



REPLY TO ROSEN:

# Temperature–growth relationship is robust

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Rosen (1) argues that because our statistical model relating temperature to economic growth does not explain all of the variation in economic growth over the last half-century it cannot uncover the relationship between temperature and growth. This is a little like saying a medicine cannot possibly be effective at reducing headaches if it does not also address all other ailments. Just as there are many determinants of overall human health, there are many causes of variation in economic output. The point of our analysis is not to explain all of these sources of variation, but rather to plausibly isolate the role of temperature from these other sources.

To do so, we relate fluctuations in temperature to fluctuations in economic output, controlling flexibly for any differences between countries in either temperature or growth; for any factors causing either temperature or growth to trend smoothly within individual countries (e.g., increases in education or improvements in policies); and for shocks common to all countries (e.g., macroeconomic shocks). In essence, we ask whether a deviation from temperature trend in a given country caused a higher or lower deviation from growth trend in that country, after accounting for any other shocks to the global economy. Our method is not new, and has been the standard econometric approach for causal inference in panel data for at least 2 decades (see ref. 2 for the textbook treatment).

Further, in our paper we quantify the explanatory power of a model with only time trends versus a model that also includes temperature (figure S2 of ref. 3), and

report that “historical temperature fluctuations explain on average 8.6% of the overall variation in country-level annual income growth fluctuations” (3). In addition, we emphasize throughout the paper that the total impact for each country represents the accumulated impact of long-term temperature change. The magnitude of the accumulated impact relative to the annual impact is clearly illustrated in figure 1 of ref. 3.

Rosen (1) then argues that we force all countries to respond similarly to temperature. We disagree. First, our method allows countries at different temperatures to respond differently: Colder, wealthier countries can respond differently than hotter, poorer countries. Indeed, this is the whole point of using a flexible framework. Second, earlier work (4) showed evidence that differences in the structure of economies was not a clear determinant of how countries responded to temperature change, and that industrial economies—just like agricultural economies—can be strongly affected by changes in temperature. This latter finding is supported by a large body of subsequent research in the United States, China, and globally (5–7).

Rosen’s (1) final concern is that the historical regression did not give higher weight to larger countries. Rosen raised this same concern to the editors of *Nature* after Burke et al. (4) was published. As was shown in the response to that letter, weighting the regression by country size did not meaningfully change inference about how temperature affected output. As our paper (3) uses the same regression, this finding has not changed.

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- 3 N. S. Diffenbaugh, M. Burke, Global warming has increased global economic inequality. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 9808–9813 (2019).
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- 5 T. Deryugina, S. Hsiang, “The marginal product of climate” (NBER Working Paper 24072, National Bureau of Economic Research, Cambridge, MA, 2017).

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