Global non-linear effect of temperature on economic production

Marshall Burke, Solomon M. Hsiang & Edward Miguel

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Growing evidence demonstrates that climatic conditions can have a profound impact on the functioning of modern human societies1, 2, but effects on economic activity appear inconsistent. Fundamental productive elements of modern economies, such as workers and crops, exhibit highly non-linear responses to local temperature even in wealthy countries3, 4. In contrast, aggregate macroeconomic productivity of entire wealthy countries is reported not to respond to temperature5, while poor countries respond only linearly5, 6. Resolving this conflict between micro and macro observations is critical to understanding the role of wealth in coupled human–natural systems7, 8 and to anticipating the global impact of climate change9, 10. Here we unify these seemingly contradictory results by accounting for non-linearity at the macro scale. We show that overall economic productivity is non-linear in temperature for all countries, with productivity peaking at an annual average temperature of 13 °C and declining strongly at higher temperatures. The relationship is globally generalizable, unchanged since 1960, and apparent for agricultural and non-agricultural activity in both rich and poor countries. These results provide the first evidence that economic activity in all regions is coupled to the global climate and establish a new empirical foundation for modelling economic loss in response to climate change11, 12, with important implications. If future adaptation mimics past adaptation, unmitigated warming is expected to reshape the global economy by reducing average global incomes roughly 23% by 2100 and widening global income inequality, relative to scenarios without climate change. In contrast to prior estimates, expected global losses are approximately linear in global mean temperature, with median losses many times larger than leading models indicate.
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References


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**Author information**

These authors contributed equally to this work.
Marshall Burke & Solomon M. Hsiang

**Affiliations**

**Department of Earth System Science, Stanford University, California 94305, USA**
Marshall Burke

**Center on Food Security and the Environment, Stanford University, California 94305, USA**
Marshall Burke

**Goldman School of Public Policy, University of California, Berkeley, California 94720, USA**
Solomon M. Hsiang

**National Bureau of Economic Research**
Solomon M. Hsiang & Edward Miguel

**Department of Economics, University of California, Berkeley, California, 94720, USA**
Edward Miguel

**Contributions**
M.B. and S.M.H. conceived of and designed the study; M.B. and S.M.H. collected and analysed the data; M.B., S.M.H. and E.M. wrote the paper.

**Competing financial interests**
The authors declare no competing financial interests.

**Corresponding author**
Correspondence to: Marshall Burke

Replication data have been deposited at the Stanford Digital Repository (http://purl.stanford.edu/wb587wt4560).

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**Extended data figures and tables**

1. **Extended Data Figure 1:** Understanding the non-linear response function. (550 KB)
   a. Response function from Fig. 2a. **b–f**, The global non-linear response reflects changing marginal effects of temperature at different mean temperatures. Plots represent selected country-specific relationships between temperature and growth over the sample period, after accounting for the controls in Supplementary Equation (15); dots are annual observations for each country, dark line the estimated linear relationship, grey area the 95% confidence interval. **g**, Percentage point effect of uniform 1°C warming on country-level growth rates, as estimated using the global relationship shown in a. A value of ~1
indicates that a country growing at 3% yr\(^{-1}\) during the baseline period is projected to grow at 2% yr\(^{-1}\) with +1°C warming.

\(\hat{Y}\) : Dots represent estimated marginal effects for each country from separate linear time-series regressions (analogous to slopes of lines in b–f), and grey lines the 95% confidence interval on each. The dark black line plots the derivative \(\frac{\partial Y}{\partial T}\) of the estimated global response function in Fig. 2a. i, Global non-linearity is driven by differences in average temperature, not income. Blue dots (point estimates) and lines (95% confidence interval) show marginal effects of temperature on growth evaluated at different average temperatures, as estimated from a model that interacts country annual temperature with country average temperature (see Supplementary Equation (17); \(\frac{\partial Y}{\partial T_{it}} = \hat{\beta}_1 + \hat{\beta}_2 \cdot T_{it}\)). Orange dots and lines show equivalent estimates from a model that includes an interaction between annual temperature and average GDP. Point estimates are similar across the two models, indicating that the non-linear response is not simply due to hot countries being poorer on average. j–k, More flexible functional forms yield similar non-linear global response functions. j, Higher-order polynomials in temperature, up to order 7. k, Restricted cubic splines with up to 7 knots. Solid black line in both plots is quadratic polynomial shown in a. Base maps by ESRI.

2. Extended Data Figure 2: Growth versus level effects, and comparison of rich and poor responses. (444 KB)

a, Evolution of GDP per capita given a temperature shock in year \(t\). Black line shows a level effect, with GDP per capita returning to its original trajectory immediately after the shock. Red line shows a 1-year growth effect, and blue line a multi-year growth effect. b, Corresponding pattern in the growth in per-capita GDP. Level effects imply a slower-than-average growth rate in year \(t\) but higher-than-average rate in \(t + 1\). Growth effects imply lower rates in year \(t\) and then average rates thereafter (for a 1-year shock) or lower rates thereafter (if a 1-year shock has persistent effects on growth). c, Cumulative marginal effect of temperature on growth as additional lags are included; solid line indicates the sum of the contemporaneous and lagged marginal effects at a given temperature level, and the blue areas its 95% confidence interval. d–l, Testing the null that slopes of rich- and poor-country response functions are zero, or the same as one another, for quadratic response functions shown in Fig. 2. Black lines show the point estimate for the marginal effect of temperature on rich-country production for different initial temperatures (blue shading is 95% confidence interval) (d, g, j)), the marginal effect poor-country production for different initial temperatures (e, h, k), and the estimated difference between the marginal effect on rich- and poor-country production compared at each initial temperature (f, i, l). d–f, Effects on economy-wide per-capita growth (corresponding to Fig. 2b). g–i, Agricultural growth. j–l, Non-agricultural growth. m–u, Corresponding \(P\) values. Each point represents the \(P\) value on the test of the null hypothesis that the slope of the rich-country response is zero at a given temperature (m, p, s), that the slope of the poor-country response is zero (n, q, t), or that rich- and poor-country responses are equal (o, r, u) for overall growth, agricultural growth, or non-agricultural growth, respectively. m–u, Red lines at the bottom of each plot indicate \(P = 0.10\) and \(P = 0.05\).

3. Extended Data Figure 3: Comparison of our results and those of Dell, Jones and Olken5. (285 KB)

a, Allowing for non-linearity in the original Dell, Jones and Olken (DJO)\(^5\) data/analysis indicates a similar temperature–growth relationship as in our results (BHM) under various choices about data sample and model specification (coefficients in Supplementary Table 3). b, Projections of future global impacts on per-capita GDP (RCP8.5, SSP5) using the re-estimated non-linear DJO response functions in again provide similar estimates to our baseline BHM projection (shown in blue, and here using the sample of countries with > 20 years of data to match the DJO preferred sample). c, Projected global impacts differ substantially between DJO and BHM if DJO’s original linear results are used to project impacts. Lines show projected change in global GDP per capita by 0- and 5-lag pooled non-linear models in BHM (blue), and 0- and 5-lag linear models in DJO (orange). d, Projected regional impacts also differ strongly between BHM’s non-linear and DJO’s linear approach. Plot shows projected impacts on GDP per capita in 2100 by region, for the 0-lag model (\(x\)-axis) and 5-lag model (\(y\)-axis), with BHM estimates in blue and DJO estimates in orange. See Supplementary Discussion for additional detail.

4. Extended Data Figure 4: Projected impact of climate change (RCP8.5, SSP5) on regional per capita GDP by 2100, relative to a world without climate change, under the four alternative historical response functions. (672 KB)

Pooled short-run (SR) response (column 1), pooled long-run (LR) response (column 2), differentiated SR response (column 3), differentiated LR response (column 4). Shading is as in Fig. 5a. CEAsia, Central and East Asia; Lamer, Latin America; MENA, Middle East/North Africa; NAmer, North America; Ocea, Oceania; SAsia, South Asia; SEAsia, South-East Asia;
SSA, sub-Saharan Africa.

5. Extended Data Figure 5: Projected impact of climate change (RCP8.5) by 2100 relative to a world without climate change, for different historical response functions and different future socioeconomic scenarios. (388 KB)
   a–p, The first three columns show impacts on global per-capita GDP (analogous to Fig. 5a), for the three different underlying socioeconomic scenarios and four different response functions shown in Fig. 5b. Last column (d, h, l, p) shows impact on per capita GDP by baseline income quintile (as in Fig. 5c), for SSP5 and the different response functions. Colours correspond to the income quintiles as labelled in d. Globally aggregated impact projections are more sensitive to choice of response function than projected socioeconomic scenario, with response functions that allow for accumulating effects of temperature (LR) showing more negative global impacts but less inequality in these impacts.

6. Extended Data Figure 6: Estimated damages at different levels of temperature increase by socioeconomic scenario and assumed response function, and comparison of these results to damage functions in IAMs. (327 KB)
   a, Percentage loss of global GDP in 2100 under different levels of global temperature increase, relative to a world in which temperatures remained at pre-industrial levels (as in Fig. 5d). Colours indicated in figure represent different historical response functions (as in Fig. 5b). Line type indicates the underlying assumed socioeconomic scenario: dash indicates ‘base’ (United Nations medium variant population projections, future growth rates are country-average rates observed 1980–2010), dots indicate SSP3, solid lines indicate SSP5. b–d, The ratio of estimated damages from each IAM using data from ref. 12 (shown in Fig. 5d) to damages in a. Colours as in a for results from this study; IAM results are fixed across scenarios and response functions. Temperature increase is in °C by 2100, relative to pre-industrial levels. e, Explanation for why economic damage function is concave: increasingly negative growth effects have diminishing cumulative impact in absolute levels over finite periods (see Supplementary Discussion). Red curve is $e^{\delta \zeta}$ after $\zeta = 50$ years.

Extended Data Tables
1. Extended Data Table 1: Regression estimates for global sample, main estimate and robustness (107 KB)

2. Extended Data Table 2: Comparing temperature effects on per-capita growth in rich versus poor countries (133 KB)

3. Extended Data Table 3: Projected impacts of climate change on global GDP per capita by 2100 under RCP8.5, relative to a world without climate change (147 KB)

Supplementary information

PDF files
1. Supplementary Information (1.1 MB)
   This file contains Text and Data, Supplementary Tables 1-3 and additional references (see Page 1 for more details).