1960–2004. The results indicate that the diffusion of residential air conditioning significantly contributed to the dramatic reduction in heat-related mortality over 1960–2004, while having (as expected) no effect on the incidence of cold-related mortality. The calculations provided by the authors suggest that the diffusion of residential AC alone explains close to 90% of the decline in extreme heat's

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[15] A related literature in economics is the literature studying avoidance behavior in response to air pollution. See e.g., Neidell (2009), and Graff-Zivin and Neidell (2009).

[16] An excellent study of the effect of temperature extremes on residential energy consumption is Auffhammer and Aroonruengsawat (2011). They relate rich household-level electricity billing data to temperature-day bins by climatic region for the entire state of California and find important heterogeneity in the response function across climate zones.

effect on mortality during the twentieth century.[17] Further, the protective effects of AC appear to have been more pronounced among infants and the 65+ population, two of the groups most sensitive to extreme temperatures.

Graff-Zivin and Neidell (2010) present the best study of time allocation responses to extreme temperatures. They use data from the American Time Use Survey (ATUS) for 2003–2008 and examine the response of time spent indoors/outdoors to exposure to extreme temperatures. The models are based on individual-level data and include year-month and county fixed effects so the identification is driven by variation in temperature over time within counties and within seasons.

The main finding that is relevant for this review is that time spent indoors significantly increases when maximum daily temperatures exceeds 100 °F or are below 65 °F. The magnitude of the increase in indoor time in response to extreme heat is non-negligible: it corresponds to about 2% of the average time spent indoors in their sample. While the Graff-Zivin and Neidell analysis does not inform the human health impact of climate change directly, it makes two key points. First, individuals do change their behavior in response to exposure to temperature extremes, for comfort or health reasons. The Becker–Grossman model in Section 2 predicts that any cost in terms of lost utility from shifting time spent outdoors to indoors must be compensated by an equal or larger utility from increased health or comfort. Second, the magnitude of the adjustment documented is large enough to expect that it might lead to significant improvements in health in a future that includes the extensive warming predicted by most GCMs.

Finally, Deschenes and Moretti (2009) consider geographical mobility as an adaptive response to exposure to temperature extremes. Using daily U.S. vital statistics for 1972–1988, they find that cold temperature spells lead to significant and large increases in mortality, especially for the 65+ population. The predicted extent of cold-related mortality is larger than heat-related mortality. They also test whether mobility decisions of individuals are correlated with the health benefits associated with avoiding extreme cold. The main finding of this analysis is that the probability of moving to a state with a warmer climate is higher for the age groups that are predicted to benefit more in terms of lower mortality compared to the age groups that are predicted to benefit less.[18] While this analysis suggests that health considerations are taken into account for mobility decisions, it is based only on the response to the lower segment of the temperature distribution. As global average temperatures continue to rise, it remains to be seen if the reverse migration pattern from the Southwest to the Northeast will emerge.

4.3. Climate change impact predictions

Once an estimate of the temperature–mortality (or health) relationship is obtained the question becomes what to make of that information? There is a marked difference between the public health and economics literature in that regard. The literature in public health — epidemiology primarily uses this information for broad public health recommendations such as the creation or evaluation of early warning systems and outreach systems. However, these papers generally provide little detail about the implications of their results for predicting the health impacts of climate change.

In contrast, several papers in economics (Deschenes and Greenstone, 2011, Deschenes et al., 2009, Barreca, 2012) combine the estimated temperature–mortality relationships with end-of-century (i.e., 2070–2099) daily climate change predictions from state of the art climate models and “business-as-usual” scenarios. Under a series of assumptions, this allows the calculation of partial estimates of the health-related social costs of climate change. These are partial estimates because mortality rates are the only health outcome analyzed in these studies. As mentioned in the introduction, the health impacts of climate change are likely to be significantly broader. To date, these calculations have been produced only for the United States, although work in progress by Burgess et al. (2011) is implementing a similar approach for India. Clearly more work is needed to empirically assess the likely impacts of climate change on health in other countries.

The predictions in Deschenes and Greenstone (2011), based on the error-corrected Hadley 3 A1FI climate model and scenario, suggest that climate change will lead to approximately 63,000 additional deaths annually in the United States at the end of the century, or a net of 3% increase in the annual mortality rate. This estimate accounts for the increase in heat-related mortality and the decrease in cold-related mortality associated with climate. Barecca (2012) reports similar estimates. To put the 3% increase estimate in some context, it is useful to compare it to the observed improvements in longevity in the United States over the last 30 years. During this period, the age-adjusted mortality rate declined by approximately 1% per year. Thus, even if the end of century mortality predictions are taken literally, the increase in mortality predicted to occur under climate change is roughly equivalent to the typical improvement in longevity that has been observed about every third year in the United States from 1968 to 2002.[19]

Another approach to characterize the predicted impacts of climate change on mortality is to report the present discounted value (PDV) of the stream of expected monetized losses associated with the predicted increase in mortality. This approach requires daily climate model predictions for all years of the 21st century and all climate model grid points (as opposed a single average prediction for the 2070–2099 period). In addition, the mortality estimates need to be transformed in years of life loss using life tables and age-specific estimates of the temperature–mortality relationship. Years of life loss estimates can then be monetized using an estimate for the value of statistical life (VSL). Therefore, these monetized calculations entail strong data requirements. To date, only Deschenes and Greenstone (2011) have produced such calculations.

Deschenes and Greenstone (2011) use two different sets of assumptions regarding the VSL. One specification assumes a fixed VSL of US $100,000 per life-year while the other allows for a real per capita income growth of 2% per year and an elasticity of the value of a life-year with respect to income of 1.6, which leads to increases in the VSL (or value of life-years) over time (Costa and Kahn, 2004). Using a discount rate of 3% yields a PDV of the U.S. mortality cost of climate change of US$1.0 to US$5.5 trillion. By comparison, the corresponding PDV of the adaptive residential energy costs of climate change varies from $0.5 to $3.0 trillion, depending on the assumed rate of growth for energy price (0 or 5% annually). This simple decomposition of social cost of climate change associated with mortality as the single health outcome and residential energy consumption as the single adaptation highlights that adaptation is economically important: it accounts for about one third of this partial social cost.

Finally, it is important to recognize that these projections of health impacts at the end of the century requires a number of strong assumptions, including that the climate change predictions are correct, that relative prices will remain constant or evolve deterministically according to a projection, the same technologies will prevail, and the demographics of the U.S. population (e.g., age structure) and their geographic distribution will remain unchanged. These assumptions are strong, but

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[17] While providing significant health benefits, the greater use of cooling technologies such as fans and air conditioning could potentially increase the rate of climate change because fossil fuels (e.g., coal and natural gas) remain the dominant forms of raw energy used in electricity production.

[18] Deschenes and Moretti also note that there are many unobserved factors that determine mobility decisions and so the reported correlations do not necessarily have a causal interpretation.

[19] This simple calculation assumes that the rate of increase in longevity will continue according to the historical trend. If there are diminishing returns to health capital, then future improvements in longevity will occur at a slower pace than has been observed in the last 30 years, and the three percent increase in end of century mortality should be evaluated accordingly.

their benefit is that they allow for a transparent analysis based on the available historical data.

In particular, the assumption of stability of medical and other technologies and the fact that all studies based on historical data are necessarily identified by data about the past and by short-run variation in temperature (as opposed to long-run variation in temperature) generally leads to an overstatement of human health costs of climate change since the set of possible health-preserving adaptations will necessarily be more limited in the short-run than in the long-run. In the absence of a random assignment of climates across populations, no research design based on real-world data can address this point to its full extent: all empirical studies of the prospective effect of climate change on health suffer from this limitation, and should be interpreted accordingly. Still, extremely valuable information can be gained from carefully conducted empirical studies, especially those that leverage medium frequency shocks (i.e. monthly or annual level).

5. Implications and conclusions

My reading of the empirical literature on the impact of extreme temperature exposure on health highlights three sets of implications for the practice of IAMs, and for future empirical research. First, the empirical identification of the response function linking extreme temperatures to health is difficult. The main challenges are that the response functions are likely to be nonlinear, reflect complicated dynamic relationships, and are possibly confounded by omitted variables bias and/or by secular and seasonality trends. As such, the response functions and parameter estimates that are taken from the empirical literature and integrated in IAMs must be critically chosen and evaluated.

Second, it is likely that there is significant heterogeneity in the response functions, reflecting both secular changes over time (as a result of economic growth and technological improvements), and across countries (reflecting differences in economic environments, adaptation possibilities, and population vulnerabilities). Few empirical studies have investigated these issues and so little is known about either types of variation. The question is how to calibrate a regional IAM to reflect actual variation across regions in the response functions when the variation has not been properly documented. Clearly it would be incorrect to extrapolate the little credible evidence available for the U.S. to developing countries in a regional IAM.

Third, very little is known empirically about the health-preserving effects of adaptation in response to extreme temperatures. The limited set of existing studies of health, adaptation and climate change all focus on the United States, and on very few adaptation strategies. In addition, only one study to date has estimated the interaction effect between extreme temperature and access to adaptation measures. Therefore the exact magnitude by which adaptation can mitigate the detrimental effect of extreme temperatures on health remains largely unknown. Further, the effectiveness of some of the most prominent adaptation strategies listed in the policy literature such as early warning systems and public outreach have not been properly been studied to date.

The research summarized in this review also offers broader implications for policy and motivates future research. The first point is that most of the research has focused on the United States where the required data sets are readily available. It is especially important to develop estimates for countries where economies are more weather-dependent or where current temperatures are higher than in the United States. These countries are also generally poorer and equipped with less infrastructure, and so identifying feasible and life-preserving adaptations is especially important. The climatic factors that impact health in poorer countries are also more likely to be more numerous than in the developed counterparts due to greater dependence on agriculture. Thus studies should go beyond examining temperature extremes and consider other factors such as rainfall fluctuations and humidity. Additional research will contribute to reducing the human health burden of climate change and also inform the development of rational climate policy which requires knowledge of the health and other costs of climate change from around the world.

The second point is that there is a pressing need for developing databases and research designs to study additional forms of adaptation, in the United States and elsewhere. The available evidence is taken from a handful of studies, and more information is needed before concrete policy recommendations can be proposed. These studies clearly show that in the context analyzed adaptation is incomplete. Nevertheless the results indicate that adaptation is both economically important and contributes to reducing mortality attributable to temperature extremes.

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