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GOLDILOCKS ECONOMIES? TEMPERATURE STRESS AND THE DIRECT IMPACTS OF CLIMATE CHANGE

Geoffrey Heal
Jisung Park

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ABSTRACT

We review recent literature on the effect of temperature stress on economic activity, operating through basic human physiology. There is growing evidence from both micro and macro studies of causal impacts of extreme temperature on health, labor supply, and labor productivity, driven in large part by extreme heat stress. There is also a suggestion of an optimal temperature zone for economic activity, though empirical research on potential adaptive responses remains thin. This emerging literature has implications for the consequence of climate change, and may also provide a partial explanation of why hot countries are generally poorer than temperate or cold ones.

Geoffrey Heal
Graduate School of Business
516 Uris Hall
Columbia University
New York, NY 10027-6902
and NBER
gmh1@columbia.edu

Jisung Park
Department of Economics
Littauer Center
1805 Cambridge Street
Cambridge, MA 02138
jisungpark@fas.harvard.edu

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Abstract: We review recent literature on the effect of temperature stress on economic activity, operating through basic human physiology. There is growing evidence from both micro and macro studies of causal impacts of extreme temperature on health, labor supply, and labor productivity, driven in large part by extreme heat stress. There is also a suggestion of an optimal temperature zone for economic activity, though empirical research on potential adaptive responses remains thin. This emerging literature has implications for the consequence of climate change, and may also provide a partial explanation of why hot countries are generally poorer than temperate or cold ones.
Key words: climate, heat stress, productivity, climate change, temperature
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INTRODUCTION

Whether temperature affects human economic activity has long been a matter of interest. As Dell, Jones and Olken (2014) note, this interest goes as far back as the ancient Greeks, and continues in Arabic literature of the Middle Ages and European literature of the Enlightenment; biologists have noted climate-related differences in human morphology at least since Allen (1877). Recent interest in understanding the potential costs of climate change has generated renewed attention and imbued the debate with fresh policy relevance.

While much research in climate economics has focused on the *indirect* human impacts of changes in the earth's climate – for instance, the impacts of heat on crop yields or of sea-level rise on infrastructure – a nascent literature has highlighted the existence of additional *direct* impacts of extreme temperature operating through human physiology. These impacts can take the form of insults to health (morbidity and mortality), reductions in labor productivity and labor supply, as well as possible reductions in the rate of human capital accumulation, all of which may decrease GDP and overall social welfare in both the short and long run.

A wave of recent studies uses high-frequency weather variation to identify causal impacts of temperature stress on economic activity, especially as they operate through these more direct channels.[2] By using panel data, these studies are able to control for factors such as institutions or individual ability that may affect health and productivity but are unrelated to temperature (at least in the short run). For instance, Deschenes and Greenstone (2014) find that an additional day above 90°F leads to a 0.11% increase in annual mortality in the United States, controlling for location-specific characteristics. Similarly, Cachone et al (2013) document significant negative

[1] Columbia University and Harvard University, gmh1@columbia.edu and jisung park@fas.harvard.edu
[2] There are also a growing number of studies that identify causal impacts of weather variation on welfare operating through more indirect channels such as agricultural output and conflict. For an excellent review of this burgeoning literature, see Dell, Jones, Olken (2014).

impacts of extreme heat on automobile plant output in the U.S., controlling for plant-specific productivity and seasonality in production; a week with six or more days above 90°F reduces output that week by 8% on average. At the macro level, several studies including pioneering work by Dell et al (2012) find that hotter-than-average years reduce output growth, industrial value-added, and exports in many developing and middle-income countries.

This nascent literature may be viewed as part of a broader shift in perspective: from thinking of economic agents as affecting but being unaffected by the climatological features of their immediate environment, to more explicitly modeling the ways in which they may be adversely affected by temperature and weather – especially in the context of productive activity.

In light of recent methodological developments and renewed policy relevance, this paper reviews this emerging literature through a biological prism: that is, through a biological model of human economic activity under environmental stress.

We first provide a brief overview of the biological basis for direct, temperature-driven welfare impacts. We then present a stylized review of the emerging economics of temperature stress and human activity. The emerging consensus seems to be that extreme temperature stress is detrimental to economic activity, and that physiological channels related to labor supply and labor productivity may in part be driving the well-documented negative relationship between hotter years and lower output at the macro level. These effects are large: a loss of several percent of output in response to a one degree centigrade temperature shock is not uncommon.

We end with a discussion of potential policy implications, as well as directions for future research. As we describe in greater detail below, this new literature may have important implications for estimates of the social cost of carbon, especially to the extent that these are affected by possible distributional implications and impact heterogeneity. Incorporating possible adaptive responses by firms and individuals remains an important methodological challenge in connecting this rapidly evolving literature to more policy-relevant estimates of long-term climate damages.

DIRECT HUMAN IMPACTS OF TEMPERATURE

A Biological Model of Human Activity

Human beings are biological organisms. 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)". As such, we have clear biological constraints on the environments in which we can live and function comfortably.

A key feature of our environment is the combination of temperature, air pressure, 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 comfort zone, a narrow band (between 18°C and 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 intuit the link between temperature stress and human performance.

Most of the biochemical processes that keep us alive are temperature-sensitive, operating well only in a narrow range around 37 degrees C (98.6 Fahrenheit). We are hard-wired to keep our core temperature within this range, and automatically route blood away from the skin if we are too cold, towards it if we are too hot, and start sweating (or shivering) once excess heat (or cold) crosses a certain threshold. While there is some evidence for recent evolutionary adaptations, for the most part humans share a very similar baseline genetic adaptability to temperature (Campbell, 1974).

As the body heats, it uses its stores of water and salt to create sweat, which dissipates heat. When heat stress is prolonged and these stores are not adequately replenished, heat begins to cause dizziness, muscle cramps, and fever. In the extreme, hot or cold temperatures can cause acute cardiovascular, respiratory, and cerebrovascular reactions. 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 Schrader, 2015). Combined with humidity and intense physical exertion such as exercise or manual labor, heat can lead to acute cardiovascular or respiratory failure.

When humidity-inclusive temperatures (WBGT[3] or heat indices) reach 35°C (95°F), extended periods of outdoor activity become impossible for even the most physically fit adults, because human bodies can no longer dissipate heat (hyperthermia). While such temperatures do not occur regularly today, Sherwood and Huber (2011) point out that, in worst-case scenarios, climate change could make large swaths of the world uninhabitable for most of the year without extensive air conditioning.

Exposure to cold can have similarly adverse consequences for physical functioning as well, 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). On the whole, 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 prolonged.

Even at less extreme levels, temperature can influence human behavior in non-trivial ways. Task productivity has been shown to decline with temperature stress, beginning at even moderate deviations from the optimal zone (27°C). A longstanding literature in industrial ecology and physiology documents a systematic relationship between temperature stress and reduced performance (Seppanen et al. 2006). Lab experiments have quantified this relationship by randomly assigning subjects to rooms of varying temperatures and asking them to perform cognitive and physical tasks.[4] In a meta-review of the experimental literature, Seppanen et al. (2006) find that the average productivity loss from temperatures above 25°C is on the order of 2% per degree C for the various tasks surveyed, with non-linearity in responses as temperature deviate further from the optimum of roughly 20°C. Although most attention has focused on the consequences of high temperatures for performance, there is also a penalty from low temperatures, a fact that may be important in thinking about the potential distributional consequences of climate change.

[3] Wet bulb globe temperature.

[4] These include estimation of time, vigilance, and higher cognitive functions such as mental arithmetic and simulated flight (Grether 1973, Froom et al. 1993).

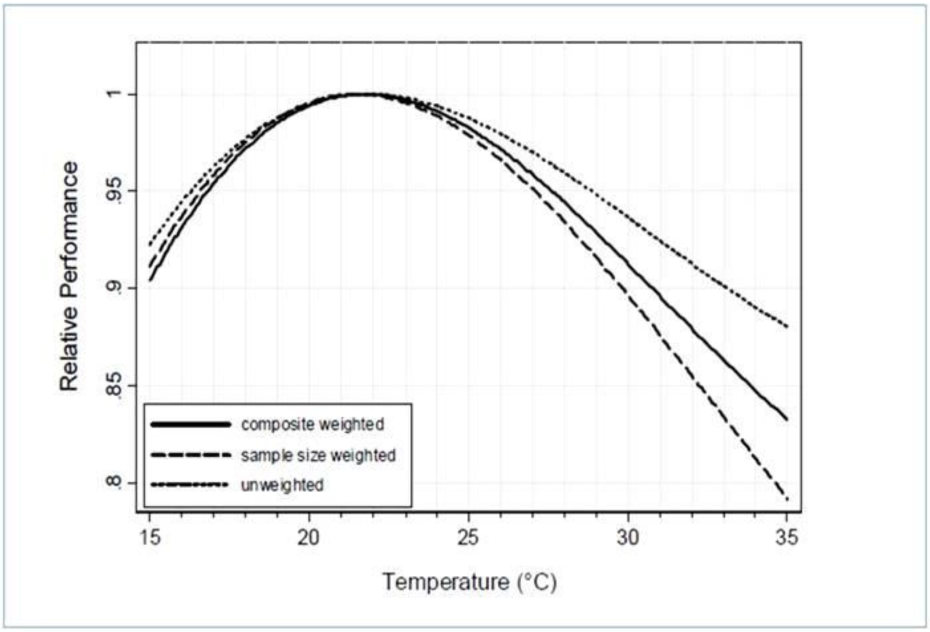

Figure 1: Temperature and Task Productivity in Laboratory Settings (Seppanen et al. 2006)

Methodological Challenges in Estimating Direct Human Impacts of Temperature Stress

Drawing the link from this physiological understanding to economically relevant contexts, especially for policy application, is not a trivial task. This is primarily due to issues of context and causal inference. First, we must account for the ways in which individuals respond to temperature stress, which requires estimation in economically relevant contexts. Second, there may be correlations between existing climates and other factors that affect health and productivity, factors that may or may not be readily observable to the econometrician (causal inference).

Context

Incentives and behavioral responses are important in the context of extreme temperature shocks, especially because there are many possible margins of adjustment, and because the final welfare impact will depend in part on the effectiveness and adjustment costs of adaptive responses. For instance, 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 take a taxi rather than walk to work. She may turn on a fan at her work station 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, work a night shift, or decide not to work that day at all, perhaps due to disturbed sleep the night before. If such heat shocks persist over time, she may attempt to switch occupations to a job that involves less physical exertion or provides better protection from the elements, or may decide to migrate to a milder climate altogether. To the extent that many lab experiments (such as those surveyed in Seppanen et al) are unable to account for these adjustments, one must be cautious in extrapolating from these lab-based point estimates to policy contexts.

As we discuss in more detail below, recent work by economists has placed a considerable focus on the difference between the biological and behavioral effects of temperature stress, a distinction that may be important when it comes to measuring welfare consequences of climate change (Graff Zivin and Neidell, 2013; Park and Heal, 2014).[5] Many recent empirical studies estimate impacts of temperature shocks on health or economic activity *in situ*, allowing the econometrician to identify impacts net of at least the short-run responses that individuals and firms may engage in. While accounting for potential long-run adaptive responses remains an important empirical challenge, the emerging consensus seems to be that there are, at least in the short run, significant productivity impacts due to temperature stress in economically relevant contexts.

Causal Inference

Omitted variables have posed a challenge for applying this physiological understanding to economic/climate policy because many previous economic studies have relied on cross-sectional relationships. Whether or not health and productivity are *causally* affected by temperature is important in two ways. First, it influences our historical understanding of the relative wealth of nations, and has important implications for a more policy-relevant understanding of the challenges that developing countries may have to overcome in achieving high standards of living. More prospectively, understanding whether temperature has a direct causal effect on productivity and health – rather than merely a correlational association operating through indirect channels (or arising from historical accidents, as suggested by Acemoglu and Robinson, 1999) – is crucial in estimating the true social cost of carbon.

Recent methodological advances have allowed researchers to isolate the causal impacts of temperature shocks by leveraging panel estimation methods, and to do so with an increasingly flexible characterization of the adaptive responses economic agents may undertake in situ. The rest of this paper focuses on studies that estimate direct physiologically-driven causal impacts of temperature stress in economic contexts.

The Emerging Economics of Temperature Stress and Human Activity

Mortality and Morbidity Impacts of Temperature Stress

Anecdotal evidence linking extreme heat and death abounds. In the heat wave of 2003 for example, France suffered approximately 14,000 heat-related deaths – over 40,000 for Europe as a whole. In the epidemiological literature, the effect of heat waves on mortality – particularly among infants and the elderly – is well documented (Kovats and Hajat 2008; Graff Zivin and Schrader, 2015). A growing body of work from the economics literature suggests that even in rich countries with high levels of electrification, extreme heat waves can trigger large-scale mortality responses (Deschenes and Greenstone 2014).

Deschenes and Greenstone (2014) use weather fluctuations at the daily level to identify annual mortality responses by state in the US. They find that an additional day with mean temperature exceeding 90° F leads to an increase in the annual age-adjusted mortality rate of about 0.11 percent. A day with mean temperature below 20° F is associated with an increase in annual mortality of roughly 0.07 to 0.08 percent. While mortality impacts arise from both hot and cold days, there seems to be greater non-linearity in response for heat than for cold. The authors also

[5] Park and Heal (2014) show that, for a wide range of functional forms, the response to a temperature shock away from thermoregulatory optimum will be the same for all margins of adjustment.

find evidence of adaptive responses by economic agents, both in the short and long run, which seem to mitigate mortality impacts considerably.

The impacts of extreme temperature on mortality are replicated in a variety of contexts. In a survey of the temperature-mortality literature, Deschenes (2012) notes that days above 90°F and below 40°F are associated with statistically significant increases in the annual mortality rate in the US across a number of different studies. Perhaps not surprisingly, these effect vary in size across the age distribution, with older individuals (e.g., 65+ or 75+) experiencing generally higher risk. Children are also more vulnerable to heat stress (Graff Zivin and Schrader, 2015).

In general, the lion's share of health impacts arises from a small number of acute extreme temperature events at the tails of the temperature distribution, though it is worth noting that most of the evidence comes from studies in developed economies such as the United States. There is limited evidence for avoidance behaviors that are effective at mitigating these impacts, but once again, causal estimates are limited to the U.S. context.

The Effects of Temperature Stress on Labor-Leisure Choices

As Graff Zivin and Neidell (2014) and Park and Heal (2014) note, responses by workers to temperature shocks may take many forms. Temperature stress may lead to a decline in direct task productivity in addition to causing direct disutility to the worker. These two direct impacts will in turn affect labor productivity, labor supply (hours worked), labor effort, and what one might call adaptive effort or defensive expenditures.[6]

Given the many margins of adjustment possible, having an underlying model based on the physiological intuition is important, especially if one is interested in performing welfare analysis of temperature-driven impacts.[7]

Consider a simple model of labor supply that extends the normal labor-leisure tradeoff. Utility depends on hours of leisure, income, core body temperature and effort expended. Task productivity also depends on core body temperature. Core body temperature in turn depends on the external temperature, and on effort. The relationship between productivity and temperature is single-peaked. Similarly, one can imagine that the relationship between utility and core body temperature is single-peaked, reflecting the fact that we are most comfortable at a core temperature of 37°C, and departures from this lead to a loss of wellbeing.

Within this framework the individual chooses hours of work/leisure and the level of effort to maximize utility, given a market-determined relationship between hours worked, productivity, effort and income. With minimal assumptions,[8] one can show that the single-peaked relationship between temperature and productivity (emerging from experimental work in laboratory conditions and summarized in figure 1) also emerges from an optimizing choice of working

[6] Park and Heal (2014) use the term "Effective Labor Supply" to encompass the realized labor inputs in the context of temperature stress, net of adjustments along these many margins by individual workers.

[7] However, as Park and Heal (2014) show, under most circumstances, the realized production impacts of an exogenous temperature shock can provide a sufficient statistic for welfare analysis, in principle allowing researchers to estimate temperature-driven welfare impacts without necessarily identifying the varying contributions of labor supply, task productivity, defensive expenditure, and direct disutility separately.

[8] Park and Heal (2014) assume quasi-linear utility, which abstracts away from income effects, and, importantly, abstract away from labor market imperfections, which may drive a wedge between the wage rate and the realized marginal product of labor.

hours and effort. An increase in temperature leads to more hours of work and more effort at low temperatures and fewer hours and less effort at high temperatures.[9]

Graff Zivin and Neidell (2014) report findings consistent with this stylized model. Using data from the American Time-Use Survey, they 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, workers in industries with high exposure to climate reduce daily time allocated to labor by as much as 1 hour, which represents a 14% reduction in labor supply. High exposure industries are defined as industries where the work is primarily performed outdoors, as well as manufacturing, where facilities are typically not climate-controlled and the production process often generates considerable heat.

The vast majority of this reduction happens at the end of the day when fatigue from prolonged exposure to heat has probably 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. This relationship is most pronounced for those not currently employed, who presumably have the greatest flexibility in their scheduling.

Labor Productivity in Developing Countries

Building on the experimental literature on task productivity under temperature stress, recent studies have explored the causal impact of extreme temperature on worker productivity in contexts such as call centers or manufacturing plants. The magnitudes of temperature impacts are remarkably consistent across a variety of contexts, though, as we note below, important work on long-run adaptive responses such as air conditioning remains to be done, especially to the extent that researchers are interested in using these estimates to inform climate policy.

Niemelä et al. (2002) examine the productivity of call center workers in different ambient temperatures and find that, above 22 degrees C, each additional degree C is associated with a reduction of 1.8 percent in labor productivity. Fisk et al. (2002) find similar results for call center workers, noting that high temperatures above 24-25 degrees C are associated with poorer performance.

Adhvaryu et al (2013) 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 decline as opposed to increased absenteeism. Sudarshan et al (2014) find similar plant-level productivity declines among Indian manufacturers, even when controlling for region, firm, and individual-specific factors. Hot days above 25 degrees C cause lower productivity in manufacturing plants, with a magnitude of roughly minus 2.8% per degree C. They are able to show that the effect is driven mostly through reduced worker productivity, as opposed to increased worker absenteeism due, for instance, to disrupted sleep during warm nights.

These studies occur in developing countries where air conditioning is, for the most part, a scarce commodity. There seems to be evidence, however, that labor productivity impacts of temperature stress occur even in developed economies such as the US, which one might suppose to have high levels of air conditioning penetration.

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[9] This has empirical significance in that it implies that the effect of an increase in temperature on productivity will depend on the initial temperature, being positive at low temperatures and negative at higher ones, and ambiguous somewhere in between.

Labor Productivity in Developed Economies

Cachon et al. (2013) take plant-level output data from 1994-2004 for one particular sector of the US economy – automobiles – and test whether hot days reduce output, controlling once again for fixed effects, as well as for other weather shocks (e.g. wind storms, snow, rain). They find that hot days are associated with lower output across the board. At the extreme, a week with six or more days above 90°C 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 by plant, the results suggest that, even in capital intensive industries of relatively well-adapted economies, the productivity impacts of extreme temperature may be non-trivial. It is particularly interesting that in a country as rich as the US, there is a negative impact of temperature shock on productivity: one might have thought that factories in the US would be fully adapted to their local climate and would have the resources to neutralize weather shocks, but this is apparently not the case.

The Macroeconomic Consequences of Thermal Stress

Recent studies also suggest that temperatures extremes affect labor supply and labor productivity at the level of regional and national economies.

Hsiang (2010) measures the impact of hotter-than-average years on output in 28 Caribbean countries from 1970 to 2006, while controlling for precipitation and cyclones. Unusually hot summers lead to nonagricultural output declines of 2.4% per 1°C that year. Two of the three affected sectors are service-oriented and provide the majority of output in these Caribbean economies, while the other affected sector is industrial (mining and utilities). Importantly, Hsiang (2010) isolates the impact of hot summers on output, as opposed to the potentially confounding influence of milder winters.

Dell et al. (2012) measure the effect of hotter-than-average years on industrial value-added within a global sample of 124 countries over the period 1950 to 2003. They find that hotter years are associated with lower economic growth, but only in poor countries (countries with below median world income in 1990). 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. They also find that hot years reduce the level of industrial output, again only in poor countries, to the tune of 2.04% 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 reduced production of electronic equipment and light metal manufactures, suggesting that the impacts are driven by direct productivity impacts rather than indirectly through spillovers from agriculture. Jones and Olken (2010) use trade data and find similar results: a 2.4% decline in exports per degree C hotter-than-average year in poor countries.

Park and Heal (2013) use similar cross-country weather data to Dell et al. (2012), but different income data, and test the hypothesis that the labor productivity impacts of a given temperature shock will vary 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 implied total factor productivity in already hot countries, and the reverse effect in colder countries.[10] Park and Heal also find that air conditioning seems to mitigate the impact of temperature stress in hot countries: hot countries with high levels of air conditioning per capita show less impact from high temperatures than those with low levels.[11]

Sub-national evidence from the United States strengthens the case for macroeconomic impacts driven by temperature stress and its effect on labor productivity. Deryugina and Hsiang and (2014) use county-level income data and find that days above 15°C are associated with negative income shocks which persist over the period 1969 to 2011. Similarly, Park (2015) uses US county-level payroll data from 1986 to 2012 and finds that there are adverse effects of hot days (above 90°F, 32°C) on non-agricultural output. A county with one additional day above 90°F (32°C) experiences 0.021% lower growth in per capita payroll the next year, an effect that is reversed in subsequent years, but which is magnified in regions that are not accustomed to heat stress at such extremes, which is taken as evidence for adaptation to heat stress.

Both Deryugina and Hsiang (2014) and Park and Heal (2015) find impacts on non-agricultural sectors, suggesting that the impact is not due to contemporaneous decline in agricultural yield. Furthermore, Park and Heal (2015) find that the sectors that experience the largest negative impact are construction and mining, both of which occur outdoors and involve significant manual labor and physical exertion (categorized according to NIOSH definitions).

Of course, while these macroeconomic associations are suggestive of labor-related impacts, one cannot rule out other correlated channels. While some of these studies measure non-agricultural output specifically, observed associations may be due to spillovers from agriculture, if yield reductions have general equilibrium effects in other sectors. Similarly, these impacts may in part be driven by demand-side responses. Perhaps individuals replace retail consumption such as going to the movies or eating out with more home produced consumables such as playing board games or eating in, in response to very hot or very cold days. Finally, it is as yet unclear how much of these impacts is driven by other weather patterns that are correlated with temperature but not controlled for by the econometrician, including wind speed, sunlight/cloud cover, as well as pollution levels, the last of which we discuss in some more detail below.

Figures 2 and 3 illustrate the effect of temperature on productivity at the level of counties in the U.S.. Figure 2 shows how non-agricultural payroll per capita varies with annual daily mean temperature, clearly showing a single-peaked relationship, and figure 3 shows how the same variable falls as the number of extremely hot days rises.

Levels Impacts vs Growth Rate Impacts

There is some ambiguity about whether temperature influences the level of output per capita or its rate of growth – an important distinction given the time-scales involved with future climate change (Pindyck, 2012).

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[10] Dell et al (2012) also find a positive effect of temperature in rich countries, but one that is not statistically significant. Rich countries are largely cold, so this finding and the positive impact of temperature in cold countries in Park and Heal are in general consistent with Dell et al (2012).

[11] Air conditioning per capita is constructed by cumulating trade data on imports of air conditioning equipment from the UN COMTRADE database.

A priori, it is not clear which is more likely. To fix ideas, consider a firm that manufactures widgets using some combination of labor, capital, and technology, all of which may depend on temperature.

On the one hand, the physiological and task productivity literature suggest a levels effect of temperature on production. Extreme temperature reduces worker productivity, effort, or labor supply that day/month/year, which would result in fewer widgets produced and sold. On the other hand, it may be the case that extreme temperature affects the rate of innovation in widget manufacturing. Perhaps the types of tasks and worker interactions that lead to new discoveries or production process enhancements are susceptible to heat-related disruptions.

Empirically, a negative levels effect of temperature on output in time t would manifest as a reduction in the growth rate of output from t to t+1, followed by faster-than-average growth once the temperature shock was reversed. A growth rate impact would manifest as a permanently lower baseline growth rate, which would affect the entire future trajectory of output.

What does the literature suggest? Hsiang (2010) and Deryugina and Hsiang (2014) document a levels relationship between income and temperature. Dell et al. (2012) find support for both levels and growth rate impacts in the case of poor countries only, and suggest that this may be because temperature affects innovation and investment. Park and Heal (2014) find evidence for a levels effect, albeit one with high persistence over time. The micro literature (e.g. Cachone et al, 2013) suggests a persistent levels effect as well: impacts that reduce the level of output relative to trend for some time, but which are eventually reversed once the temperature shock disappears.

A factor contributing to Dell et al (2012)'s suggestion that temperature affects the growth of output is that they find long lags in the impact of temperature on both variables. Even in the case of output per capita, they find that this is still affected by a temperature shock up to ten years after the shock. Park and Heal (2014) find the same: a temperature shock has an impact up to ten years after its occurrence. This persistence is not an obvious implication of the physiological model, which suggests that the impact of temperature shock should be short term: the task-performance effects of temperature are reversible (unless the temperature shock is extreme and results in permanent damage). Persistence of the consequences of a shock seems to suggest damage to some form of capital, human or physical or natural, as a result of the shock, or as Dell et al (2012) note, a reduction in the rate of innovation (which is damage to the rate of formation of intellectual capital). Somewhat suggestively, Dell et al (2012) find that hot years seem to affect investment, but not in a statistically significant way.

One possible mechanism that could cause long-term persistence of the consequences of a shock is the impact of temperature stress – or other forms of environmental stress – on pregnant women. Exposure to stress in pregnancy has been shown to cause low birth weight (among other adverse outcomes), which is correlated with lower performance of the child on a range of criteria later in life, including lower performance in standardized tests and lower earnings (Almond and Currie, 2011, Graff Zivin and Shrader 2015). This is a possible mechanism for multi-decadal persistence of the effects of temperature shocks.[12] Similarly, lagged impacts may be a product of the impacts of temperature stress on human capital accumulation: temperature extremes may interfere with the educational process, with students less able to concentrate when it is unusually hot, as

[12] Supporting this idea, a study by Fisman and Russ (2014) looks at the effect of *in utero* exposure to temperature stress in Ecuador, and finds a significant drop in lifetime earnings and test scores for people whose mothers experienced temperature shock while pregnant.

suggested by Graff Zivin, Hsiang and Neidell (2015), who find adverse impacts of ambient heat on standardized test scores.

Another such mechanism may work through pollution. In the presence of volatile organic chemicals and nitrogen oxides, heat creates ozone, which harms respiratory systems. Health damage from this source may persist after the heat-wave that created the ozone (Graff Zivin and Neidell, 2014). More generally heat may lead to a disease burden that remains after the heat has passed: for example, in El Nino 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 after effects of the disease will remain beyond the El Nino event.

In summary, there seems to be a significant negative impact of temperature stress on labor productivity in hot regions, though there is still significant disagreement over whether this is primarily a levels effect or a growth rate effect. There is remarkable consistency in the sizes of the effects across levels of analysis, with per degree C point estimates clustered around minus 2%. There is also evidence for a positive effect of abnormally high temperatures in cold countries.

IMPLICATIONS FOR POLICYMAKERS AND RESEARCHERS

While further research is needed to incorporate adaptive responses,[13] the recent literature provides valuable clues to researchers and policymakers regarding the potential welfare consequences of climate change, as well as understanding fundamental determinants of economic wellbeing and growth.

First, the existence of labor productivity impacts from temperature stress may imply that the social costs of carbon are systematically misstated. Most integrated assessments of climate damages do not include labor productivity impacts. As Tol (2009) notes in a review of 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 losses due to labor productivity decline are on the order of two percentage points of output per degree Celsius in hot countries, then this new channel alone would imply social costs of carbon that are much higher in those countries than current estimates, which take damages to be on the order of a few percentage points of world GDP.

Second, the focus on direct impacts of thermal stress sheds important insights on the possible distributional consequences of climate change. Evidence suggests that the net impact of warming on labor productivity in any given country may depend on the relative burden of heat and cold stress that country faces to begin with. As has been shown, the impact of a 1°C hotter-than-average year seems to vary considerably across geographic contexts, with large negative impacts in hot (and poor) countries, but possibly positive impacts in very cold countries (generally rich).

[13] As noted above, these point estimates may be biased predictors of the labor productivity impacts of future climate change, due to the possibility of long-run adaptation.

This potentially regressive effect of climate change is additional 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 believe the impacts of added heat stress due to climate change may be regressive. Poorer groups are less likely to be unable to afford adaptive equipment such as air conditioning, or even electrification and refrigeration. The mortality responses from temperature stress also seem to be much larger in developing countries and among lower income groups within countries, though it is not yet clear how much of this discrepancy is due to higher direct susceptibility versus impacts arising from interactions with other indirect channels such as agricultural yields (Graff Zivin and Schrader, 2015).[14]

Poorer individuals are also more likely to work in sectors that are more sensitive to temperature stress: namely, in manual labor-intensive industries and outdoor work intensive sectors such as agriculture or construction. It is also generally the case that manual labor and occupations intensive in outdoor work pay lower wages on average and exhibit less flexible work hours. According to the US Bureau of Labor Statistics, the average construction laborer makes 25 percent less than the median US worker, and laborers in Farming, Fishing, and Forestry occupations make 48 percent less.[15]

Third, this emerging literature emphasizes the importance of impact heterogeneity in the context of climate change. An aggregate effect of zero at the global level could be compatible with significant losses in hot countries and gains in cold ones, in which case at the aggregate or world level the net impact could be small. However, this net impact would disguise a redistribution of income from poor to rich countries (strictly, from hot to cold, but the categories overlap to a substantial degree). This means that, in order to understand fully the impact of temperature on welfare, researchers need to work with a disaggregated model that can differentiate between hot and cold countries – a capability lacking in some of the simpler integrated assessment models.

At the same time, the fact that non-agricultural sectors of the United States, one of the world's richest and presumably most well-adapted economies, are subject to productivity shocks due to routine temperature variation (Cachon et al. (2013), Deryugina and Hsiang (2014), Park and Heal (2015)) suggests that it is highly unlikely that even moderate amounts of warming will result in aggregate welfare gains.

CONCLUSIONS AND FUTURE DIRECTIONS

This paper has provided a review of the emerging literature on the direct impacts of temperature stress, viewed through the prism of human biology. This rapidly evolving literature raises many interesting questions, with relevance for researchers as well as policymakers.

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

[15] Poorer individuals are more likely to live in areas with higher levels of ambient air pollution, which we can interact with temperature in harmful and even deadly ways. (Graff Zivin and Neidell, 2014).

An Optimal Temperature Zone for Economic Activity?

Much of the existing economic literature on the deep determinants of growth has focused on the negative impact of heat. The stylized fact is often that hotter countries – as opposed to more inclement places – tend to be poorer. But the more recent literature suggests both heat and cold stress matter, though the impacts of cold stress seem somewhat smaller. Mortality impacts occur from both heat and cold (Deschenes and Greenstone, 2014); task productivity and labor supply declines in both extremes (Sepannen, 2006; Graff Zivin and Neidell, 2014, Park and Heal 2013). Even at the macro level, there seems to be increasing evidence for an optimal temperature zone for economic activity. Indeed, the historical focus on the adverse consequences of heat at the cross-country level may be a product of the fact that there are simply very few *nation states* in very cold places of the world. Studies that use sub-national data find evidence for reduced economic activity in cold-stressed areas, including Nordhaus (2006) who assesses output density per grid cell, Deryugina and Hsiang (2014) who use county-level income, and Park and Heal (2015) who look at county-level payroll per capita.

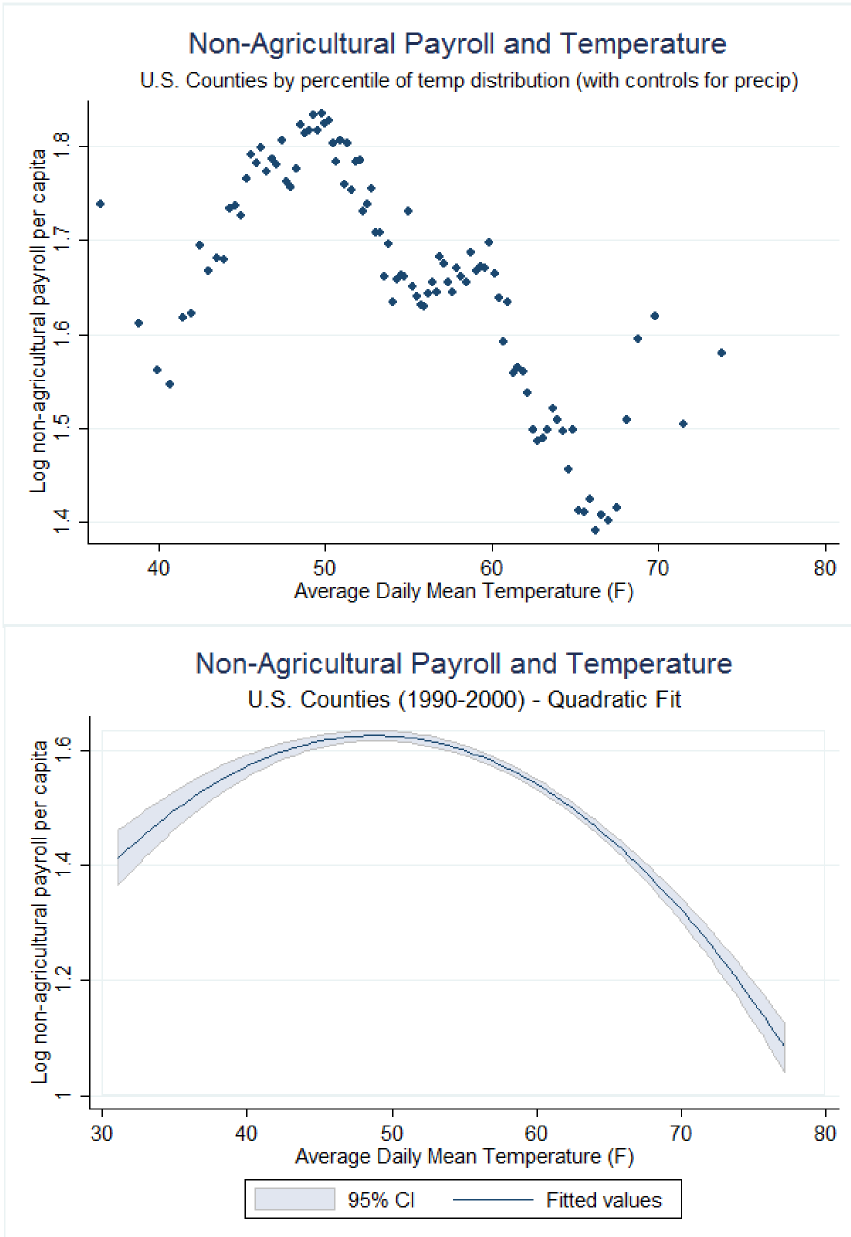

Figure 2: Payroll per capita vs temperature for U.S. counties

Whether extreme heat and cold both affect economic activity, or just heat alone, matters for a number of reasons. First, it is important in understanding which causal mechanisms are at play at the macro level. Second, it may be important in thinking about the net impacts from climate change, especially for higher latitudes. If warming is a spread preserving mean shift, and there are negative impacts from extreme cold which are reduced due to global warming, it may be possible for this to offset some of the negative impacts of warming, though the net welfare costs will depend on both the relative magnitude of current impacts as well as the relative costs of adaptive responses in either direction.[16]

[16] This literature may also inform longstanding debates regarding economic convergence. For instance, Barro and Sala-i-Martin (1992) examine panel data and find evidence for convergence both across countries as well as across

Mean-shifts versus Extreme Events: How Non-Linear are the Damages from Temperature Stress?

Do we expect most of the direct impacts from temperature stress to arise from the shift in the climatic mean – for instance, +4°F average annual temperatures? Or from the increased incidence of extreme temperature events: 40 more days above 90°F? An important research priority lies in figuring out the extent of non-linearity of temperature-driven economic impacts.

The agricultural literature documents clear non-linearities in the dose-response curve with respect to temperature (Schlenker et al, 2005), and the emerging literature seems to suggest that sharp non-linearities exist in the context of health, labor supply, and labor productivity impacts as well, though the evidence is not yet conclusive. This distinction plays an important role in determining whether moderate amounts of warming will lead to positive impacts for temperate rich economies, as has been suggested by many (e.g. Tol, 2009). From a methodological perspective, decomposing the varying impacts of mean-shifts versus changes in the incidence of extreme events may provide important clues to the extent of possible adaptive responses to long-run climate change, as well as the ways in which climate change will interact with existing labor market institutions and the welfare consequences thereof.

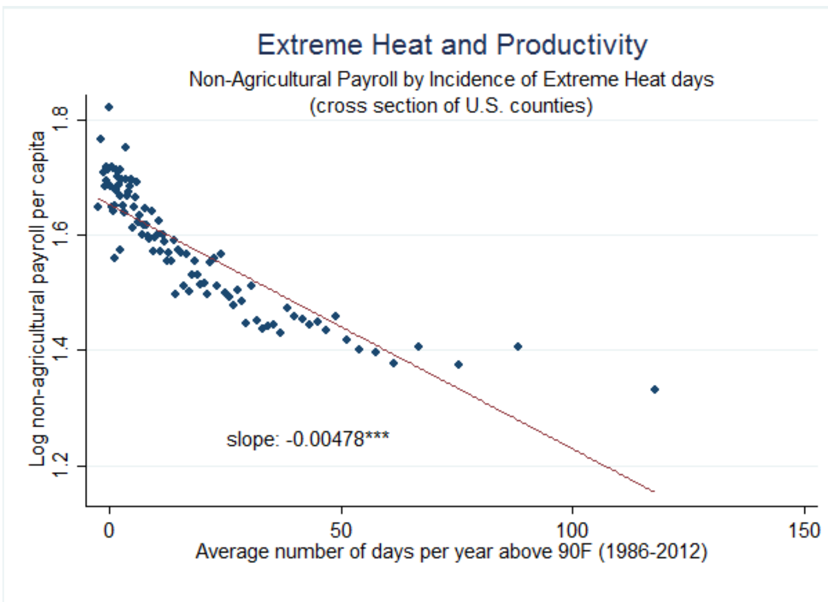

Figure 3: Payroll per capita vs. extreme heat days for U.S. counties.

The Speed, Scope, and Costs of Adaptation

Generally speaking, what researchers estimate in these panel studies are short-run weather-sensitivities, and one cannot simply extrapolate to obtain long-run climate-sensitivity estimates, due to the prospect of adaptation. Adaptations may be as simple as reductions in labor effort or

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states within countries, but that the implied rates of convergence are slower than would be expected given "reasonable" parameter values for technological progress, growth in the labor force, depreciation and time preference. While they explain this gap by suggesting broader definitions of capital it seems possible that hotter, poorer economies may exhibit less convergence than predicted by neoclassical growth models, which rely on diminishing marginal product of capital, because of the impact of hotter temperatures on effective labor supply and TFP growth.

hours or investment in air conditioning equipment. Of course, such seemingly simple adaptations may be prohibitively costly or effectively unavailable in many developing country contexts. An air conditioner is of no use if electric infrastructure fails at precisely the times of day when its cooling services are most in need.

Dell et al (2012) attempt to allow for this by working not just with annual data but with data grouped into longer intervals – up to ten years. They do not find evidence of significant adaptation, which would be manifest in the form of less temperature sensitivity in the cases of longer periods. Park and Heal (2014) also work with data intervals longer than one year, and find limited evidence of adaptation.

Deschenes and Greenstone (2014) suggest that air conditioning was a key driver of declines in heat-related mortality in the US, find that adult mortality due to heat in the US is higher in Northern states than Southern states, in part due to lower levels of air conditioning in Northern states, which experience fewer extreme temperature days. Park and Heal (2013) find that air conditioning can mitigate the impact of heat on productivity in hot countries, suggesting an important role for cooling technologies worldwide.

Overall we can now see temperature as a variable that matters to economic performance in its own right, and not as a determinant of other outcomes such as agricultural productivity or disease exposure. Using latitude as an instrument for institutions, as much of the macroeconomic growth and convergence literature has done in the past (e.g. Hall and Jones, 1999), seems less valid as an estimation strategy to the extent that one believes temperature exerts a causal influence on productivity. And while more research is needed to quantify the role that adaptive responses may play, the emerging consensus seems to be that extreme heat has direct and significant consequences for labor productivity even in regions and industries that one might expect to be well-adjusted to their thermal environments. As E.O. Wilson observes, we, as biological creatures, cannot ignore our evolutionary heritage and the temperature-sensitivities that it obliges.

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