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Temperature Stress and the Direct Impact of Climate Change: A Review of an Emerging Literature

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Introduction

The late Singaporean Prime Minister Lee Kwan Yew once proclaimed that the first thing he did upon election was install air conditioners in all the buildings where the civil service worked. Referring to the stiflingly hot Singaporean climate, he went on to suggest that air conditioning was "one of the signal inventions of history," having "changed the nature of civilization by making development possible in the tropics" (Yew 1999).

While intellectual inquiry into whether and how temperature affects human economic activity long predates the invention of modern cooling technology,[1] recent debates about the potential costs of climate change have generated renewed interest in this issue and heightened its policy relevance. The importance of this issue for policy is in part a product of continued uncertainty regarding the true social cost of carbon (Pindyck 2013), which currently does not account for possible labor productivity impacts of climate change (Tol 2009; Burke, Hsiang, and Miguel 2015). Much of the climate economics research to date has focused on *indirect* economic impacts of changes in the earth's climate—for example, the impacts of heat on crop yields or of sea level rise on infrastructure. While these are important channels through which climate may affect welfare, an emerging literature suggests that the *direct* economic consequences of extreme temperature on human physiology may also be of first-order significance. These impacts can take the form of damage to human health, reductions in labor productivity and supply, and possible reductions in the rate of human capital accumulation—all of which may decrease gross domestic product (GDP) and overall social welfare in both the short and long run.

In this Reflections, we review this emerging literature on the economics of extreme heat stress, focusing on several recent panel studies that permit causal identification of its consequences. Across a range of contexts (health, labor supply, and labor productivity), micro- and

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[1]As Dell, Jones, and Olken (2014) point out, this interest goes as far back as the ancient Greeks, and continues in the Arabic literature of the Middle Ages and the European literature of the Enlightenment. Biologists have noted climate-related differences in human physiology at least since Allen (1877).

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macroeconomic studies find evidence for nontrivial impacts of heat stress, in particular on hot days with temperatures above 78 °F (25°C). These findings make a compelling case for including labor-related impacts in integrated assessment models, which estimate the social cost of carbon, and highlights the possibility of climate change affecting poorer populations disproportionately.

The recent economics literature offers two key methodological innovations, which we argue should be expanded. First, these studies provide causal estimation of the impacts of temperature in economically relevant contexts, shoring up weaknesses inherent in cross-sectional studies (omitted variable bias) and laboratory experiments (limited contextual relevance).[2] By using observed panel data (a combination of time series and cross-section data), these studies are able to control for factors such as institutions or individual abilities, which may affect health and productivity but are unrelated to temperature (at least in the short run), and estimate the human impacts of heat stress as they occur in real-world settings such as homes, factories, construction sites, or entire local economies.

Second, the new literature allows for more inclusive welfare analysis than the existing biomedical or policy simulation literature, analysis that accounts for behavioral responses of firms and individuals to temperature stress as well as for interactions with institutional settings. This orientation is especially relevant to the context of climate policy, since the realized welfare consequences of climate change will vary tremendously both across geographies (due, for instance, to different institutional settings) and across time (given the prospect of adaptation).

We begin the next section with a brief overview of the biological basis for direct, temperature-driven welfare impacts. Then we present a stylized review of the emerging economics of temperature stress and human activity. We conclude with a discussion of potential policy implications, as well as directions for future research.

The Biology of Temperature Stress

Human beings are biological organisms, with clear biological constraints on the environments in which we can live and function comfortably. As entomologist E. O. Wilson puts it, "Humanity is a biological species, living in a biological environment, because like all species, we are exquisitely adapted in everything, from our behavior, to our physiology, to that particular environment in which we find ourselves" (Wilson 2002).

A key feature of our environment is the combination of temperature and humidity that determines the heat balance of the human organism. We are quite easily perturbed and distracted when temperatures veer above or below our thermal comfort zone—a narrow band between 64 °F (18 °C) and 72 °F (22 °C), typically referred to as room temperature. Anyone who has watched construction workers toil in midday heat or attended a class in a freezing lecture hall can readily attest to the clear link between temperature stress and human performance.

Physiological Consequences of Exposure to Extreme Temperature

As the body heats, it uses its stores of water and salt to create sweat, which dissipates heat. If heat stress is prolonged and these stores are not adequately replenished, heat begins to cause

[2]This parallels a point made by Dell, Jones, and Olken (2014), regarding methodological innovations of economic studies that use high-frequency weather data for causal identification.

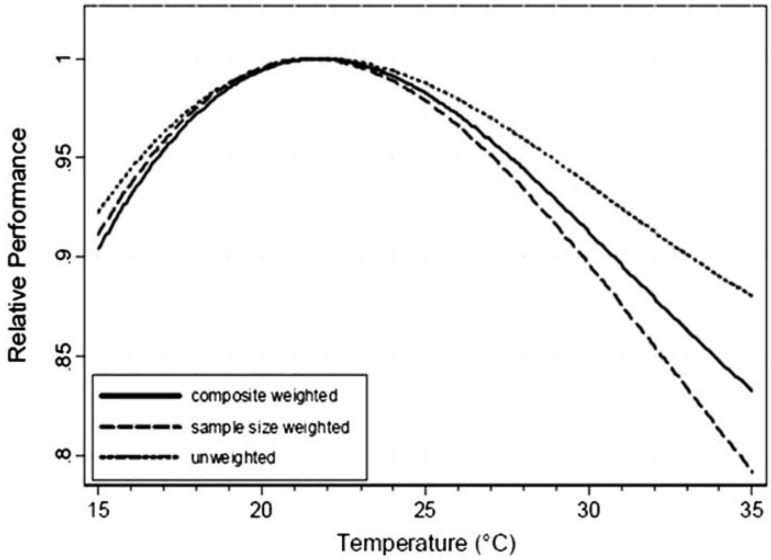

Figure 1 Temperature and task productivity in laboratory settings (Seppenen, Fisk, and Lei 2006)

dizziness, muscle cramps, and fever. In the extreme, hot or cold temperatures can cause acute cardiovascular, respiratory, and cerebrovascular reactions.[3]

When humidity-inclusive temperatures[4] reach 95 °F (35 °C), extended periods of outdoor activity become impossible for even the most physically fit adults because human bodies can no longer dissipate heat (hyperthermia).[5] While such temperatures do not occur regularly today, it is certainly possible that, under worst-case scenarios, climate change could make many areas of the world uninhabitable for most of the year without extensive air conditioning.[6]

Experimental Evidence on the Human Impacts of Temperature Stress

Even at less extreme levels, temperature can influence human behavior in nontrivial ways. Task productivity has been shown to decline with temperature stress, beginning at even moderate deviations from the optimal zone [72 °F (22 °C)]. A longstanding literature on industrial ecology and physiology, pioneered by experimental studies of British naval officers (Mackworth 1946), documents a systematic relationship between temperature stress and reduced performance. Numerous lab experiments have quantified this relationship by randomly assigning subjects to rooms of varying temperatures and asking them to perform cognitive and physical tasks such as guiding a steering wheel or deciphering Morse code (Grether 1973; Froom et al. 1993). In a meta-review, Seppanen, Fisk, and Lei (2006) find that the average productivity loss from

[3]Exposure to heat is associated with increases in blood viscosity and blood cholesterol levels (Deschenes and Moretti 2009), which can eventually cause increased morbidity in the form of heat exhaustion and stroke (Graff Zivin and Shrader 2016). Combined with humidity and intense physical exertion such as exercise or manual labor, heat can lead to acute cardiovascular or respiratory failure.

[4]Technically we are referring to the wet bulb temperature.

[5]Exposure to cold can have similarly adverse consequences for physical functioning, causing cardiovascular stress due to changes in blood pressure, vasoconstriction, and an increase in blood viscosity, which can lead to blood clots (Huynen et al, 2001). Overall, the medical literature documents very clear temperature dependencies of physiological functioning, with fatal consequences even for healthy adults when temperatures are very high (or low) and exposure is prolonged.

[6]See Sherwood and Huber 2010.

temperatures above 77 °F (25 °C) is on the order of 2% per degree Celsius for the various tasks surveyed, with nonlinearity in responses as the temperature deviates further from the optimum of approximately 68 °F (20 °C). These findings are summarized in figure 1, reproduced from Seppanen, Fisk, and Lei (2006), which shows how task performance (normalized to one at its best) falls off with departures from the optimal temperature.[7]

Methodological Challenges to Estimating Welfare Impacts

Drawing the link from this physiological perspective on human activity to economic policy applications is no easy task. Given the well-documented cross-sectional relationship between tropical climates and low standards of living, it may be tempting to extrapolate the impacts of climate change on economic productivity based on the experimental literature (e.g., Sherwood and Huber 2010). However, several factors must be taken into account to perform welfare analysis aimed at informing economic policy.

Economically Relevant Contexts

First, we must account for the ways in which individuals respond to temperature stress, which requires estimation of heat-related impacts in economically relevant contexts rather than in the lab. Behavioral responses—and the incentive systems that may constrain them—are especially important in the context of extreme temperature shocks, because there are many possible margins of adjustment and the final welfare impact will depend in part on the incentives individuals face in choosing certain adjustments over others.

For example, a worker at a manufacturing plant may respond to an unusually hot day in a number of ways. She may choose to wear lighter clothing or to take a taxi rather than walk to work. She may turn on a fan at her workstation or ask to turn up the air conditioning if it is available. If these options are not available, and the heat stress is severe, she may decide to work fewer hours that day, to petition to work a night shift, or to call in sick. She may also decide to work less intensively, taking more frequent breaks. Whether or not she decides to adjust her hours or reduce her effort will depend in large part on how she is paid. Thus the optimal response for someone who is paid a piece rate contract—in which payment is directly proportional to how much output she produces—will differ from someone who is paid on a fixed annual contract or simply by the hour.

Moreover, if such heat shocks persist over time, the worker may try to switch to a job that involves less physical exertion or provides better protection from the elements, or she may decide to migrate to a less extreme climate altogether. From the perspective of the firm, persistent reductions in worker productivity due to climate change may induce a reallocation of inputs from labor to capital, altering capital–labor ratios and possibly affecting relative wages (by affecting low- versus high-skilled workers differently) and the distribution of total income (by affecting relative returns to capital and labor).

To the extent that many lab experiments [such as those reviewed by Seppanen, Fisk, and Lei (2006)] are unable to account for these worker and firm adjustments, researchers and

[7]Although most attention has focused on the consequences of high temperatures for performance, low temperatures also have a negative impact, a fact that may be important when considering the potential distributional consequences of climate change.

policymakers must be cautious about extrapolating from these lab-based point estimates to policy contexts, especially for long-run climate change.

Causal Inference

Second, there may be correlations between existing climates and other factors that affect health and productivity, and these factors may or may not be readily observable to the econometrician, possibly obscuring causal inference. To understand the effect of temperature on productivity, one would ideally like to replicate an economy and compare its behavior under different temperature regimes, in both the short and long run. Since this is not feasible, we have to examine observational data on how each economy responds to temperature variations and how this response varies across economy/climate regimes. The first studies using this approach (e.g., Horowitz 2001) were based on regressions over a cross section of countries with different annual average temperatures. Although these studies show a clear negative correlation between temperature and productivity, they are unable to tell us very much about the extent to which high temperatures actually *cause* low productivity. Whether differences in temperature cause differences in health and productivity, as opposed to being correlated with other factors such as institutions, influences our understanding of the determinants of the relative wealth of nations, and thus has important implications for thinking about challenges that developing countries face in light of climate change. A thorough understanding of the social cost of carbon requires that we understand whether temperature has a direct causal effect on productivity and health in economically relevant contexts, how significant the contemporaneous impacts are today, and how we expect these impacts to evolve as climate change unfolds.

Recent methodological advances have enabled researchers to isolate the causal impacts of short-run temperature shocks using panel estimation methods, and to do so with an increasingly flexible characterization of the adaptive responses economic agents may undertake in the long run. Thus, in the remainder of this article, we discuss several studies that estimate the direct physiologically driven causal impacts of temperature stress in economic contexts. We highlight these advances in the context of three related, but separate, outcomes: health, labor supply, and production output.

Impacts of Temperature Stress On Health

A growing body of work in the economics literature suggests that even in rich countries, which generally have high levels of electrification, extreme heat waves can trigger large-scale mortality responses. Using weather fluctuations at the daily level, Deschênes and Greenstone (2011) identify annual mortality responses by state in the United States. They find that an additional day with a mean temperature that exceeds 90°F (32 °C) leads to an increase in the annual age-adjusted mortality rate of about 0.11 percent.[8] Although both hot and cold days have mortality impacts, there appears to be greater nonlinearity in the response to heat. Unlike many existing case studies and epidemiological findings, Deschênes and Greenstone are able to convincingly

[8] A day with a mean temperature that is below 20 °F (−6 °C) is associated with an increase in annual mortality of roughly 0.07 to 0.08 percent.

estimate causal impacts of temperature on mortality net of location-specific factors, as well as possible forward displacement or "harvesting." In related work, Barreca et al. (2016) also allow for the possibility of long-run adaptive investments by households, particularly in the form of air conditioning, by estimating the heterogeneity in mortality responses to heat across different regions of the United States between 1900 and 2004. They find that the impact of extreme heat on mortality is notably smaller in states that more frequently experience extreme heat, suggesting substantial scope for adaptation in the long run. In this instance, the "long run" is approximated by differences in short-run weather responses across different regions in the cross section, paralleling recent work on the agricultural sector (Butler and Hubers 2013).[9]

The impacts of extreme temperature on mortality have been confirmed in a number of other studies and contexts, although this evidence is mostly from the developed world, where data have been more readily available[10] (Deschenes 2014). Perhaps not surprisingly, the mortality effects vary in size across the age distribution, with older individuals (e.g., older than 65 or 75 years) and children generally facing a higher mortality risk (Graff Zivin and Shrader 2016). In general, the literature indicates that most health impacts arise from a small number of extreme temperature events at the tails of the temperature distribution, a pattern that emerges in a range of other contexts, including those described next.

Impacts of Temperature Stress on Labor Supply Decisions

Prior to causing the behavioral responses we have mentioned, temperature stress may affect workers in at least two immediate ways. First, it may cause direct physical or psychological discomfort. Second, it may reduce task productivity, possibly altering the marginal return to an additional hour of labor supplied or an increment of effort exerted within any given hour. These two direct impacts may in turn affect labor productivity, labor supply (hours worked), labor effort, and, if other margins of technological adjustment are available, adaptive effort or defensive expenditures. As Graff Zivin and Neidell (2014) and Kahn (2016) note, both the proximal behavioral adjustments and the ultimate realized welfare impacts will depend on the worker's local context, that is, the extent of occupational exposure as well as the labor market incentives the worker faces. It is thus important to develop an underlying model of employee behavior that, while building on the physiological intuition discussed earlier, embeds the biological mechanisms in a utility maximization framework.[11]

[9]This approach is separate from, but seems complementary to, the "long differences" approach (e.g., Burke and Emerick 2014).

[10]In India, Burgess et al. (2014) find evidence for mortality impacts of hot days that are approximately eight times as large as those in the United States.

[11]Park and Heal (2013) use the term "effective labor supply" to refer to the realized labor inputs in the context of temperature stress, net of adjustments along these many margins by individual workers. Under some circumstances the realized production impacts of an exogenous temperature shock can provide sufficient information for welfare analysis. In principle, it allows researchers to estimate temperature-driven welfare impacts without separately identifying the varying contributions of labor supply, task productivity, defensive expenditure, and direct disutility.

Stylized Model of Labor Supply

Consider a simple model of labor supply that extends the normal labor–leisure trade-off. More specifically, assume that utility depends on hours of leisure, income, core body temperature, and effort expended. Task productivity also depends on core body temperature, and core body temperature depends on the external temperature and effort. The relationship between productivity and temperature is assumed to be single-peaked as implied by the physiological literature (recall figure 1). Similarly, we assume that the relationship between utility and core body temperature is single-peaked, reflecting the fact that humans are most comfortable at a core temperature of 98 °F (37 °C) and that departures from this temperature result in a decrease in well-being.

Within this framework, the individual chooses hours of work and the level of effort to maximize utility, with a given market-determined relationship between hours worked, productivity, effort, and income. If we assume quasi-linear utility and a direct mapping between marginal labor product and wages (i.e., a piece-rate contract),[12] it can be shown that the single-peaked relationship between temperature and productivity also emerges from an optimizing choice of working hours and effort, with an increase in temperature leading to more hours of work and more effort at lower temperatures and fewer hours and less effort at higher temperatures.[13] While welfare impacts will no doubt be sensitive to the employees' contractual structure, we use this as an illustrative baseline case to examine the possibility of short-run labor supply responses to heat stress.

Empirical Evidence of Labor Supply Responses

Using data from the American Time-Use Survey, Graff Zivin and Neidell (2014) examine whether days with extreme temperatures are associated with significant changes in time use by individuals. They find that on days with maximum temperatures above 85°F (30 °C), workers in industries with high exposure to climate reduce time allocated to labor by as much as 1 hour, which represents a 14 percent reduction in labor supply for the day.[14] The vast majority of this reduction occurs at the end of the day when fatigue from prolonged exposure to heat has likely set in. In terms of leisure activities, they find an inverted U-shaped relationship between daily maximum temperature and time spent outdoors, which is consistent with avoidance behavior and direct disutility of heat stress (and/or reduced marginal utility of outdoor consumption activities). This relationship is most pronounced for those not currently employed, who presumably have the greatest flexibility in their schedules.

It is as yet unclear whether the magnitude of these labor supply responses vary by industries according to prevailing contractual structures or local labor market conditions. For instance,

[12] Park and Heal (2013) assume quasi-linear utility, which does not allow for income effects and, importantly, labor market imperfections (which may drive a wedge between the wage rate and the realized marginal product of labor).

[13] This has empirical significance because it implies that the effect of an increase in temperature on productivity depends on the initial temperature, with the effect being positive at low temperatures, negative at higher temperatures, and ambiguous in between.

[14] High-exposure industries are defined as industries where the work is performed primarily outdoors, as well as manufacturing, where facilities are typically not climate controlled and the production process often generates considerable heat.

employees with long-term contracts might be more sensitive to heat shocks if effort or hours are not readily observable, since pay is not tied directly to performance, whereas self-employed individuals may have a greater incentive to "double down" and persevere despite discomfort and some reduced productivity. As Kahn (2015) points out, even when wages are tied to productivity, the overall impact of temperature stress on labor market outcomes may depend on local supply and demand factors. Whether such factors affect the distributional consequences of climate change–induced heat stress is a topic that we believe warrants further exploration.

Impacts of Temperature Stress on Production

There appears to be evidence that extreme heat stress on human agents can affect output in major industrial sectors such as manufacturing or construction, and possibly influence the overall level and growth rate of the economy as a whole. While much of the existing research on the macroeconomic consequences of climate change have focused on indirect channels such as reductions in agricultural yield (e.g., Mendelsohn, Nordhaus, and Shaw 1994; Schlenker, Hanemann, and Fisher 2005) or sea level rise, recent evidence suggests that there may be substantial output reductions arising from the direct impact of extreme heat on labor inputs (Cachon et al. 2012; Sudarshan and Tewari 2013; Deryugina and Hsiang, 2014; Park, 2016).

Production Impacts at the Plant Level

The temperature–productivity nexus has been investigated at both the micro and macro levels. There are numerous studies of the production impacts of extreme heat at the plant level. For example, using plant-level output data from 1994 to 2004 for automobile manufacturing in the United States, Cachon et al. (2012) test whether hot days exert a causal influence on output, controlling for plant-level characteristics as well as seasonality in production patterns.[15] Across the board, they find that hot days are associated with lower output. At the extreme, a week with six or more days above 90°F (32°) reduces that week's production by about 8%. While their study design is unable to fully disentangle the contributions of productivity decline and worker absenteeism or to test for the extent of air conditioning at each plant, the results suggest that the productivity impacts of temperature stress may be nontrivial, even for capital-intensive industries in countries whose economies are relatively well adapted to extreme temperature. It is particularly surprising that there is a negative impact of temperature shock on manufacturing productivity in a country as rich as the United States; one might have expected that U.S. factories would be fully adapted to their local climate and have the resources to neutralize weather shocks.

Using a similar research design, Niemelä et al. (2002) examined the daily productivity of Indian call center workers in different ambient temperatures and found that above 72 °F (22°C), each additional degree Celsius is associated with a 1.8 percent reduction in labor productivity. More recently, Adhvaryu et al. (2014) show that manufacturing worker efficiency at the plant level declines substantially on hotter days, an effect that is driven primarily by on-the-job task productivity declines rather than increased absenteeism. Sudarshan and Tewari

[15]They also control for fixed effects, as well as for other weather shocks (e.g., wind storms, snow, rain).

(2013) find similar plant-level productivity declines among Indian manufacturers, even when controlling for region, firm, and individual-specific factors, with hot days [above 77 °F (25°C)] causing a 2.8 percent reduction in plant-level productivity per 1.8 °F (1°C) increase in temperature above 77 °F (25°C). Adhvaryu et al. (2014) and Sudarshan and Tewari (2013) are able to show that the effect is driven primarily by reduced worker productivity rather than by increased worker absenteeism.

County and Sectoral Evidence

County-level studies of the United States provide evidence of macroeconomic impacts of temperature stress, likely operating through its effect on labor inputs. Using annual income data and daily weather data for 1969 to 2011, Deryugina and Hsiang (2014) find that years with more days above 59 °F (15 °C) are associated with significantly lower income per person: average per-day income declines by 1.5% for each 1.8 °F (1°C) increase in daily average temperature beyond 15°C (59°F). Thus, relative to a day with an average temperature of 59 °F (15°C), a day at 84 °F (29°C) lowers annual income by roughly 0.065 percent, meaning that a year with 20 additional hot days can reduce income by more than 1.2 percentage points—on par with a minor recession, although such events are, historically at least, quite rare.

Similarly, Park (2016) uses U.S. county-level payroll data for 1986 to 2012 and finds that hot days have adverse effects on production. By focusing on payroll data and excluding agricultural sectors, Park (2016) narrows the focus to the impacts of extreme heat on marginal labor product, net of long-run adaptive investments by firms. A county with one additional day above 90 °F (32 °C) experiences 0.048% lower per capita payroll the next year. Industries such as construction and mining, which are more vulnerable to environmental stress,[16] respond more negatively, with per-day impacts that are 3.5 times larger in these exposed industries relative to sectors such as financial services, which are not particularly exposed to the elements [−0.073 percent versus −0.019 percent per day above 90 °F (32 °C)].

Appealing to intuition that is similar to Barreca et al. (2016), Park (2016) estimates the heterogeneity in these short-run extreme heat impacts across different climatic regions and finds that places that are more accustomed to hot days [above 80°F (27 °C)] suffer proportionately smaller impacts for the same heat shock. Thus hot days reduce output by substantially less in areas such as Houston or Orlando, where heat stress is more common, than in places like Boston or San Francisco, suggesting scope for long-run adaptation as firms and individuals invest in mitigating technologies.[17] Both Deryugina and Hsiang (2014) and Park (2016) find temperature impacts on nonagricultural sectors, suggesting that the impact is not due to a contemporaneous decline in agricultural yield.[18]

[16]This categorization is based on National Institute for Occupational Safety and Health (NIOSH) definitions and refers to occupations that take place primarily outdoors and/or involve substantial physical exertion.
[17]These findings are consistent with work by Mansur, Mendelsohn and Morrison (2008), who use differences in energy expenditures and technology types across regions within the US to estimate adaptive responses in energy use.
[18]Although these macroeconomic associations use high frequency weather data to control for omitted variable bias, we still cannot rule out the existence of other correlated factors. For example, some of these studies measure non-agricultural output specifically, but the observed associations may be due to spillovers from agriculture if yield reductions have general equilibrium effects in other sectors. It remains unclear whether these impacts are driven by other weather patterns that are correlated with temperature but not controlled for by the econometrician, including wind speed, sunlight/cloud cover, and pollution levels (which we discuss in more detail later).

Production Impacts at the Regional and National Level

Several country-level studies reveal similar patterns using annual temperature fluctuations. Hsiang (2010) examined the impact of hotter-than-average years on output in 28 Caribbean countries from 1970 to 2006 and found that unusually hot summers lead to annual nonagricultural output declines of 2.4 percent per 1.8 °F (1 °C) for that year, controlling for the influence of tropical storms.

Looking at a larger panel of 124 countries from 1950 to 2003, Dell, Jones, and Olken (2009, 2012) measure the effect of hotter-than-average years on a range of macroeconomic variables, including GDP per capita and industrial value added. They find that hotter years are associated with lower economic growth rates, but only in poor countries, that is, countries with per capita income below the global median in 1990.[19] They also find that hot years reduce the level of industrial output (again only in poor countries) by 2.04 percent per degree Celsius and agricultural yield by roughly 2.4%. Importantly, the reduction in industrial output arises not only from downstream processors of agricultural products, but also from decreased production of electronic equipment and light metal manufacturers, suggesting that the impacts are driven by direct productivity impacts rather than indirectly through spillovers from agriculture. Jones and Olken (2010) obtain similar results using trade data: a 2.4 percent decline in exports per degree Celsius for hotter-than-average years in poor countries.

Using cross-country weather data that is similar to Dell, Jones, and Olken (2012), but different income data, Park and Heal (2013) test the hypothesis that the labor productivity impacts of a given temperature shock will vary nonlinearly with the initial climates, as suggested by the single-peaked relationship between temperature and productivity in the physiological literature. They find that hotter-than-average years lead to lower-than-average output and lower implied total factor productivity in already hot countries, and find the reverse effect in colder countries, in which hot years are associated with increased productivity. This potentially explains why Dell, Jones, and Olken (2012) find a temperature impact only in poor countries and not in the entire sample: poor countries are, in general, hot countries and show a negative effect. In the sample as a whole, the positive effect in rich (cold) countries offsets the negative effect in poor (hot) countries. More recently, this same pattern has been shown using different weather and income data across a similar set of countries (Burke, Hsiang, and Miguel 2015).[20] Park and Heal (2013) also find that air conditioning seems to mitigate the impact of temperature stress in hot countries. That is, hot countries with high levels of air conditioning per capita show less impact from high temperatures than countries with low levels of air conditioning per capita.[21] This is consistent with the comment from Lee Kwan Yew cited in the introduction, and helps to explain why cities such as Singapore and Hong Kong are highly productive despite their high temperatures.

[19]More specifically, expressed relative to baseline variability, their estimates imply that a one-standard deviation increase in annual temperature is associated with a reduction in the growth rate of about 0.69 percentage points.
[20]Dell, Jones, and Olken (2012) also find a positive effect of temperature in rich countries, but it is not statistically significant. Because rich countries tend to be cold, this finding is generally consistent with the Park and Heal (2013) finding of a positive impact of temperature in cold countries.
[21]Air conditioning per capita is constructed by cumulating trade data on imports of air conditioning equipment from the United Nations COMTRADE database.

Do Temperatures Affect Output Levels or Growth Rates?

There is some ambiguity in the literature about whether temperature influences the level of output per capita or its rate of growth. This distinction is particularly important given the time scales involved with future climate change (Pindyck 2012). If extreme heat actually reduces the underlying level of economic growth, then climate change may lead to even greater income disparities between rich and poor countries and individuals.

A priori, it is not clear whether temperature is more likely to affect output levels or their growth rates. On the one hand, a labor productivity–based model of the effect of temperature suggests that the impact of a temperature shock should be short term; that is, the task-performance effects of temperature should in principle be reversible on milder days. It is certainly possible that many production activities occur on fixed calendars and do not automatically adjust to incorporate "overtime" to make up for lost production. However, this should manifest as a lagged effect on the level of output rather than a reduction in the rate of growth. On the other hand, it is possible that extreme heat reduces the rate at which productive capital, including physical capital, human capital, or productive ideas and innovations, accumulates in an economy and/or results in permanent damage to existing capital stock.[22]

In observed macro data, a negative effect of temperature on output levels in time t would appear as a reduction in the growth rate of output from t to $t + 1$, followed by faster-than-average growth once the temperature shock is reversed. In contrast, a growth rate impact could manifest itself as a reduction in growth in year t that is not compensated for in year $t + 1$ or a permanently lower baseline growth rate, both of which would affect the entire future trajectory of output.

What is the evidence in the environmental economics literature on this issue? Hsiang (2010) and Deryugina and Hsiang (2014) document a relationship between income levels and temperature. Dell, Jones, and Olken (2012) find evidence of temperature impacts on both output levels and growth rates, but only in the case of poor countries, and suggest that this may be because temperature affects innovation and investment. They find that even output per capita continues to be affected by a temperature shock for up to ten years after the initial shock, and that hot years have the effect of permanently reducing the natural growth rate in poor countries.

Park and Heal (2013) find that temperature affects output levels, albeit with high persistence over time; that is, temperature impacts reduce the level of output relative to the trend for some time, but they are eventually reversed once the temperature shock disappears. They find a similar lagged impact of up to ten years, but no evidence for permanent growth rate reductions.[23] The existing microeconomics literature (e.g., Cachon et al. 2012) appears to suggest that temperature can affect the level of output in a persistent way, which means the possibility of growth rate impacts cannot be ruled out.

There are several additional potential explanations for this observed persistence in the consequences of temperature shocks. One possible cause of these persistent consequences could be the impact of temperature stress on pregnant women. Exposure to environmental stress during pregnancy has been shown to cause low birth weight, which is correlated with lower

[22]Dell, Jones, and Olken (2012) find that hot years affect investment, but the result is not statistically significant.
[23]They note that a quadratic relationship between temperature and output per capita implies a relationship between the rate of growth of output per capita and temperature interacted with the rate of change of temperature, and find some evidence for such a relationship.

performance of the child in numerous areas later in life, including lower performance on standardized tests and lower earnings (Almond and Currie 2011; Graff Zivin and Shrader 2016). Thus this may be a channel for multidecadal persistence of the effects of temperature shocks.[24] Similarly, lagged impacts or growth rate impacts may result from the effects of temperature stress on human capital accumulation. For example, temperature extremes may interfere with the educational process, with students less able to concentrate when it is unusually hot, as suggested by Graff Zivin, Hsiang, and Neidell (2015), who find adverse impacts of ambient heat on standardized math scores.

Pollution may also cause persistence in the consequences of temperature stress, especially to the extent that certain air pollutants such as ozone are correlated with temperature. In the presence of volatile organic compounds and nitrogen oxides, heat creates ozone, which harms respiratory systems. The resulting health damage may persist after the heat wave that created the ozone has ended (Graff Zivin and Neidell 2014).[25]

Estimating Welfare Implications

Although further research is clearly needed to incorporate adaptive responses into economic models of heat stress, the literature to date does provide valuable insights into the potential welfare consequences of climate change as well as the fundamental determinants of economic well-being and growth. There are at least three issues for which this literature has important implications: estimating the social cost of carbon, the distributional impacts of climate change, and, closely related, the geographic diversity of climate impacts.

Implications for the Social Cost of Carbon

The existence of labor productivity impacts from temperature stress suggests that estimates of the social cost of carbon are systematically biased since most integrated assessments of climate damages do not include labor productivity impacts. As Tol (2009) notes in a review of the literature on the social cost of carbon, "the direct impact of climate change on labor productivity has never featured on any list of missing effects." If it is indeed the case that output losses due to declines in labor productivity are on the order of two percentage points per degree Celsius in hot countries, then this channel alone would imply that the social cost of carbon in these countries is much higher than current estimates, which place damages from climate change on the order of a few percentage points of world GDP.

Distributional Consequences

The literature on the direct impacts of temperature stress highlights the possible distributional consequences of climate change. The impact of a 1.8 °F (1 °C) hotter-than-average year seems

[24]This hypothesis is supported by Fishman, Russ and Carrillo (2014) and Isen, Rossin-Slater, and Walker (2015), who examine the effect of in utero exposure to temperature stress in Ecuador and the United States, respectively, and find a significant drop in lifetime earnings.

[25]More generally, heat may lead to a disease burden that remains after the heat has passed. For example, in El Niño years (which are associated with increases in temperature and humidity in some regions), the vector of dengue fever spreads beyond its normal range and the effects of the disease persist beyond the El Niño event itself.

to vary considerably across geographic regions, suggesting large negative impacts in hot (and poor) countries, but possibly positive impacts in very cold (and generally rich) countries. There is also some evidence that poorer households tend to reside in hotter environments within countries, which would exacerbate this regressive dynamic (Acemoglu and Dell 2010). This is in addition to the well-known fact that poor countries generally have less capacity to adapt to an altered climate and in many cases are extremely vulnerable to sea level rise and storm surges.

There are additional reasons to expect that the impacts of heat stress due to climate change may be regressive. Poorer groups are less likely to be able to afford adaptive equipment such as air conditioning, or even electrification and refrigeration (Kahn 2016). The mortality responses to temperature stress also appear to be much larger in developing countries and among lower-income groups within countries than in rich countries or among high-income groups.[26]

Low-income individuals are also more likely to work in sectors that are more sensitive to temperature stress: that is, in manual labor–intensive industries and outdoor work–intensive sectors such as agriculture or construction. Manual labor and occupations that are intensive in outdoor work tend to pay lower wages on average and offer less flexible work hours.[27] Moreover, poorer individuals are also more likely to live in areas with higher levels of ambient air pollution, which can interact with temperature in harmful and even deadly ways (Graff Zivin and Neidell 2014).

Geographic Diversity of Climate Change Impacts

The emerging literature on temperature stress and the impacts of climate change emphasizes the geographic diversity of these impacts. A net aggregate impact of zero at the global level could mask significant losses in hot countries and gains in cold countries, thus disguising a redistribution of income from poor to rich countries. This means that in order to fully understand the welfare impacts of temperature stress, researchers must work with regionally disaggregated models of the global economy that are capable of distinguishing between hot and cold countries, a capability currently lacking in some of the simpler integrated assessment models.

Conclusions

This Reflections has reviewed the emerging literature on the direct human impacts arising from temperature stress, in particular, extreme heat. We have highlighted several empirical studies that use panel data to estimate the causal impacts of heat stress on economically relevant outcomes, including health, labor supply, and industrial production. The emerging pattern seems to be one of adverse responses, which we suspect may have large welfare consequences. For instance, a day with temperatures exceeding 90 °F (32°C) can increase local monthly mortality rates by more than 1 percent (Deschenes and Greenstone 2011) and reduces daily labor supply in exposed sectors by up to 14 percent (Graff Zivin and Neidell 2014). A handful of such hot days can reduce production output in U.S. automobile factories by several percentage

[26]For example, the impacts of heat stress on mortality in India are roughly ten times larger than those in the United States (Deschenes, 2014).

[27]For example, the US Bureau of Labor Statistics estimates that the average construction laborer earns 25 percent less and laborers in farming, fishing, and forestry occupations earn 48 percent less than the median US worker (BLS, 2015: http://www.bls.gov/data/).

points below factory- and season-specific averages (Cachon et al. 2012) and reduce aggregate local output by upwards of 1 to 2 percentage points (Deryugina and Hsiang 2014; Park 2016).

Temperature appears to be a variable that matters to economic performance in its own right and not merely as a determinant of other outcomes such as agricultural productivity or disease exposure. This suggests that the omission of labor productivity and labor supply impacts from integrated assessment models of climate damages may be a source of nontrivial downward bias.[28] However, it is as yet unclear what the overall social welfare impacts of increased heat stress due to climate change may be, especially given the possibility of long-run adaptation.

Where do environmental economists go from here? We believe that this recent work on the human impacts of temperature stress highlights two important methodological contributions that economics has made and should continue to make to this cross-disciplinary literature. While the biological intuition concerning heat stress and its associated physiological impacts is simple, the economic calculus of moving from physical response to realized welfare reduction is far from straightforward. Modeling work from the biological sciences (e.g., Sherwood and Huber 2010; Kjellstrom 2011), for instance, has often extrapolated experimental "dose–response" relationships between heat stress and human performance many decades into the future, attempting to simulate the heat-related productivity impacts of climate change. While such studies may be useful bounding exercises, we would argue that, when it comes to making economic policy decisions, such extrapolations omit crucial welfare considerations.

As has been pointed out by Graff-Zivin and Neidell (2013) and Kahn (2016) among others, behavioral responses by firms and individuals must be taken into account to obtain welfare estimates, even approximate ones. The nature of these responses, as well as the overall welfare costs to society, will depend crucially on local economic contexts, which may be in terms of labor market institutions (e.g., contract versus piecework) or the availability of adaptive technologies (e.g., cost of electricity, air conditioning, relocation). Thus a priority for future research in this area should be to integrate the insights from the biological sciences with economic models of behavioral responses and causally identified statistical estimates of realized impacts, net of short- and long-run adjustments by firms and individuals.

References

Acemoglu, Daron, and Melissa Dell. 2010. Productivity differences between and within countries. *American Economic Journal: Macroeconomics* 2:169–188.

Adhvaryu, Achyuta, Namrata Kala, and Anant Nyshadham. 2014. *The light and the heat: Productivity co-benefits of energy-saving technology.* Working paper. Available at www.achadhvaryu.com/#5

Allen, Joel A. 1877. The influence of physical conditions in the genesis of species. *Radical Review* 1:108–140.

Almond, Douglas, and Janet Currie. 2011. Killing me softly: The fetal origins hypothesis. *Journal of Economic Perspectives* 25:153–172.

Auffhammer, Maximilian, Solomon M. Hsiang, Wolfram Schlenker, and Adam Sobel. 2013. Using weather data and climate model output in

[28]In addition, if temperature affects the productivity of labor rather than that of capital, it may not be appropriate to represent the damages from climate change as a proportional drop in output depending only on the temperature and not on how the output is produced. Labor-intensive outputs may be affected more than those that are capital-intensive.

economic analyses of climate change. *Review of Environmental Economics and Policy* 7:181–198.

Barreca, Alan, Karen Clay, Olivier Deschenes, Michael Greenstone, and Joseph S. Shapiro. "Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the Twentieth Century." *Journal of Political Economy* 124, no. 1 (2016): 105–159.

Burgess, Robin, Olivier Deschenes, Dave Donaldson, and Michael Greenstone. 2014. The unequal effects of weather and climate change: Evidence from mortality in India. London School of Economics, Unpublished working paper.

Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. 2015. Global non-linear effect of temperature on economic production. *Nature* 527:235–239.

Burke, Marshall and Kyle Emerick. Adaptation to Climate Change: Evidence from U.S. Agriculture. Working paper, January 2015, at web.stanford.edu/~mburke/papers/Burke_Emerick_2015.pdf

Butler, E. E., & P. Huybers, (2013). Adaptation of US maize to temperature variations. *Nature Climate Change*, 3(1), 68–72.

Cachon, Gerard, Santiago Gallino, and Marcelo Olivares. 2012. Severe weather and automobile assembly productivity. Columbia Business School Research Paper 12/37.

Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken. 2009. Temperature and income: Reconciling new cross-sectional and panel estimates. *American Economic Review: Papers and Proceedings* 99:198–204.

———. 2012. Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics* 4:66–95.

———. 2014. What do we learn from the weather? The new climate–economy literature. *Journal of Economic Literature* 52:740–798.

Deschenes, Olivier. 2014. Temperature, human health, and adaptation: A review of the empirical literature. *Energy Economics* 46:606–619.

Deschênes, Olivier, and Michael Greenstone. 2011. Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the US. *American Economic Journal: Applied Economics* 3:152–185.

Deschenes, Olivier, and Enrico Moretti. 2009. Extreme weather events, mortality, and migration. *Review of Economics and Statistics* 91:659–681.

Deryugina, Tatyana, and Solomon M. Hsiang. 2014. Does the environment still matter? Daily temperature and income in the United States. Working paper 20750. Cambridge, MA: National Bureau of Economic Research.

Fishman, Ram Jason Russ and Paul Carrillo. Long-Term Impacts of High Temperatures on Human Capital and Economic Productivity, Institute for International Economic Policy, Working Paper 2015-18

Froom, P., Y. Caine, I. Shochat, and J. Ribak. 1993. Heat stress and helicopter pilot errors. *Journal of Occupational and Environmental Medicine* 35:720–732.

Graff Zivin, Joshua, and Matthew Neidell. 2012. The impact of pollution on worker productivity. *American Economic Review* 102:3652–3673.

———. 2013. Environment, health and human capital. *Journal of Economic Literature* 51:689–730.

———. 2014. Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics* 32:1–26.

Graff Zivin, Joshua, Solomon Hsiang and Matthew Neidell. Temperature and Human Capital in the Short- and Long-Run. NBER Working Paper 21157, May 2015

Graff Zivin, Joshua, and Jeffrey Shrader. 2016. Temperature extremes, health, and human capital. *Future of Children* 26:31–50.

Grether, W. 1973. Human performance at elevated environmental temperatures. *Aerospace Medicine* 44:747–755.

Horowitz, John K. 2001. The income-temperature relationship in a cross-section of countries and its implications for global warming. Working paper 01-02. College Park, MD: University of Maryland.

Hsiang, Solomon M. 2010. Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences* 107:15367–15372.

Huynen, M. Martens, Pim Martens, Dieneke Schram, Matty P. Weijenberg, and Anton E. Kunst. "The impact of heat waves and cold spells on mortality rates in the Dutch population."

Environmental health perspectives 109, no. 5 (2001): 463.

Isen, Adam, Maya Rossin-Slater, and R. Walker. 2015. Heat and long-run human capital formation. Unpublished manuscript.

Jones, Benjamin and Benjamin A. Olken. Climate Shocks and Exports. *American Economic Review*, Vol 100 No. 2 May 2010 (pp 454–59)

Kahn, Matthew E. The Climate Change Adaptation Literature, *Rev Environ Econ Policy* (Winter 2016) 10(1): 166–178, dio:10.1093/reep/rev023

Kjellstrom, T. 2011. Climate change, occupational health and workplace productivity. *Proceedings OH&S Forum* editors Harri Vainio and Suvi Lehtinen.

Kovats, R. S., and S. Hajat. 2008. Heat stress and public health: a critical review. *Annual Review of Public Health* 29:41–55.

Mackworth, Norman H. 1946. Effects of heat on wireless telegraphy operators hearing and recording Morse messages. *British Journal of Industrial Medicine* 3:143–158.

Mansur, Erin T., Robert Mendelsohn, and Wendy Morrison. 2008. Climate change adaptation: A study of fuel choice and consumption in the US energy sector. *Journal of Environmental Economics and Management* 55:175–193.

Mendelsohn, Robert, William D. Nordhaus, and Daigee Shaw. 1994. The impact of global warming on agriculture: a Ricardian analysis. *American Economic Review* 84:753–771.

Niemelä, Raimo, Mika Hannula, Sari Rautio, Kari Reijula, and Jorma Railio. 2002. The effect of air temperature on labour productivity in call centres—a case study. *Energy and Buildings* 34:759–764.

Park, Jisung. 2016. "Will we adapt? Temperature shocks, labor productivity, and adaptation to climate change in the United States (1986–2012). Discussion paper 2016-81. Cambridge, MA: Harvard Project on Climate Agreements.

Park, Jisung, and Geoffrey Heal. 2013. Feeling the heat: Temperature, physiology & the wealth of nations. Working paper 19725. Cambridge, MA: National Bureau of Economic Research.

Pindyck, Robert S. 2012. Uncertain outcomes and climate change policy. *Journal of Environmental Economics and Management* 63:289–303.

———. 2013. Climate change policy: What do the models tell us? *Journal of Economic Literature* 51:860–872

Schelling, Thomas C. 1992. Some economics of global warming. *American Economic Review* 82:1–14.

Schlenker, Wolfram, W. Michael Hanemann, and Anthony C. Fisher. 2005. Will US agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach. *American Economic Review* 95:395–406.

Seppanen, O., William J. Fisk, and Q. H. Lei. 2006. Effect of temperature on task performance in office environment. LBNL-60946. Lawrence Berkeley National Laboratory, Berkeley, CA.

Sherwood, Steven C., and Matthew Huber. 2010. An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences* 107:9552–9555.

Sudarshan, Anant, and Meenu Tewari. 2013. *The economic impacts of temperature on industrial productivity: Evidence from Indian manufacturing.* Working paper.

Tol, Richard S. J. 2009. The economic effects of climate change. *Journal of Economic Perspectives* 23:29–51.

Wilson, Edward O. 2002. *The future of life*. New York: Vintage.

Yew, Lee Kwan. 1999. As quoted in Dialogues on civilization. *New Perspectives Quarterly* 26:.

Abstract

This article reviews the recent literature on the economics of exposure to temperature extremes. There is growing evidence from both micro and macro studies that in the short run, exposure to extreme temperature affects health, labor supply, and labor productivity, although empirical research on potential adaptive responses in the long run remains thin. We argue that, in addition to providing well-identified causal estimates of heat-related damages, environmental economics has an important role to play in estimating the full welfare costs of temperature stress, taking into account behavioral responses and institutional settings.