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What's the Climate Worth?

By Marshall Burke

Later this month, policymakers from around the world will gather in Paris for a long-anticipated meeting to negotiate a new agreement addressing global climate change. The popular discourse and large amount of media coverage around this event suggest there is a lot at stake, and a commonly heard view is that these negotiations could be one of our last real chances to save the planet from substantial harm.

Unfortunately, things may be even more dire than previously estimated, at least from an economic perspective. When policymakers consider the economic damages caused by a warming planet, they often cite estimates that an increase of 4 degrees Celsius by 2100 will cost the world 4 percent of its gross domestic product (GDP).

It turns out that prediction might be too low. In a new study I co-authored with Sol Hsiang and Ted Miguel of Berkeley that was just published in the journal Nature, we show that existing estimates of the potential economic damages from climate change might understate damages by a factor of five or more. From a policy perspective, our findings suggest that investments in emissions reductions today might pay much higher dividends than we had previously assumed.

Figure 1 shows the main estimates of the relationship between changes in temperature and global economic output that are currently being used in policy discussions. These estimates constitute the so-called "damage functions" that are embedded in the main economic tools currently used to inform climate policy: the integrated assessment models (IAMs). Pioneered by the Yale economist Bill Nordhaus, IAMs are simple models of how the economy and the climate system interact. They specify a damage function — an assumed relationship of how economic output responds to changes in temperature — and then derive optimal decisions about how much to invest in mitigation by studying how the economy

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About The Author

Marshall Burke is a Faculty Fellow at the Stanford Institute for Economic Policy Research, a Center Fellow at the Center on Food Security and the Environment, and Assistant Professor of Earth System Science. He received his BA in International Relations from Stanford in 2003, and his PhD in Agricultural and Resource Economics from Berkeley in 2014. His research focuses on understanding how changes in environmental conditions affect a range of social and economic outcomes, and on understanding the causes and consequences of rural productivity improvements. He has authored over 20 published papers, which have appeared in both economics and science journals, including *Science, PNAS,* the *Review of Economics and Statistics*, and the *Economic Journal*, and which have been cited over 2,900 times.

and the climate are expected to co-evolve over many years into the future. The models and their damage functions were largely constructed in the 1990s and early 2000s, with the damage functions a combination of expert estimates and calibration to earlier studies. Output from these models has directly informed global policy decisions about emissions mitigation and also currently informs environmental rule making by individual governments (including the U.S. government).

As shown in Figure 1, damages in these models are assumed to be a relatively small share of global GDP for even reasonably large amounts of warming. For instance, the most negative estimate is 4 percent loss of global GDP by 2100 for 4 degrees Celsius of warming. To put this number in context, consider a world growing at 1 percent per capita between now and 2100, a rate well below the historical rate. At this growth rate, the world will be 133 percent richer by 2100 without climate change and — according to these numbers — at least 129 percent richer in a world 4 degrees Celsius warmer. Put another way, by the year 2100, climate change would have put us at most four years behind in per capita GDP terms from where we would have been otherwise — clearly not nothing, but somewhat at odds with a lot of the popular discourse about the damages that unmitigated climate change could bring.

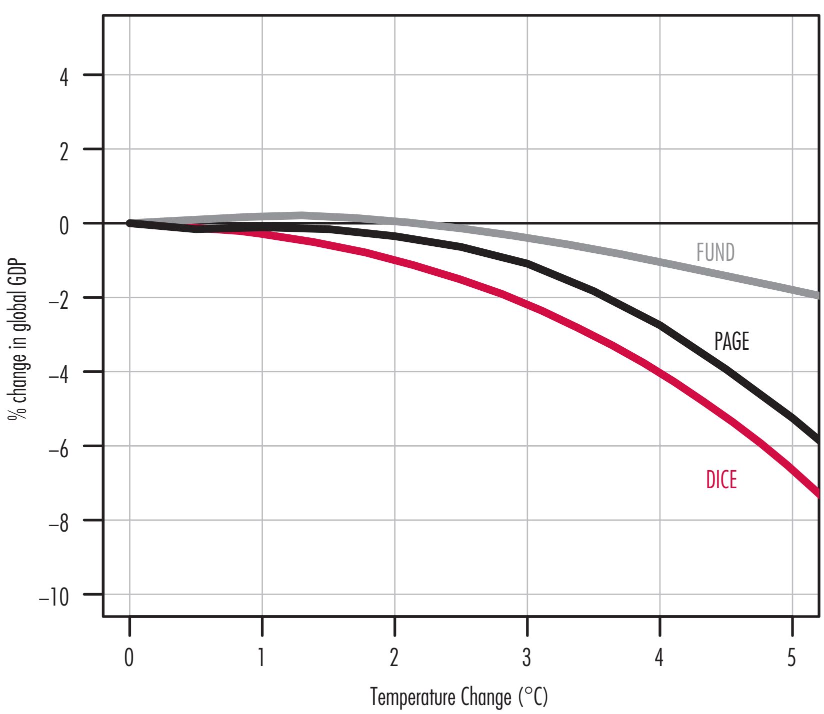
A very different picture of potential impacts emerges, however, from a host of recent micro-level studies. These studies seek to understand how future climate change might affect economic output by studying how particular building blocks of the economy — for instance, individual workers, agricultural fields, or manufacturing plants — have been affected by past fluctuations in temperature and rainfall.

Findings in this micro literature generally do not paint a very rosy picture of what happens when temperatures warm. As nicely summarized in a recent review article,[1] hotter than average temperatures are associated with falling agricultural output, lower labor productivity, lower cognitive performance, worse health outcomes, and increases in various types of violent human conflict. These results show up in both rich and poor countries alike. And key in nearly all these studies is an observed "nonlinear" response of these different outcomes to temperature, or the tendency of economic performance to peak at

Figure 1

Projected impacts on global GDP for a range of potential temperature increases by 2100, as predicted by three leading integrated assessment models (DICE, PAGE, and FUND).

Temperature increases are measured in degrees Celsius above "pre-industrial" levels (circa 1850). Data are from Revesz et al. 2014.



1 Melissa Dell, Ben Jones, and Ben Olken, 2014, *Journal of Economic Literature.*

relatively cool temperatures and decline rapidly at much hotter temperatures.

This discrepancy between aggregate impact projections in the IAMs and micro-level estimates is puzzling. How can it be that economies in aggregate are not affected by temperature rise, but most of their fundamental building blocks are? One possibility is that the micro-level results just don't add up to much when aggregated up. Alternatively, perhaps the damage functions in IAMs — and the policy recommendations they imply — fail to accurately capture how aggregate output might respond to a changing climate. As authors of some IAMs themselves admit, the parameters in these damage functions are often only loosely based on data. Other commentators have been less charitable, for instance, arguing that "the models' descriptions of damages are completely ad hoc, with no theoretical or empirical foundation."[2] Reconciling these apparent micro-macro estimates has clear policy importance.

Our recent *Nature* article attempts to reconcile these micro-macro differences. We first sought to understand how, over the last half century, aggregate economic performance at a country level has responded to temperature and rainfall fluctuations. To do this, we assembled data on per capita economic output, temperature, and rainfall for every country in the world where data were available. We ended up with about 50 years of data between the years 1960 and 2010 for more than 150 countries in the world.

We then analyzed these data using statistical techniques that help isolate the effects of temperature and precipitation from other country-level or global factors that might also affect economic output. Our approach is described in detail in the paper, but the thought experiment is fairly simple: Take any country in the world and compare its economic output in a year that is hotter than normal for that country with its economic output in an average temperature year for that country. Since year-to-year fluctuations in temperature and precipitation at a given location are fairly random, this approach allows us to isolate the effect of climate variation on economic performance.

The results of this experiment are shown in Figure 2. We find that countries with cool average temperatures, such as countries in northern Europe, tend to see higher than average economic growth when temperatures are warmer than average. In contrast, countries with relatively hot average temperatures, such as countries in the tropics, tend to see slower than average economic growth when temperatures warm. The effects here are large. For fairly hot or really cold countries, 1 degree Celsius changes in annual temperature have historically moved growth rates up (for cold countries) or down (for hot countries) by a percentage point — that is, a hot country goes from growing at 2 percent per year to 1 percent per year when historical temperatures increase by 1 degree Celsius.

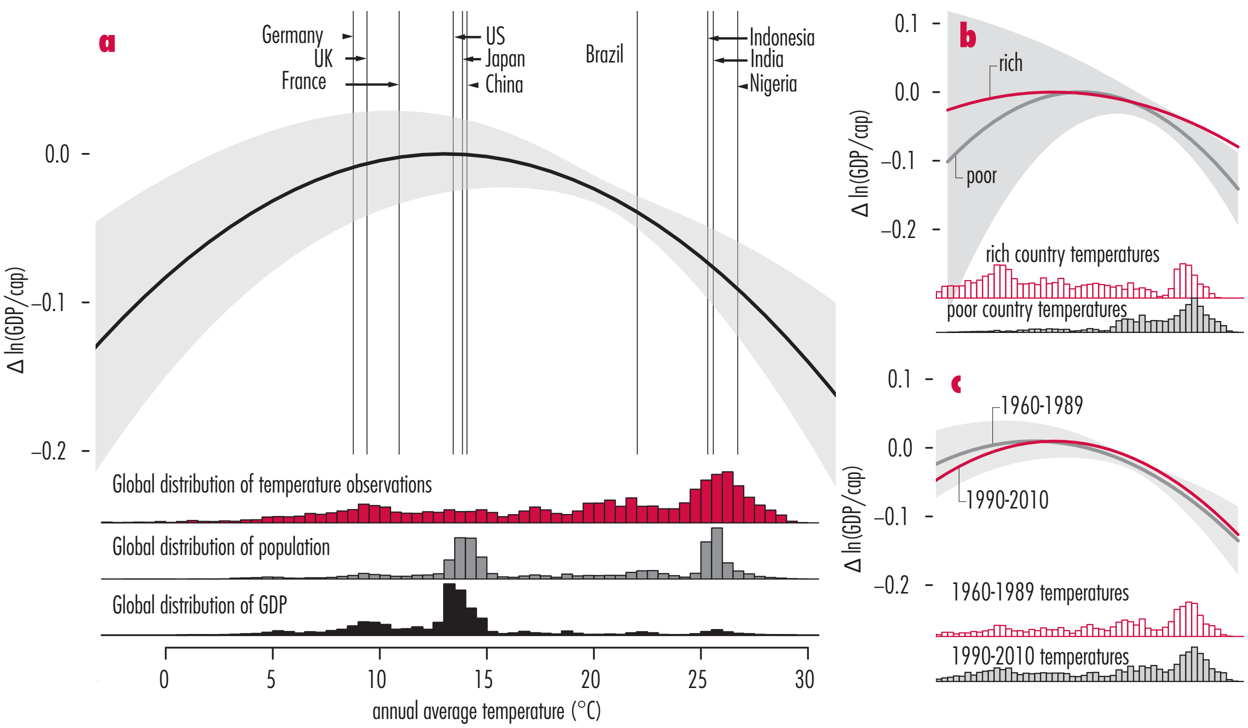
At a global scale, average growth appears to peak at an annual average temperature of around 13 C (55 F) — which happens to be near the annual average temperature of some of the world's largest economies (including the U.S. and China) and also happens to be very near the annual average temperature of some of the most productive places within these economies. For instance — coincidentally or not — both New York City and the California Bay Area have annual average temperatures very close to 13°C.

Two other things are notable in the historical data. First, we do not see any strong evidence that rich and poor countries respond differently to changes in temperature. As shown in the top-right panel of Figure 2, the rich country response curve is only slightly flatter than the poor-country response curve and the difference in slopes is not statistically distinguishable. A range of additional tests that we carry out in the paper suggest that differences in responses across countries are driven much more by differences in average temperature than differences in average income. This is consistent with the micro-level studies already discussed that document the negative effects of hot temperatures on many growth-relevant outcomes in rich countries (labor productivity, cognition, health). Second, as shown in the bottom-right panel of Figure 2, countries do not

2 See Robert Pindyck, 2013, *Journal of Economic Literature* 51(3), 860-872.

Figure 2

(a) Global response of growth in GDP per capita to annual average temperature, 1960-2010. Black line is estimated relationship, blue shaded area is confidence interval, and vertical lines show annual temperatures of major economies around the world. (b) Rich and poor country responses are statistically indistinguishable over the same period; blue region shows confidence interval for poor countries. (c) Global responses are similar during the 1960-1989 compared with the 1990-2010 period. (Reproduced from Burke et al., Nature, 2015)



appear to have gotten better at dealing with temperature fluctuations over time: The temperature response function in the earlier period of our data (1960-1989) mirrors that of the last two decades (1990-2010).

To us, these two pieces of evidence point to the difficulty that countries have had in adapting to changes in climate. Contrary to widespread conventional wisdom within the economics community, we do not see evidence in the historical data that wealth insulates economies from the effects of temperature fluctuations, nor do we see evidence that countries have gotten better at dealing with these fluctuations over time.

The final part of our paper projects potential future impacts of climate change by combining this historical understanding of how economies have responded to temperature change with climate scientists' estimates of how much temperatures might increase by the year 2100 under a "business-as-usual" emissions scenario. Our results are shown in Figure 3. Consistent with the historical data, we find that countries that are currently cooler than the historical 13 C optimum — which are typically higher-latitude countries — could actually benefit from global warming, perhaps substantially. But for the roughly three-quarters of the countries in the world that are at or beyond the current globally optimal temperature, climate change is projected to harm economic output — and

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harm it substantially for currently very hot countries in the tropics.

Globally, we find that under this business-as-usual warming scenario, the global economy could be more than 20 percent smaller by 2100 than it would have been had temperatures remained fixed at today's values. This does not mean that the world will be poorer in 2100 — it almost certainly will not, as there are countless other factors beyond climate change that will cause economies to continue to grow. Our results instead imply that the world will be substantially less rich than it would have been had temperatures not warmed.

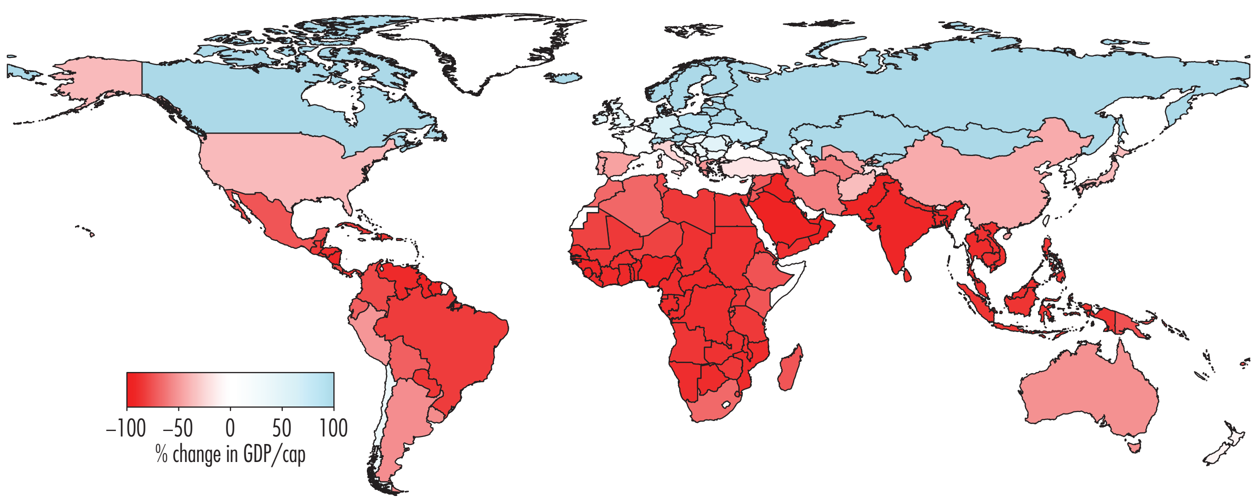
Why is this number so much larger than the existing IAM estimates shown in Figure 1? There are two main differences between IAM estimates and ours. The first is that, looking historically, we see that changes in temperature can affect the *growth rate* of economies and not just the *level of output* as assumed by IAMs. This is consistent with earlier evidence from poor countries,[3] and it is important because small impacts on the growth rate can add up to meaningful differences in the level of GDP. For instance, knocking even a tenth of a percentage point off the growth rate can lead to an overall GDP that is 10 percent lower after 100 years. The second reason our numbers are larger is that we find no evidence in the historical data that wealth insulates economies from changing temperatures. IAMs like FUND explicitly assume that countries become less sensitive as they growth wealthier, which means that large wealthy economies are relatively unharmed by changes in climate. Our read of the historical data suggests that this is unlikely to be true.

What do our results mean for policy? The main take-home is that the global economic benefit of emissions reductions could be substantially larger than previously assumed. These benefits still need to be weighed against the costs of undertaking these reductions — for instance, the costs of switching to cleaner sources of power — but our results likely mean that many mitigation options previously viewed as too costly might now be back on the table. There is likely a lot more at stake at the upcoming Paris meeting than we had thought.

3 Dell, Jones and Olken 2012, http://scholar.harvard.edu/files/dell/files/aej_temperature.pdf.

Figure 3

Projected percentage change in GDP per capita by 2100 under a business-as-usual emissions scenario, relative to a world in which the climate did not warm.



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