How Much Will Global Warming Cool Global Growth?

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Abstract

Does a permanent rise in temperature decrease the level or growth rate of GDP in affected countries? Differing answers to this question lead prominent estimates of climate damage to diverge by an order of magnitude. This paper combines indirect evidence on economic growth with new empirical estimates of the dynamic effects of temperature on GDP to argue that warming has persistent, but not permanent, effects on growth. We start by presenting a range of evidence that technology flows tether country growth rates together, preventing temperature changes from causing country-specific growth rates to diverge permanently. We then use data from a panel of countries to show that temperature shocks have large and persistent effects on GDP, driven in part by persistence in temperature itself. These estimates imply future global losses of 8 13% of GDP (or 2.2 to 3.5% per 1 degree Celsius warming) – three to six times larger than level effect estimates and 25 to 70% smaller than permanent growth effect estimates, with larger discrepancies for initially hot and cold countries.

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1 Introduction

The economic impact of global warming economic impacts plays a critical role in the research on optimal climate policy (e.g. Golosov, Hassler, Krusell and Tsyvinski, 2014; Acemoglu, Akcigit, Hanley and Kerr, 2016; Barrage, 2020), cost-benefit analysis on emissions reduction proposals (e.g. Ricke, Drouet, Caldeira and Tavoni, 2018; Burke, Davis and Diffenbaugh, 2018), and analysis of adaptation to climate change (e.g. Desmet and Rossi-Hansberg, 2015). Despite the central importance of mapping temperature changes to GDP in climate change economics, there is no consensus on the likely size of the effects. The most commonly used estimates in the literature differ by an order of magnitude, with first-order implications for climate policy (Moore and Diaz, 2015). Estimates that follow from the seminal Nordhaus (1992) DICE model suggest that, in the no-abatement emissions scenario, temperature changes will cost the global economy approximately two to three percent of GDP in 2099.[1] In contrast, a second strand of damage estimates that follow from the work of Burke, Hsiang and Miguel (2015) suggest that global warming will cost the world economy 20 to 30% of GDP in 2099.

The sharp divergence of estimates arises from disagreement over whether a permanent change in temperature will affect the levels or growth rates of income in the long run. Damage estimates in DICE are calibrated to evidence on sector-by-sector climate change impacts (see Nordhaus and Moffat (2017) for a summary) that allow warming in each period to affect output only in that period.[2] Conversely, Burke, Hsiang and Miguel (2015) use historical data to conclude that permanent changes in temperature will affect the long run *growth rate* of income. Their paper projects that countries will experience permanent growth effects from warming, with hot countries growing ever poorer and cold countries experiencing accelerating growth as they warm. However, their paper also cautions that it is difficult to discern level effects from growth effects precisely. Due to the limited number of available countries and years and the (mostly) small and transitory fluctuations in temperatures, it is inherently challenging to use a purely empirical approach with historical data to project the effects of large, permanent

[1] Barrage and Nordhaus (2023) find a 1.6% global GDP loss from 3°C of warming, and a 3.1% loss when incorporating adjustments for possible tipping points and unmeasured non-market impacts.

[2] Other estimates using sector-level micro data, such as Cruz (2021) and Nath (2021), find similar magnitudes for the contemporaneous impact of temperature on GDP.

changes in future temperatures.

This paper combines a model-based interpretation of facts about economic growth with empirical estimates from a new econometric model of the dynamic effects of temperature on GDP to make a new set of long-run projections of the impact of warming on incomes. We start by presenting a simple, stylized model of endogenous growth across countries that we use to clarify the conditions under which changes in temperature could cause permanent changes in country-specific growth rates. In the model, technological progress is produced jointly across all countries at the global frontier, and diffuses across borders such that each country's productivity is determined by a combination of domestic and international factors. Countries differ permanently in their levels of income, but they all grow at the same rate in the long run. The speed of convergence toward these parallel growth paths — as well as the persistence of effects from a transitory shock — are determined by a parameter that governs the share of domestic growth that depends on foreign technologies. In the model, the global rate of economic growth is endogenous, but individual countries can follow permanently divergent growth paths only if this parameter is zero, such that domestic growth depends exclusively on domestic factors.

We present a range of evidence that global growth is tied together across countries, which suggests that country-specific shocks are unlikely to cause permanent changes to country-level growth rates. In the data, countries at the frontier of global technology tend to grow at similar rates, with no discernible correlation between country growth and country patenting. Related, differences in levels of income across countries persist strongly, while growth differences tend to be transitory. This is consistent with a model in which countries follow a common growth process but can vary dramatically and permanently in their levels of income. Finally, the evolution of TFP in rich countries explains a meaningful, though modest, portion of TFP growth in non-OECD countries. Together, these facts point to a model in which international spillovers prevent countries from differing permanently in their growth rates as temperatures change. This argument relates closely to that of Dell, Jones and Olken (2009), who show that growth effects of temperature can only be reconciled with the global cross-sectional gradient of income and temperature if convergence or adaptation forces prevent any growth effects from being permanent. This does not rule out, however, that permanent temperature changes can have *persistent* effects on growth for years, or even decades, as countries transition toward a new steady-state path.

To investigate whether future changes in temperature are likely to have persistent effects on growth, we use 1960–2019 data from a panel of countries to estimate the dynamic effects of temperature on GDP. We highlight several difficulties in specifying the econometric relationship between temperature and GDP that can account for part of the divergence in existing estimates. These concerns include omitted lags that can bias coefficients and create the appearance of growth effects, the approach to modeling nonlinearities in temperature, and the complications introduced by the serial correlation of temperature. To confront these issues, we estimate a nonlinear state-dependent model in which temperature shocks (rather than temperature itself) are the treatment and their effects on both temperature and GDP can vary with a country's average temperature. To allow even greater flexibility, we also estimate a linear model country-by-country and then assess how the estimated effects vary nonlinearly with country mean temperature as well as with other factors, such as the level of development.

We use Jordà's (2005) local projections method to estimate the dynamic response of both temperature and GDP to the temperature shock. The impulse response functions show that shocks to temperature have remarkably persistent effects on GDP, with the direction of the effect depending on a country's initial temperature. In hot countries (25°C), an unexpected 1°C increase in temperature reduces GDP by approximately one percentage point in the year of the shock. GDP remains depressed for years after the shock, with a slightly larger effect on output five years after the shock is realized. Cold countries show the opposite pattern, with unexpected increases in temperature boosting output persistently for several years, though the effects are smaller than in hot countries. Consistent with previous work, our estimates imply a bliss point of approximately 13°C, which is that experienced by the 10th percentile of the present day global population.

An important finding of our empirical estimates is that temperature shocks themselves show some persistence, which varies with a country's average temperature. When hot countries experience a shock to temperature in a given year, approximately 40% of the effect of the shock persists in the following year, and 20% remains five years later in the specification with year fixed effects. The persistence is even greater when we do not control for year fixed effects. Thus, the historical record allows for measuring the medium-run GDP effects of temperature shocks that consist of a mixture of transitory and permanent components, which is more informative about permanent future warming than a set of purely transitory shocks would be. We use our simple growth model to interpret the joint persistence of GDP and temperature in the data, and show that it implies a convergence parameter consistent with permanent changes in temperature having medium-term growth effects that last for over a decade.

Finally, we use the empirical impulse response functions to project the impact of global warming on individual country economic growth through 2099. In particular, we use the ratio of the cumulative response of income to the cumulative response of temperature over a 10-year horizon to represent the long-run effect of a given increment of temperature on GDP. Importantly, we allow the effects to depend on a country's initial temperature according to the nonlinear estimates, which imply that hot countries will be harmed by warming and cold countries helped. Given the inherent difficulty in making future projections using historical estimates, we also show sensitivity to multiple projection approaches including a method following Sims (1986) that models warming as a sequence of repeated shocks, and a projection using our stylized model of global growth that allows for effects beyond the 10-year horizon measured in the empirical estimates.

Our projections suggest that 3.7°C of warming would reduce global GDP by 8-13% in 2099 relative to a scenario with no warming, or 2.2 to 3.7% per degree of warming. We obtain somewhat larger effects when using the alternative projection approaches. These damage estimates are three to six times larger than estimates that assume only contemporaneous level effects from temperature changes, and substantially smaller than projections in which the growth effects are permanent at the country level. Our estimates do allow for a permanent growth effect on the *global* technology frontier that adds close to one percentage point to the end-of-century losses, though we caution that we lack direct evidence substantiating projected impacts on technological innovation specifically.

Deviations between our persistent growth effect projections and previous approaches are especially sharp in initially hot and cold countries. In Sub-Saharan Africa, for instance, our projections imply that warming reduces output by 21%. In contrast, estimates that assume only a contemporaenous level effect of temperature would suggest a 5% decline in this region, and those that assume a permanent growth effect would suggest an 88% reduction by 2099. Conversely, in colder Europe, our estimates suggest warming will increase GDP by about 0.6%, whereas a permanent growth-effect projection would imply a near doubling of income.

Our effort builds on several related papers that project the effects of global warming on the global economy. Dell, Jones and Olken (2012) pioneered the empirical approach of using historical data to explore the temperature-GDP relationship, and showed that temperature has persistent negative effects on output in poor countries. Burke, Hsiang and Miguel (2015) followed by highlighting the nonlinear effects of temperature, with rising temperatures benefiting colder regions and harming hotter ones. Their paper was also the first to couple estimates from historical data with climate model forecasts of future temperature change to project the effects of global warming on country-level GDP.

More recent work employs a variety of empirical methods aimed at discerning whether a permanent increase in temperature has level or growth effects on income. Burke and Tanutama (2019) use sub-national panel data from 37 countries to show that temperature shocks have persistent effects on output. Colacito, Hoffmann and Phan (2019) find persistent effects of summer temperatures on state-level output in the U.S. Kahn, Mohaddes, Ng, Pesaran, Raissi and Yang (2021) estimate an autoregressive distributed lag model on country-level data and find that persistent absolute deviations of temperature from historical norms have negative growth effects. Bastien-Olvera, Granella and Moore (2022) use country-specific time-series regressions that filter out high-frequency variation, and find that temperature has persistent effects on output in many countries. Each of these papers concludes that their estimates are consistent with permanent effects of temperature on growth. Conversely, Newell, Prest and Sexton (2021) and Desbordes and Eberhardt (2024) argue for level effects. The former of these conducts a cross-validation exercise comparing the out-of-sample predictive power of a variety of specifications, yielding a preferred specification that implies damages of 1-3% of global GDP from several degrees of warming, similar to the magnitude of effects in existing DICE-style damage functions. Most recently, Bilal and Känzig (2024) use time series regressions of global GDP on global temperature to project a much larger 46% decline in global GDP by 2100.

A small number of related papers also motivate their empirical work using growth models. Kalkuhl and Wenz (2020) and Casey, Fried and Goode (2023) use closed-economy Solow and Ramsey growth models, respectively, to show that capital stock dynamics govern recovery from a transitory shock, whereas TFP drives long-run growth.[3] The

[3]Kahn, Mohaddes, Ng, Pesaran, Raissi and Yang (2019) also present a model of economic growth in

empirical work in these papers shows that the level of temperature does not affect growth when controlling for year-to-year changes in temperature, which they interpret to be consistent with long-run changes in temperature having level effects. These papers distinguish between exogenous and endogenous growth in TFP as the key criteria determining the long-run effects of global warming. In contrast, this paper argues that economic growth is endogenous only at the global level. In our projections, a permanent change in a country's temperature has persistent medium term growth effects that eventually recede into long run level effects. Thus, we project effects of warming that are much larger than those that assume exogenous growth at the country level, and much smaller than those that assume endogenous growth at the country level.

Before proceeding, it is worth acknowledging that a number of important topics in the economics of climate change go beyond the scope of this paper. These include, but are not limited to, valuation of non-market damages (e.g. Hsiang et al., 2013; Carleton et al., 2022), hurricanes and coastal flooding that are tied to global rather than national warming (e.g. Balboni, 2019; Desmet et al., 2021; Fried, 2022), climate tipping points (e.g. Lemoine and Traeger, 2016; Dietz, Rising, Stoerk and Wagner, 2021), valuation of uncertainty and risk aversion (e.g. Weitzman, 2009; Traeger, 2014; Barnett, Brock and Hansen, 2020; Kiley, 2024), and long run adaptation (e.g. Burke and Emerick, 2016; Cruz and Rossi-Hansberg, 2021; Moscona and Sastry, 2021; Nath, 2021; Rudik, Lyn, Tan and Ortiz-Bobea, 2021; Conte, 2022; Bilal and Rossi-Hansberg, 2023).

This paper focuses on the expected impact of rising temperatures on GDP, an exercise which is itself subject to important caveats. To start with, our estimates are based on the effects of changes in temperature over the range experienced by the countries in our sample. When we make projections for the already-hot countries going forward, we are relying on temperature environments beyond anything experienced in our data. Thus, projections for the already-hot countries are tenuous. In addition, we make projections for each country in isolation based on their current and future temperatures, and the simple model we use for interpretation accounts for global interconnectedness only through the diffusion of technology. As mentioned, climate change could unleash other global effects, such as tipping points, international migration, supply chain disruptions, shifting trade

which countries differ permanently in their baseline growth rates. The growth rate in their model falls with deviations from historical temperatures in either direction, but is independent of the level of temperature.

flows, or technological innovation that promotes adaptation. To the extent that this has not yet happened in our sample, our estimates exclude those effects.

The rest of the paper proceeds as follows. Section 2 lays out a simple model of global growth along with related patterns in the data. Section 3 highlights some econometric challenges in the analysis of temperature-GDP relationships, and discusses how best to avoid them. Section 4 presents our econometric framework and estimates. Section 5 offers long run projections of the effect of global warming on GDP by country and for the world as a whole. Section 6 concludes.

2 Background on globally-interconnected growth

2.1 A Stylized model of global growth

As discussed, projecting climate damages depends on whether a permanent change in temperature leads to a permanent change in the *level* of GDP or the *growth rate* of GDP. Given the consensus that long run growth is driven by technological improvements, the key question becomes whether a permanently higher temperature will affect the level or the growth rate of technology in the long run.

To clarify the conditions for level versus growth effects of rising temperatures, we present a stylized model of country technology growth rates. We provide the full model in Appendix A, and present only key equations and intuition here. As we proceed, we have in mind that temperature could have lasting effects via the efficiency or profitability of investments in technological improvements.

In this model, country i's income per capita can be expressed as:

$$Y_{it}/L_{it} \propto \cdot M_{it}^{\frac{1}{\sigma-1}} \cdot Q_{it}.$$

A country is richer the higher its mass of intermediate good varieties M and the higher its process efficiency Q. The number of varieties is linked to the size of the local market. The parameter $\sigma > 1$ is the elasticity of substitution between varieties; the lower this elasticity, the greater the "love of variety" and therefore the gains from having more variety.

A country's process efficiency, in turn, evolves according to

$$Q_{it} \propto \mu_{it} \cdot \left(Q_{it-1}\right)^{1-\omega} \left(Q_{t-1}^{*}\right)^{\omega}. \tag{1}$$

Here μ denotes the efficiency of technology adoption and innovation efforts in a country-year. Q^* is the process efficiency of countries at the technological frontier. The parameter $0 \leq \omega \leq 1$ governs the degree to which a country builds on frontier technology versus its own previous technology level. The process efficiency in frontier countries follows

$$Q^*_{t+1} \propto \mu^*_t \cdot Q^*_t.$$

One can think of shocks to adoption efficiency μ_{it} in a follower (non-frontier) country as generating transition dynamics in process efficiency. To convey the role of ω in such transition dynamics, suppose a country is on its balanced growth path with constant μ_i, and then is hit by a temporary negative shock to its technology adoption efficiency, μ_{it}, say due to rising temperatures. Figure 1(a) illustrates that a temporary shock has a purely temporary impact on a country's technology if $\omega = 1$. That is, if a country builds solely on technology in the frontier countries, then it will quickly recover. At the other extreme, when $\omega = 0$ and a country builds only on its own technology, the level effect is permanent. In intermediate cases ($0 < \omega < 1$) temporary μ shocks have persistent but not permanent effects on the level of a country's technology.

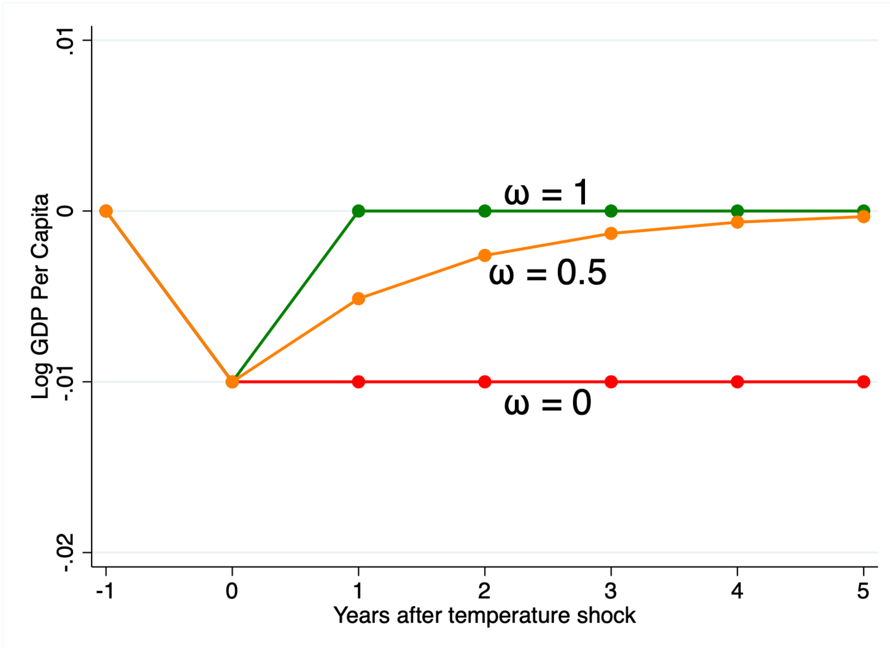
Figure 1(b) displays the effect of a *permanent* negative shock to a country's adoption efficiency. When $\omega = 1$, this has a permanent level effect. When $\omega = 0$, however, there is a permanent growth effect since the country is developing its own technology in isolation and will forever make less progress. When $0 < \omega < 1$ there is a persistent growth effect that builds to a larger permanent level effect. This is because future innovators build on inferior domestic technology. But there is no long run growth effect so long as $\omega > 0$, as in the presence of cross-country knowledge spillovers countries eventually grow at the same rate as the frontier countries. For a non-frontier country, its own adoption efforts ultimately have level effects but not growth effects.

2.2 Evidence consistent with globally-interconnected growth

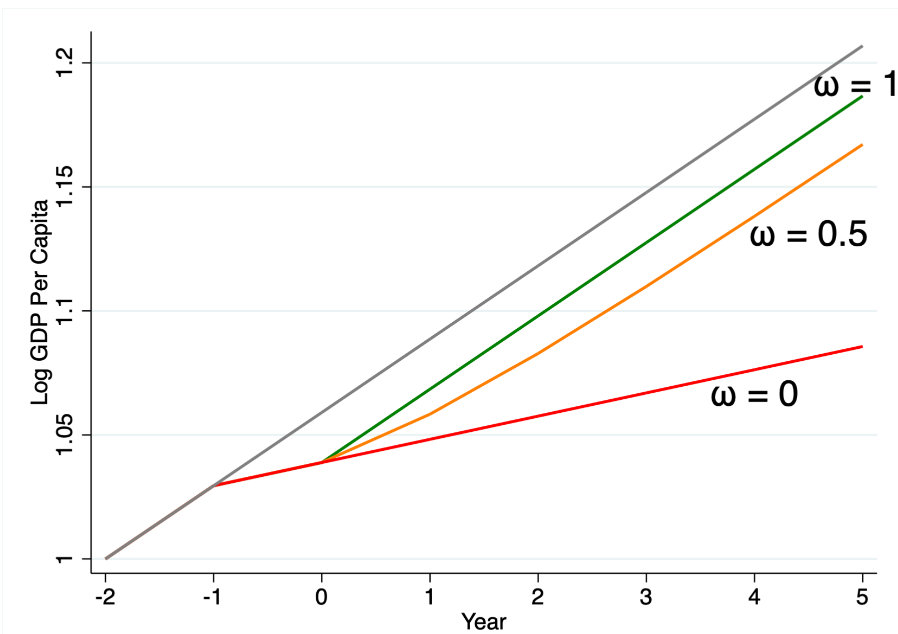
When contemplating the effect of a country's population size, human capital, climate, or other characteristic, a key question is whether one should think of its long run growth rate as connected to global knowledge spillovers ($\omega > 0$) or entirely independent ($\omega = 0$). In this section, we provide three pieces of evidence that point to interconnected growth in general. In the following section, we present some suggestive cross-country evidence that

Figure 1: Impact of ω on Speed of Convergence

(a) Recovery from a Transitory Shock in Year 0



(b) Growth Path Following a Permanent Shock in Year 0

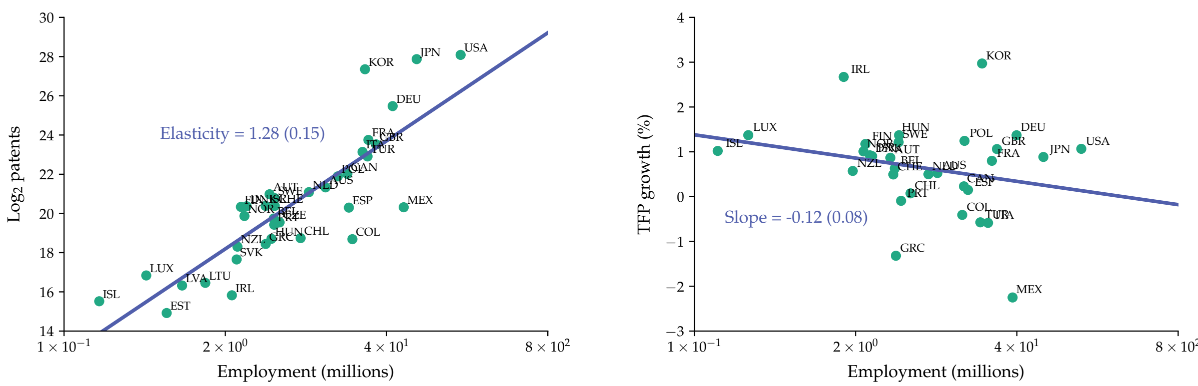


Notes: Graphs display model simulations of how the effects of shocks to a country's efficiency of technology adoption, μ, vary with the degree of international knowledge spillovers, ω. Panel (a) shows the effects of a temporary shock, and panel (b) shows the effects of a permanent shock relative to the baseline balanced growth path (gray line). $\omega = 1$ represents the case in which countries build only on global frontier technologies, and $\omega = 0$ represents the case in which each country has access to only its own technologies.

this interconnectedness also applies to temperature.

First, rich countries have grown at similar rates in recent decades despite different rates of domestic innovation. The left panel of Figure 2 plots patents filed in the U.S. by origin country employment in 2019 across OECD economies. Not surprisingly, countries with higher employment patent more. The right panel, however, shows that larger OECD countries exhibit no faster TFP growth. Consistent with ideas flowing across OECD economies, countries that innovate more do not grow faster.

Figure 2: Employment and Patents / Employment and Growth



Notes: Patents are from the U.S. PTO in 2019. Employment and TFP are from Penn World Table 10.0.

Countries also have persistently different investment rates in human and physical capital. Such differences are strongly correlated with country income *levels*, but not country *growth rates*. Easterly, Kremer, Pritchett and Summers (1993) and Klenow and Rodriguez-Clare (2005) document the weak connection of investment rates to income growth rates, and Klenow and Rodriguez-Clare (1997), Hall and Jones (1999), Caselli (2005), and Jones (2016) document the strong connection between investment rates and income levels.

For the second piece of evidence, we test whether country differences in TFP levels and growth rates persist over time, using data from 1960 to 2019 from the Penn World Tables (PWT). Table 1 presents regressions of levels and growth rates of TFP on year effects and a single country fixed effect. We run these regressions one country at a time such that the null hypothesis is that each country's TFP level or growth rate is the same as the global average over the sample period. One can reject common TFP *levels* for 55 to 70% of countries, depending on the specification, but can reject common TFP *growth rates* for only 2 to 9% of countries. Thus, level differences persist, but growth differences do not. We show this pattern visually in the top left panel of Appendix Figure A-9, which

Table 1: Tests of Country Differences in TFP Levels and Growth Rates

	(1)	(2)	(3)
Dependent Variable: Log Level of TFP			
Average p-value on Country FE	0.179	0.180	0.118
Percent of Countries with p-value < 0.05	54.9%	52.8%	69.7%
Dependent Variable: Growth Rate of TFP			
Average p-value on Country FE	0.773	0.475	0.514
Percent of Countries with p-value < 0.05	2.0%	9.0%	7.9%
Year FE	✓	✓	✓
Without Penn World Table Data Flag Countries		✓	✓
No Variety Adjustment			✓
Observations	3978	3471	3471
Countries	102	89	89

Notes: Data is over 1960 to 2019 from Penn World Table 10.0. For each country and year, we multiply the variable rtfpna by the 2005 ratio of ctfp/rtfpna for that country. We exponentiate the result by the inverse of the "labsh" variable to obtain TFP in labor-augmenting form. We then net out the potential contribution of variety by dividing by employment raised to the power $1/\sigma - 1$ using $\sigma = 4$. For the middle column we exclude countries the PWT flags as being outliers. For the third column we also drop the variety adjustment.

is adapted from Müller, Stock and Watson (2022). Table 1 also shows that the regression results hold with and without PWT outlier countries, and with and without adjusting for possible variety effects linked to the scale of a country's employment.

The third and final piece of evidence on interconnected growth comes from estimating ω using equation (1) from our simple model. Recall that ω governs the degree to which a country builds on the world frontier technology: $\omega = 1$ implies that a country builds solely on the world frontier technology whereas $\omega = 0$ implies that the country builds only on its own technology. We take logs and allow adoption efficiency μ_{it} to follow a country-specific AR(1) process. See Appendix A.3 for details on the estimation procedure.

Table 2 reports our high estimated weight (around 90%) on a country's prior technology level, but at the same time a statistically significant weight on frontier technologies

(5% to 13%). When we constrain the coefficients to sum to 1, the weights are 92.5% and 7.5% on domestic versus foreign technologies. A value of $\omega = 0.075$ ($1 - \omega = 0.925$) implies persistent effects on TFP levels from transitory shocks to country adoption efficiency, μ, and substantial medium run growth effects from a permanent change in μ. This is important to keep in mind when we later consider the possibility that higher temperatures in a country hinder its technology adoption and thereby have persistent effects on its TFP. The final column shows there may be some upward bias in OLS estimates of ω, as the true ω which generates an OLS ω of 0.075 in simulated data is 0.071.

Table 2: Regressions of Q_{it} on Q_{it-1} and Q^*_{it-1}

	Unconstrained		Constrained		Bias-Corrected ω
	Coeff. on $\ln Q_{it-1}$	Coeff. on $\ln Q^*_{it-1}$	Coeff. on $\ln Q_{it-1}$	Coeff. on $\ln Q^*_{it-1}$	Consistent with the constraint
Baseline	0.931	0.100	0.925	0.075	0.071
	(0.006)	(0.012)	(0.005)	(0.005)	
OECD Q*	0.935	0.133	0.928	0.072	0.063
	(0.007)	(0.022)	(0.006)	(0.006)	
No Employment Weighting	0.923	0.047	0.926	0.074	0.061
	(0.006)	(0.018)	(0.005)	(0.005)	
No Variety Adjustment	0.926	0.081	0.924	0.076	0.069
	(0.006)	(0.009)	(0.006)	(0.006)	
With Outlier Countries	0.890	0.103	0.890	0.110	0.073
	(0.007)	(0.021)	(0.007)	(0.007)	

Notes: The underlying data is from Penn World Table version 10.0. The baseline row uses U.S. TFP net of a variety adjustment as a proxy for Q*, weights countries by their employment, and excludes PWT outlier countries from the sample. The regression specification is equation (1), taking logs and allowing for μ_{it} to follow an AR(1) process with country-specific intercept, serial correlation, and innovation variance. The bias-corrected ω is the one that generates the constrained empirical OLS $\widehat{\omega}$ when OLS estimation is carried out on simulated data. See Appendix A.3 for details.

In sum, we have presented three pieces of evidence in support of interconnected growth (i.e., $\omega > 0$). Frontier countries grow at similar rates despite large differences in domestic innovation; level differences in incomes across countries tend to persist while growth differences do not; and frontier country TFP growth explains a significant, though modest, share of growth in non-frontier countries.

Our evidence adds to existing research finding that long run country growth rates are tied together. This work includes the conditional convergence literature, which says per capita incomes converge to parallel growth paths with levels determined by investment rates in physical capital, human capital, and technology. The development accounting literature sheds further light by decomposing differences in income into differences in inputs versus TFP. And the technology diffusion literature presents evidence of technology flowing across countries through patents, foreign direct investment, and trade. We summarize each of these rich bodies of evidence in Appendix B.

2.3 GDP-Temperature correlations

If $\omega > 0$ and temperature affects a country's adoption efficiency (μ_{it}), then temperature will affect the level of GDP per capita but not its long-run growth rate. To explore whether this prediction is consistent with the data, we estimate two cross-country regressions. In the first, we regress the log level of GDP per capita in 2019 on country average temperature. In the second, we regress average growth of GDP per capita from 1970 to 2019 on country average temperature.[4]

Figure 3 presents scatter plots along with the fitted values of the regressions. The left panel shows a clear negative relationship between the log level of per capita GDP and average temperature across countries. In the global sample of countries in 2019, each 1°C increase in average temperature is associated with 8.2% lower GDP per capita with a *t*-statistic of 7.7.[5] In contrast, the right panel shows little association between per capita GDP *growth* and average temperature across countries. Each 1°C is associated with only 0.025% lower average annual growth over the 50-year period, not statistically different from zero.[6] These results are consistent with globally-interconnected growth.

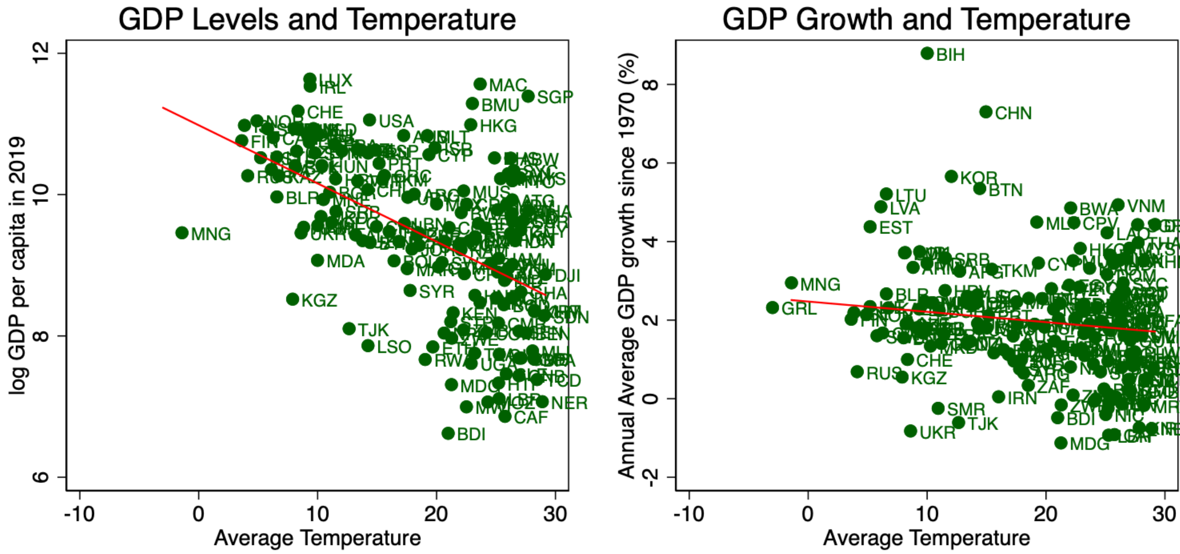
The cross-country evidence has advantages and disadvantages. As argued by Dell et al. (2009), the cross-sectional comparison between temperature and GDP levels has the advantage of capturing the long-run effects of exposure to heat on the macroeconomy,

[4]GDP levels are in PPP terms from the Penn World Tables (PWT,) and the growth rates are constructed from the World Bank's World Development Indicators (WDI) in constant local currency units. The WDI and temperature data are discussed below in Section 4.1.

[5]We exclude a small number of oil-intensive economies for this analysis that are disproportionately hot and rich. When including these countries, each 1°C is associated with 6.8% lower GDP per capita.

[6]Adding an additional control for the initial log level of GDP in 1970 approximately doubles the coefficient on temperature to 0.05% annual growth per °C, which is still small relative to the level differences and connotes a long run level effect in the conditional convergence literature *a la* Barro (1991).

Figure 3: Global Correlation With Temperature in Levels and Growth



Notes: Temperature data is from the Global Meteorological Forcing Dataset. GDP levels are from the Penn World Tables and GDP growth rates are from World Development Indicators.

including both the accumulation of effects over time and whatever efforts have been made to adapt to them. However, cross-sectional regressions have several disadvantages. First, they are subject to omitted variable bias. For example, hotter countries often have weaker institutions and it is difficult to ascertain whether temperature caused the weaker institutions and if so whether that causal link is still relevant in the modern world. Second, the cross-country estimates do not reveal anything about the intermediate-run effects of temperature. We cannot tell whether temperature shocks have purely transitory effects on economic output or persistent impacts that create growth effects in the medium term before countries converge back to the common growth path determined by global factors. For these reasons, we turn to country panel data analysis in the next two sections.

3 Modeling temperature effects on GDP in panel data

Historical panel data provides a potential path to improving causal identification and studying the effects of temperature on GDP at different time horizons. Estimating these effects accurately and using them to make out-of-sample projections of the effects of future global warming on future GDP, however, is an inherently challenging exercise. As Newell et al. (2021) demonstrate, point estimates can vary widely depending on the specification, and imprecision of estimates can render them statistically indistinguishable.

Using estimates based on variation within the historical range of temperatures to project the effects of steadily rising future temperatures adds another layer of complication.

This section outlines some of the econometric challenges associated with modeling the relationship between temperature and GDP, and demonstrates that the wide range of estimates in the literature owes partly to specifications that impose constraints that are not consistent with the data. The last part of this section introduces our econometric framework, which is designed to avoid these potential issues.

3.1 Modeling challenges

Here we highlight three challenges to estimating the effect of temperature on GDP. First, that recovering unbiased coefficients and distinguishing level and growth effects requires controlling for lags of both the independent and dependent variables. Second, that the most widely-used nonlinear model of temperature effects does not identify coefficients based on within-country variation alone and does not capture the data as well as a state-dependent alternative. Third, because temperature is serially correlated, temperature shocks rather than temperature itself should be used to estimate dynamic causal effects. Projecting the GDP effects of future climate change from historical data requires taking into account the dynamic response of both temperature and GDP following a shock.

3.1.1 Level vs. growth effects and the importance of including lags

Dell et al. (2012), Newell et al. (2021), and Casey et al. (2023) point out that some models common in the literature (e.g. the Burke et al. (2015) baseline specification) force temperature to have growth effects by regressing the *first difference* of log GDP on the *level* of a polynomial in temperature. Dell et al. and Casey et al. argue that one should instead include both a level and a first difference of temperature to determine whether temperature has level or growth effects, following Bond, Leblebicioğlu and Schiantarelli (2010). This requires no serial correlation in either GDP growth or temperature. Both GDP growth and temperature display significant serial correlation, however, so sufficient lags of *both* variables must be included to generate unbiased causal estimates of temperature on GDP. The literature often excludes lags of GDP growth, temperature, or both.[7]

[7]Notable exceptions are Kahn, Mohaddes, Ng, Pesaran, Raissi and Yang (2019), Acevedo, Mrkaic, Novta, Pugacheva and Topalova (2020), and Berg, Curtis and Mark (2023), who include lags of both GDP growth and temperature in their baseline specifications.

We illustrate the importance of including lags of both GDP growth and temperature using a stylized linear time series model that relates GDP growth to temperature:

$$\Delta y_{it} = \rho \Delta y_{it-1} + \beta T_{it} + \theta_1 T_{i,t-1} + \theta_2 T_{i,t-2} + \mu_i + \mu_t + \eta_{it}, \qquad \eta_{it} \sim \mathcal{N}(0, \sigma_\eta^2)$$

$$T_{it} = \gamma T_{it-1} + \lambda_i + \lambda_t + \zeta_{it}, \qquad \zeta_{it} \sim \mathcal{N}(0, \sigma_\zeta^2)\,.$$

Δy_{it} is GDP growth in country i in year t, T_{it} is temperature, and the μ's and λ's represent country and year fixed effects.

If temperature has only a transitory, one-period effect on the log level of GDP it must be the case that $\theta_1 = -\beta(1+\rho)$ and $\theta_2 = \beta\rho$. That is, the coefficients on the lagged values of temperature must reverse the previous effect on GDP growth. This is what Newell et al. (2021, p.4-5) mean by *sign reversal*. With no serial correlation of GDP growth ($\rho = 0$), temperature must enter as a first difference, i.e. $\theta_1 = -\beta$ and $\theta_2 = 0$, as argued by Dell et al. (2012) and Casey et al. (2023). However, GDP growth is serially correlated in the data, so the more general restrictions immediately above apply.

What happens if we estimate the model with the lagged temperature and GDP terms omitted? To answer this question, in Appendix C.1 we conduct some simple Monte Carlo simulations from a model in which temperature has a temporary, contemporaneous negative effect on the level of GDP and both temperature and GDP are serially correlated. The regressions on simulated data in Appendix Table A-1 have several key takeaways. First, a specification that omits the lags of both temperature and GDP will imply that temperature has a growth effect on GDP, and not capture that this effect is temporary rather than permanent. Second, when temperature is serially correlated, omitting lagged temperature causes the coefficient on contemporaneous temperature to be biased away from its true value. Third, while controlling for lagged temperature is sufficient to eliminate the bias on the contemporaneous coefficient on temperature, it is also necessary to control for lagged GDP growth to recover unbiased estimates for lagged temperature.

The algebraic example and the Monte Carlo experiment illustrate two main points. First, even without serial correlation of GDP or temperature, specifications that omit lagged temperature cannot distinguish growth effects from level effects because they do not measure reversals of the initial effect in subsequent years. For instance, we show in

Appendix C.2 that adding lags of temperature to the main specification in Burke et al. (2015) partially offsets the contemporaneous effect. Second, serial correlation in temperature and GDP growth imply that enough lags of both must be included to obtain unbiased estimates. How many lags one must include depends on the serial correlation properties of GDP growth and temperature and whether there are lagged effects of temperature.

3.1.2 Modeling nonlinear temperature effects

One of the most important contributions of Burke, Hsiang and Miguel (2015) is their consideration of nonlinear effects of temperature. Citing evidence such as agricultural studies of inverse U-shape relationships between crop yields and temperature, they hypothesized that the effects of temperature on aggregate GDP are likely to be nonlinear. Their baseline model specifies a quadratic in temperature, which has also been used in many subsequent papers.

Consider a model with the standard approach to representing nonlinearity:

$$\Delta y_{it} = \beta_1 T_{it} + \beta_2 T_{it}^2 + X_{it} + \eta_{it}, \tag{2}$$

where Δy_{it} is the growth rate of per capita GDP in country i in year t, T_{it} is temperature in country i in year t, X_{it} is a set of control variables that include country and time fixed effects and possibly lags of variables, and η_{it} is the error term. This type of nonlinearity in a fixed effects model results in the demeaned squared variable itself being a function of the group mean. Thus, the source of identification is not strictly from "within group" variation (McIntosh and Schlenker, 2006).

We propose an alternative specification to capture nonlinearities in the way temperature affects GDP. In particular, we argue that the nonlinearity is more likely to be *state dependence*, i.e., a shock to temperature will have different effects on GDP depending on the country's mean historical temperature.

Consider the simple case in which temperature is not serially correlated, so the shock is equivalent to the deviation from mean. We can decompose temperature in country i in year t into a country effect $\overline{T_i}$, a common year effect $\overline{T_t}$, and the shock τ_{it}. That is, $T_{it} = \overline{T_i} + \overline{T_t} + \tau_{it}$. Substituting this expression into the quadratic in temperature in (2) and combining terms that vary only by country or time with the fixed effect terms in the

X_{it}'s yields the following:

$$\Delta y_{it} = \beta_1 \cdot \tau_{it} + 2\beta_2 \cdot \overline{T_i} \cdot \overline{T_t} + 2\beta_2 \cdot \overline{T_i} \cdot \tau_{it} + 2\beta_2 \cdot \overline{T_t} \cdot \tau_{it} + \beta_2 \tau_{it}^2 + X_{it} + \eta_{it}. \tag{3}$$

This decomposition shows that including temperature as a quadratic implies that the temperature shock τ_{it} enters nonlinearly in several terms: a quadratic term, interaction terms between the temperature deviation and both country and year effects, as well as an interaction between country and year effects. Moreover, there are implied parameter constraints across the various terms. Critically, the second and third terms in (3) show that the variation used to identify β_2 comes not only from within-country variation in temperature, but also from variation in the average temperature across countries, $\overline{T_i}$. Thus time-invariant country variables may bias the estimation of the temperature quadratic.

Our proposed state-dependent model contains one nonlinear term that appears in the Burke et al. (2015) quadratic specification — the interaction of the temperature deviation τ_{it} with the country mean temperature $\overline{T_t}$ — but omits the other three nonlinear terms:

$$\Delta y_{it} \quad = \quad (\theta_1 + \theta_2 \cdot \overline{T_i}) \cdot \tau_{it} + X_{it} + \eta_{it} \quad = \quad \theta_1 \cdot \tau_{it} + \theta_2 \cdot \overline{T_i} \cdot \tau_{it} + X_{it} + \eta_{it},$$

A non-zero θ_2 allows the effect of a temperature shock on GDP to depend on a country's average temperature. This specification more clearly differentiates the parameters that rely on within- and between-country variation. To determine which model better fits the data, we estimate a model that contains both the quadratic in temperature and our state-dependent alternative. For the reasons given in the last section, we include three lags of temperature and GDP growth as controls along with the fixed effects.

Table 3 shows the estimates using our data. Column 1 shows the standard quadratic-in-temperature specification. Both the linear and quadratic term coefficients are statistically significant and the magnitudes imply marginal effects on contemporaneous GDP growth that change from positive to negative at temperatures above 11 degrees. Column 2 shows the estimates with both the quadratic term and our state-dependent term. The coefficient on the quadratic term falls to zero, while the state-dependent term is negative and statistically different from zero. Thus, the quadratic term is no longer informative once the state-dependent term is included. Column 3 shows the estimates for the model with just the linear term and our state-dependent term. Both are statistically different

Table 3: Testing the Quadratic in Temperature vs. State-Dependent Model

	Dependent Variable: GDP Growth in year t		
	(1)	(2)	(3)
Temperature$_{it}$	0.479*	0.881**	0.876**
	(0.276)	(0.282)	(0.286)
Temperature$^2_{i,t}$	-0.022**	0.002	
	(0.007)	(0.012)	
τ_{it}*$\overline{\text{temp}}_i$		-0.074**	-0.069**
		(0.029)	(0.017)

Notes: τ_{it} is the temperature shock. All regressions contain country- and year- fixed effects and three lags of temperature and GDP growth. ** indicates p-value < 0.05, * indicates p-value < 0.1

from zero. The estimates imply that the effects of temperature on current GDP switch from positive to negative for country mean temperatures of 13 and above. In sum, the data favor the state-dependent model over the quadratic-in-temperature model.[8]

3.1.3 Dynamic causal effects of temperature on GDP

Finally, we discuss two issues related to dynamic treatment effects. The first issue is that most of the literature has used temperature itself as the implicit exogenous treatment. However, because temperature in each country is serially correlated, temperature itself cannot be used as the treatment. Estimation of causal effects in a dynamic context requires not only the usual conditions of instrument relevance and exogeneity, but also a third condition — lead/lag exogeneity — which requires that an instrument not be correlated with any future or past structural shock including its own leads or lags (Stock and Watson, 2018). When temperature is serially correlated, a regression of GDP growth on current temperature confounds the effects of a current shock to temperature with the effects of past shocks to temperature. This is why macroeconomic analyses routinely use *shocks* to estimate causal effects, as discussed in Ramey (2016). For this reason, we use identified temperature shocks as our treatment, where the shock is identified as the innovation to

[8]Kahn et al. (2021) consider the absolute value of the deviation of temperature from a moving average. When we add their nonlinear term to our model in Column 3, the resulting coefficient is not statistically different from zero, whereas the estimated coefficients and standard errors on the linear and state-dependent terms are similar to those in Column 3 of our table.

temperature in a nonlinear time series model.

The second issue is how to translate the coefficients on the temperature shocks to project the effects of sustained increases in temperature on GDP. If a shock leads to a persistent change in temperature, that persistence must be accounted for when mapping estimated effects of temperature on GDP to make projections. Acevedo, Mrkaic, Novta, Pugacheva and Topalova (2020) and Newell et al. (2021) are two recent papers noting that temperatures are serially correlated. However, it is not clear whether these papers account for the persistence of temperature when they construct their GDP projections.

An additional complication is that temperature can have both transitory ("weather") and permanent ("climate change") components. Even the transitory component can lead to changes in temperature that last several years, such as El Niño events. Thus, a shock to temperature can impact future GDP through both a delayed effect of a temperature shock on GDP and through persistence in the temperature response itself. Decomposing the temperature shocks into transitory and permanent components is difficult in samples with a few decades of data.[9]

Specifications in which estimated temperature shocks display substantial persistence may be especially informative about the effects of permanent future climate change. We capture this in our approach below using a procedure that accounts for the persistence of temperature and considers its effects on GDP in the medium-term. Specifically, we use our state-dependent local projections model to estimate impulse response functions of both temperature and log GDP to temperature shocks. As the horizon increases, the effects of the transitory component of temperature should die out, so that the effects of the more persistent component are dominant.[10]

To scale our estimates of the GDP effects by the temperature treatment in the historical sample, we compute the *cumulative response ratio* (CRR), defined as the integral under the impulse response of log GDP divided by the integral of the impulse response of temperature, both up to horizon H. This cumulative response ratio is analogous to the cumulative fiscal multipliers introduced by Mountford and Uhlig (2009). In the temperature context, the CRR allows us to scale the estimated effect of a temperature shock on GDP by the

[9] Several papers have attempted to isolate the lower frequency component of temperature. Dell, Jones and Olken (2012) study the effects of changes in 15-year average temperatures. Bastien-Olvera, Granella and Moore (2022) employ time series filters to extract low frequency variation in temperature.

[10] See Hamilton (2018) for a discussion of this idea as a way to detrend data.

cumulative change in temperature that drove the effect.[11] The CRR at short horizons will be dominated by the transitory component of shocks to temperature, whereas the CRR at longer horizons will be dominated by the permanent component.

3.2 Our econometric framework

In the previous section, we established four key points about specifying GDP-temperature models: (i) including lags of both temperature and GDP in the model allows for unbiased estimates of immediate and persistent effects; (ii) the state-dependent model dominates the quadratic-in-temperature for modeling nonlinear effects; (iii) coefficients on temperature shocks rather than temperature itself should be used to estimate dynamic causal effects; and (iv) cumulative response ratios (CRRs) can be used to scale the GDP effects by the cumulative changes in temperature. In this section, we incorporate these lessons into our econometric model for estimating the effects of temperature on GDP.

To make causal statements, we need to identify an exogenous shock to temperature. Our temperature shock is the innovation to temperature from a nonlinear autoregressive model of country temperature. For this shock to be valid, we require that country GDP not affect country temperature. While it is reasonable to assume that idiosyncratic changes in a country's GDP do not affect a country's temperature, perhaps country GDP is correlated with global GDP and the latter affects global temperatures. In one of our main specifications, we control for year fixed effects, which should lessen this concern. In specifications without fixed effects, we include current and lagged U.S. TFP growth (as a measure of frontier technology growth), as well as lags of global GDP. Another factor that lessens the magnitude of the potential bias is that only around 10 to 20% of the effect of a pulse of CO_2 on temperature occurs in the first year (Carleton et al., 2022).

To estimate the temperature shock, we project temperature in each country on its own lags, which we interact with country mean temperatures to allow the dynamics to vary across colder and hotter countries, as well as country fixed effects and either year fixed effects or global controls (global GDP growth and U.S. TFP growth). We then use the innovation in this nonlinear regression in the state-dependent regressions

[11] In the applied time series literature, *cumulative* often refers to cumulative growth rates, e.g. $y_{t+H} - y_{t-1}$ as in Acevedo et al. (2020). In contrast, our measure uses cumulative *level* effects, measured as the integral under the impulse response function of levels, i.e., $\sum_{h=0}^{H} (y_{t+h} - y_{t-1}) = \sum_{h=0}^{H} y_{t+h} - (H+1) \cdot y_{t-1}$.

for temperature and GDP. In particular, we estimate the temperature shock $\boldsymbol{\tau_{it}}$ as the innovation to temperature in the following:

$$T_{it} = \sum_{j=1}^{p} \gamma_j T_{i,t-j} + \sum_{j=1}^{p} \theta_j T_{i,t-j} \cdot \overline{T_i} + \mu_i + \mu_t + \boldsymbol{\tau_{it}} \tag{4}$$

where T_{it} is temperature in country i in year t, $\overline{T_i}$ is country mean temperature, μ_i are country fixed effects, μ_t are either year fixed effects or global controls, and p refers to the number of lags included. The second summation term allows the coefficients on lagged temperature to vary with country mean temperature. We include these lag interactions because we find that the dynamic response of temperature to a temperature shock is different in hot versus cold countries.[12]

We next estimate the impulse responses of temperature and GDP per capita to the estimated temperature shock from (4) . To do this, we use Jordà's (2005) local projection method. This simple, intuitive method estimates the effect of a treatment in period 0 on the variable h periods after the treatment by regressing the variable at horizon $t + h$ on the shock at t, as well as lagged control variables. The coefficient on the shock at t is the estimate of the impulse response function at h. The local projection method is particularly useful in the case of nonlinear models, since obtaining impulse response functions from a nonlinear structural vector autogression is challenging.[13]

The two sets of local projections (for temperature and GDP per capita) are as follows:

$$T_{i,t+h} = \alpha_0^h \boldsymbol{\tau_{it}} + \alpha_1^h \boldsymbol{\tau_{it}} \cdot \overline{T_i} + X_{it} + \zeta_{it}, \quad h = 1, ..., H. \tag{5}$$

$$\text{where } X_{it} = \{T_{i,t-j},\ T_{i,t-j} \cdot \overline{T_i}\ \}_{j=1}^{p},\ \mu_i,\ \mu_t.$$

$$y_{i,t+h} - y_{i,t-1} = \beta_0^h \boldsymbol{\tau_{it}} + \beta_1^h \boldsymbol{\tau_{it}} \cdot \overline{T_i} + Z_{it} + \epsilon_{it}, \quad h = 0, ..., H. \tag{6}$$

[12]In theory, our use of the sample average of temperature as the state variable is problematic because climate change should make temperature nonstationary. In our sample, however, the rise in temperature is small. And we obtain very similar results if we instead use average temperatures before 1980, before the temperature increases became perceptible.

[13]Most of the literature that studies state-dependence in fiscal multipliers uses local projections (e.g. Auerbach and Gorodnichenko (2013) and Owyang, Ramey and Zubairy (2013)).

$$\text{where } Z_{it} = \{T_{i,t-j},\ T_{i,t-j}\cdot\overline{T_i},\ \Delta y_{i,t-j}\}_{j=1}^{p},\ \mu_i,\ \mu_t.$$

In the set of H regressions in (5), temperature in each year $t+h$ is regressed on the estimated temperature shock in year t, as well as controls X_{it}. The estimate of $\alpha_0^h + \alpha_1^h \cdot \overline{T_i}$ represents the impulse response at horizon h. The second term allows the effects of the shock to vary with country mean temperature. The set of regressions starts at horizon h=1 because of the unit normalization, i.e., the impact effect at h=0 is normalized to unity in equation (4) that identifies the shock.

In the *H+1* regressions described in (6), we regress the difference between log GDP per capita (y) at time $t+h$ and time $t-1$ (before the shock hits) on the temperature shock in period t and controls Z_{it}.[14] The impulse response of log GDP per capita at horizon h is $\beta_0^h + \beta_1^h \cdot \overline{T_i}$. Both sets of controls X_{it} and Z_{it} contain lags of temperature, lags of temperature interacted with country mean temperature, country fixed effects, and either year fixed effects or global controls (world GDP growth and U.S. TFP growth). Z_{it} additionally contains lags of country GDP growth.[15]

As described in Section 3.1.3, we use the local projections estimates to construct a cumulative response ratio that measures the medium-run GDP effects of a given pulse of temperature change. We construct the CRR using the coefficients from (5) and (6):

$$\text{CRR}_{\overline{T}} = \frac{\sum_{h=0}^{9} \beta_0^h + \beta_1^h \overline{T}}{1 + \sum_{h=1}^{9} \alpha_0^h + \alpha_1^h \overline{T}} \tag{7}$$

Finally, to assess robustness, we also estimate a linear local projections model for each country separately, controlling for the global variables. This model is more flexible because it allows each country to react differently to the global controls and to have its own lag coefficients. However, year effects are not identified, so global controls must be used. We then create a cross-country data set of estimated impulse responses for each horizon and regress them on a variety of country-level factors to examine heterogeneity.

[14] While there may be efficiency gains to estimating the regressions jointly using Seemingly Unrelated Regressions (SUR), we estimate them separately to preserve as many observations as possible. Our temperature data extend from 1950 to 2015, but our GDP data extend at most from 1960 to 2019 (since some countries enter the sample later). Each time we increase the horizon h, we lose another year of observations. Joint estimation of the regressions requires a fixed sample, so many observations would be lost.

[15] Including lagged GDP growth is tantamount to assuming a unit root in log GDP. In robustness checks, we specify lags in log levels and obtain similar results. We excluded precipitation variables because they were not significant and their presence did not change the estimated impulse responses.

4 Empirical estimates

4.1 Data

We use GDP per capita in constant local currency units from the World Bank's World Development Indicators. This covers up to 1960-2019 (omitting COVID years), with early years missing for some countries. We get temperature from the Global Meteorological Forcing Dataset (GMFD) version 3, produced by researchers at Princeton (Sheffield, Goteti and Wood, 2006). GMFD combines observational data with local climate models to estimate historical temperature at the $0.25^{\circ} \times 0.25^{\circ}$resolution throughout the world. We calculate country-level average temperature in each year as the population-weighted average of temperature across pixels. These data are available from 1950 to 2015. Despite the temperature data extending only to 2015, we are able to use the GDP data through 2019 for estimating the response of GDP at forward horizons.

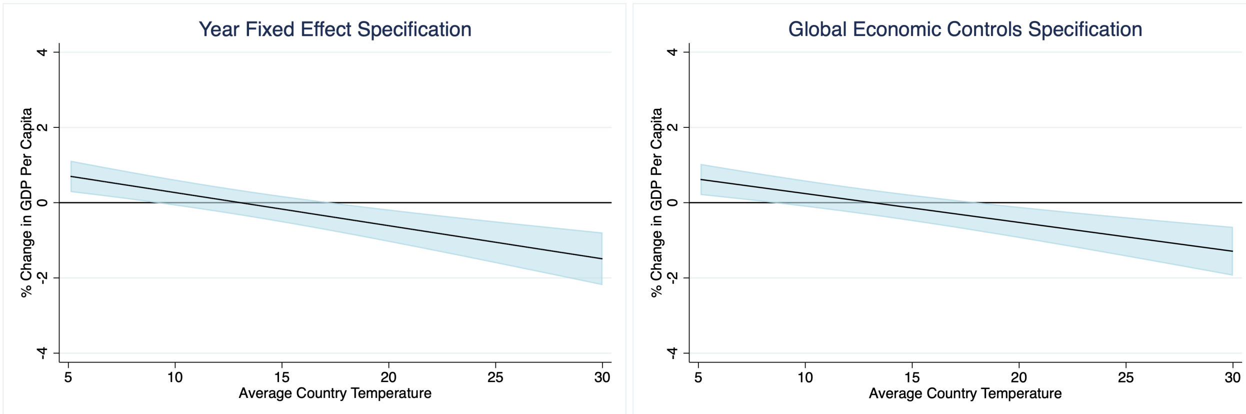
In the specifications without year fixed effects, we control for world GDP growth and a measure of frontier TFP growth. World GDP growth is in constant U.S. dollars and is from the World Development Indicators. Our measure of frontier TFP growth is based on annual utilization-adjusted U.S. TFP (Fernald, 2014).

4.2 Estimates

We estimate three versions of the model presented in Section 3.2. The first uses year fixed effects in all equations. The disadvantage of this specification is that it eliminates global warming from the data. Thus, we also estimate a specification without year effects that instead controls for global economic variables in (6). This specification has the advantage of capturing more persistence in temperature shocks, which allows them to more closely resemble the permanent changes in climate considered in the future projections. The global control variables in this specification are contemporaneous U.S. TFP growth and three of its lags (as an indicator of frontier technology) and three lags of world GDP growth. The third version is the estimation of the linear model one country at a time with the second-step regression of the country-specific impulse responses on country temperature. We discuss the results of this third model as part of the robustness checks.

Figure 4 displays estimates via (6) of the contemporaneous impact of an unanticipated 1°C shock to temperature in year t on log GDP per capita in year t. Temperature shocks

Figure 4: Contemporaneous Impact of a 1°C Temperature Shock on GDP Per Capita



Notes: Graph shows the initial impact of a 1°C temperature shock on log GDP estimated using the local projections specification in 6. The effect is allowed to vary with average historical country temperature, which is shown on the x-axis. Left panel shows estimates for the specification with year fixed effects, and right panel shows the corresponding estimates for the specification with global economic control variables instead. Temperature data are from GMFD, and GDP data are from the World Development Indicators. 95% confidence interval is shown in blue. This figure shows contemporaneous effects at horizon $h = 0$, whereas Figure 5 documents the persistence of the effects.

are obtained as the residual in (4). The effects of temperature shocks on log GDP per capita are allowed to vary with a country's average historical temperature, so the effect of an unusually hot year can differ across hot and cold countries. The left panel shows the specification that controls for year fixed effects, the right panel uses global controls.

The estimates in Figure 4 reveal that temperature has meaningful contemporaneous effects on GDP per capita. Using year fixed effects, in the hottest countries in the world (about 28°C in the historical sample), a 1°C temperature shock reduces GDP in the same year by about 1.3%. The effects of temperature shocks are smaller in places that are less hot, and positive in very cold countries. In cold countries such as Norway, which has an historical average temperature around 5°C, a 1°C temperature shock increases annual output by about 0.75%. The bliss point for temperature implied by these estimates is 13.2°C, which is similar to estimates in the literature such as Burke et al. (2015). Results are similar when year fixed effects are omitted in the right panel of Figure 4.

Next, we turn our attention to the *persistence* of the effects of a temperature shock on GDP per capita. Figure 5a displays the estimates from (6) of the impact of a shock in year t on GDP per capita in year $t + h$ for a 10-year horizon. The left panel shows results with year fixed effects, and the right panel with global economic controls instead. In each graph, the three impulse response functions apply to three average country temperatures. The red path shows the effects on a hot country with average temperature of 25°C, such as India or Indonesia; the green path for a country with a moderate average temperature of 15°C, such as Greece or Portugal; and the blue path for a cold country with average temperature of 5°C, such as Norway or Sweden.

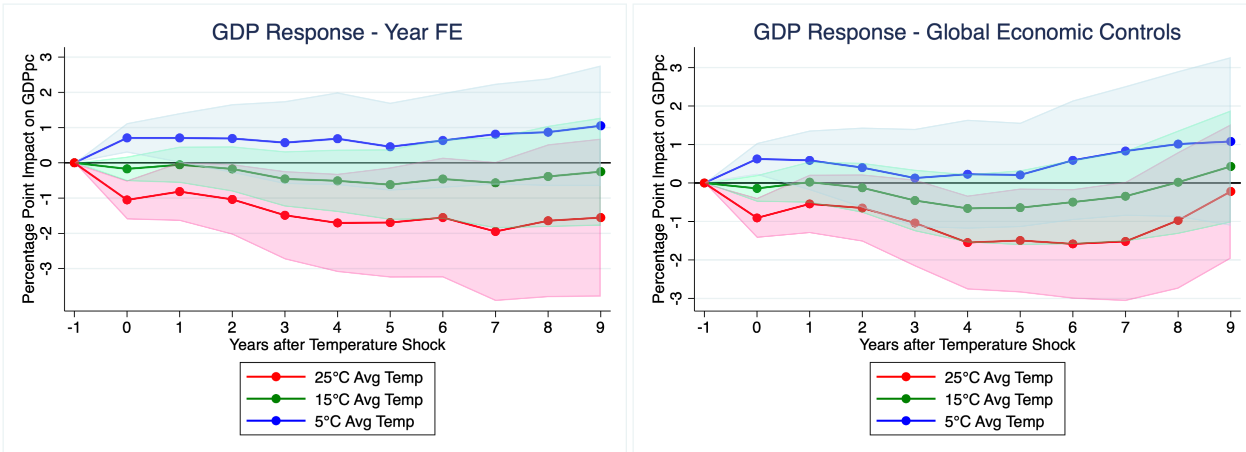
Figure 5a demonstrates that the effects of temperature on GDP are persistent in both hot and cold countries. In the specification with year FE shown in the left panel, point estimates show no evidence that GDP per capita recovers back to trend over the 10-year horizon after the shock hits in year t. In hot countries (25°C), the initial 1°C shock in year t reduces GDP per capita by about 1.1% on impact, and remains depressed by approximately 1.7% in the fifth year following the shock. Conversely, in cold countries (5°C), GDP per capita rises by 0.7% in the year of the shock and remains 0.7% above expectations five years later. Effects continue to persist in the years that follow, though the confidence intervals unsurprisingly grow larger as more lags enter the estimate. The estimates in the right panel with global controls instead of year FE show similar levels of persistence in hot countries over the first seven years after a temperature shock, though with imprecise evidence that GDP per capita recovers to trend afterward.

In order to interpret the estimated persistence of the GDP impacts of the temperature shock, we need to know whether the estimates reflect the effects of temporary, persistent, or permanent changes in temperature. Figure 5b shows the impulse response function of temperature in the years following an initial shock estimated using the specification in (5). In the graph, we set the year 0 shock equal to 1°C by construction. Recall that the temperature shock is defined in (4) as the residual in year t from a regression of temperature on country fixed effects and its own lags. The values in each proceeding year, $t + h$, represent the proportion of the initial shock that persists in the years that follow. Like the GDP IRF, we allow the persistence of temperature to differ by a country's average temperature. The red, green, and blue lines represent hot (25°C), moderate (15°C), and cold (5°C) climates, respectively.

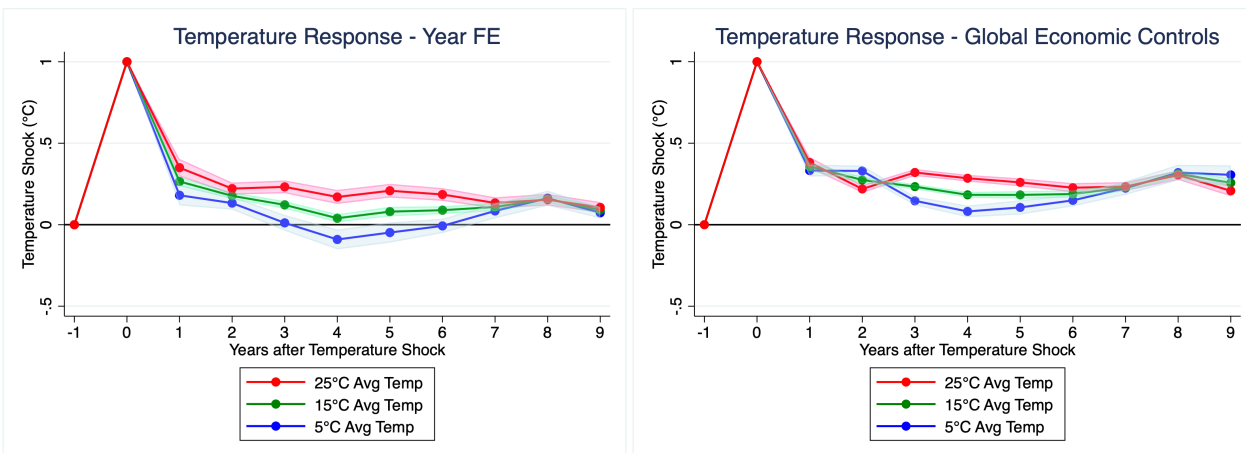
Figure 5b shows that temperature shocks display some persistence. In hot countries, the specification on the left with year fixed effects suggests that a temperature shock of 1°C in year t is followed, on average, by a shock of 0.35°C in year $t + 1$, where the shock is defined in (5) as relative to the predicted value based on the information available in year

Figure 5: Dynamic Empirical Response of Temperature and GDP per capita

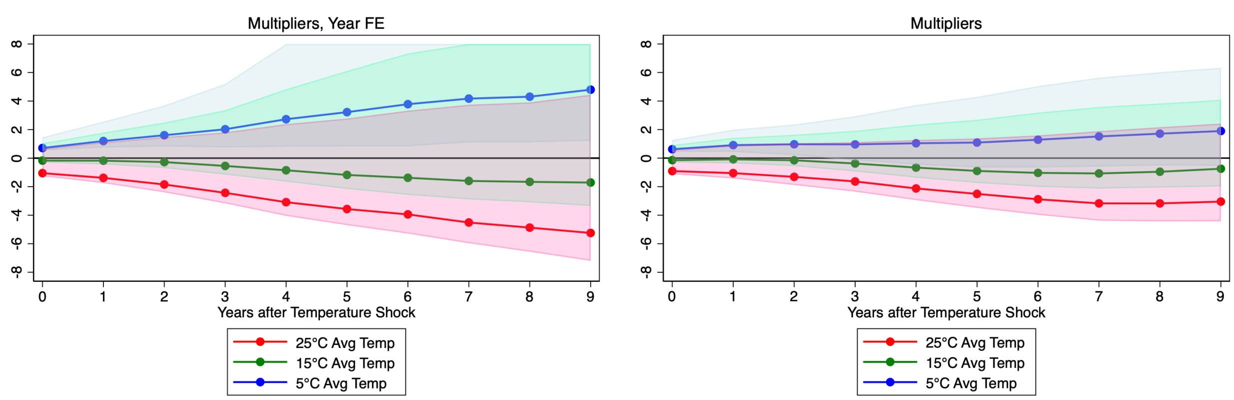
(a) GDP per capita Response



(b) Temperature Response



(c) Cumulative Response Ratio



Notes: Graphs show local projections estimates of the persistent effects of an unanticipated 1°C temperature shock in year 0. Panel (a) and panel (b) show estimates for the path of GDP per capita and temperature following the shock over a 10-year horizon, estimated using Equations 6 and 5, respectively. Panel (c) shows the cumulative response ratio of the integrals of the GDP and temperature effects up to each horizon. The left graph in each panel contains the specification with year fixed effects, and the right graph contains the specification with global economic controls instead. Blue, green, and red lines represent cold (5°C), moderate (15°C), and hot (25 °C) countries, respectively, and the 95% confidence intervals are shown with corresponding color shading. Confidence intervals in Panel (c) are bootstrapped. Temperature data are from GMFD, and GDP data are from the World Development Indicators.

t. Approximately 20% of the shock persists even in the 5th year after it is realized in hot countries, and 10% remains even in the 10th year thereafter. The results in the right panel with global controls show even greater persistence in temperature shocks, with over 20% of the initial shock persisting even a decade later. Thus, we conclude that temperature shocks in hotter places consist of a combination of transitory and permanent components. The specification without year fixed effects captures more of the permanent component of temperature shocks, but persistence arises even in the specification that removes the aggregate global trend in temperature from the estimating variation. This is partially because countries have warmed at different paces, which generates useful variation in persistent shocks that is potentially more informative about long-run warming than if the estimated shocks were purely transitory.

Figure 5c brings together the dynamic GDP per capita and temperature estimates to calculate the *cumulative response ratio* (CRR), which we defined in Section 3.1.3 and equation (7). We interpret this value as the total GDP effect of a permanent increase in temperature, accounting for both the lasting impact of the initial temperate shock and continuing impacts caused by the persistence of the shock itself. Thus, we use the CRR as a measure of the long-run level effect of a given increment of temperature. The results in the left panel of Figure 5c with year fixed effects suggest that, in hotter (25°C) countries, each 1°C increase in temperature reduces GDP by about five percentage points in the long-run, while in colder (5°C) countries the same change would raise GDP by about five percentage points. The effects in the right panel with global controls are broadly similar, though somewhat smaller due to point estimates that suggest slightly more recovery of GDP and slightly more persistence of temperature. In that specification, 25°C countries lose about three percentage points of GDP from each 1°C, and 5°C countries gain about two percentage points.[16]

4.3 Robustness and heterogeneity

Appendix D presents a number of robustness checks. Appendix Figure A-2 shows the contemporaneous and persistent effects of the temperature shock on GDP using several

[16]We do not yet show confidence bands for the multipliers. Using the Ramey and Zubairy (2018) 1-step method to estimate standard errors, we obtain standard errors at the 10-year horizon of anywhere between 2 and 3.8 depending on the mean country temperature. However, the multipliers from the 1-step procedure are not identical to those implied by the IRFs because 10 years of the sample must be dropped in the 1-step procedure. Nevertheless, these 1-step results are indicative of the imprecision of the estimates.

alternative approaches. Panel (a) shows results for a specification that controls for log levels of lagged GDP rather than first differences, and panels (b) and (c) show estimates using alternative temperature data from the Berkeley Earth Surface Temperature dataset and the University of Delaware climate dataset. The results are similar throughout.

To further probe the robustness of the results, we estimate a linear local projections model of GDP per capita and temperature separately for each country, extending a method introduced by Berg et al. (2023). This procedure allows arbitrary heterogeneity of all the parameters across countries, which avoids the dynamic panel biases discussed in Pesaran and Smith (1995). In the second stage, we regress the country-specific estimates on mean country temperature, which produces estimates of impulse responses and cumulative response ratios by country mean temperature. These estimates are analogous to the results from our state-dependent panel model, only with more flexibility.[17] The top panel of Appendix Figure A-3 shows the contemporaneous effects of temperature shocks across countries, and the second panel shows the average effects across the world's temperature distribution (for 5°C, 15°C, and 25°C countries). The results are similar to the analogous panel specification without year fixed effects.

Appendix Figure A-4 uses the country-by-country local projections approach to shed light on two additional dimensions of robustness. The top panel shows how the average estimates differ when dropping two countries (Gabon and Kiribati) with outlier effects of greater than 10% GDP losses from temperature shocks. The effects on hot countries are slightly muted compared with the version that includes all countries. In contrast, the second panel of Figure A-4 shows that allowing for nonlinearity in the heterogeneous effects by country average temperature strongly increases the implied vulnerability of the hottest countries. Here we regress the coefficient on temperature shocks across countries on a fourth degree polynomial in country average temperature. The effects on the hottest countries are nearly twice as large when allowing for this nonlinearity. Finally, the bottom panel of Figure A-4 shows the net effects of both dropping outliers and allowing for nonlinear heterogeneity. At the 10% effects threshold for dropping outliers, the nonlinear heterogeneity effect is stronger for hot countries.

[17] Berg, Curtis and Mark (2023) follow the same procedure, but do not uncover a systematic relationship between temperature effects and country characteristics.

In Figure A-5, we separately estimate the effects of temperature shocks on agricultural and non-agricultural GDP.[18] The effects on agricultural GDP are several times larger than on overall GDP. In a country with average temperature of 25°C, a 1°C temperature shock reduces agricultural GDP by about 4%, compared to about 1% for overall GDP. We find null effects of temperature on non-agricultural GDP, though the standard errors cannot rule out moderate impacts that would be consistent with the magnitudes in micro-data studies such as Zhang, Deschenes, Meng and Zhang (2018) and Somanathan, Somanathan, Sudarshan and Tewari (2021). The large divergence between effects on agriculture and non-agriculture is also consistent with the micro estimates in Nath (2021), though that paper also finds moderate effects on non-agricultural production.

Table A-2 investigates the issue of state-dependence with regard to the level of development. The table regresses the coefficients for contemporaneous effects of a temperature shock from the country-by-country local projections on several variables. Column 1 shows the heterogeneity by average temperature shown in Figure 5 — positive temperature shocks have more negative effects on hotter countries. In Columns 2, 3, and 4, we find little evidence that less developed or more agricultural economies are more susceptible to temperature shocks once we condition on average temperature, though the estimates are imprecise. Due to the imprecision of these results, we interpret them with caution in light of both the regressions on sectoral GDP in this paper and other evidence using micro data (Nath, 2021) that which suggests that more developed and less agricultural countries are less susceptible to temperature.

4.4 Model-based interpretation of empirical results

We now interpret the estimates in Section 4.2 through the prism of the model presented in Section 2. The projections to follow in Section 5 below draw straight from the cumulative response ratios estimated in Figure 5c and do not rely on the stylized model. But the model provides an additional lens through which to interpret the persistence in the estimates from historical data, and a means to produce an alternative set of future projections that provides robustness to the CRR approach. Recall that, in the model, the convergence

[18] We gather data on agricultural and non-agricultural GDP from Herrendorf, Rogerson and Valentinyi (2014), the UN National Accounts database, and the University of Groningen 10-Sector Database (Timmer, de Vries and De Vries, 2015), though the set of country-years in the resulting sample is substantially smaller than in the main analysis.

parameter ω governs both the persistence of level effects from a transitory shock and the persistence of growth effects from a permanent shock. For values of ω closer to 0, which imply weaker forces of global convergence, the level effects from a transitory shock persist longer before the economy recovers to trend, and the growth effects from a permanent shock last longer before the economy returns to the steady-state growth rate.

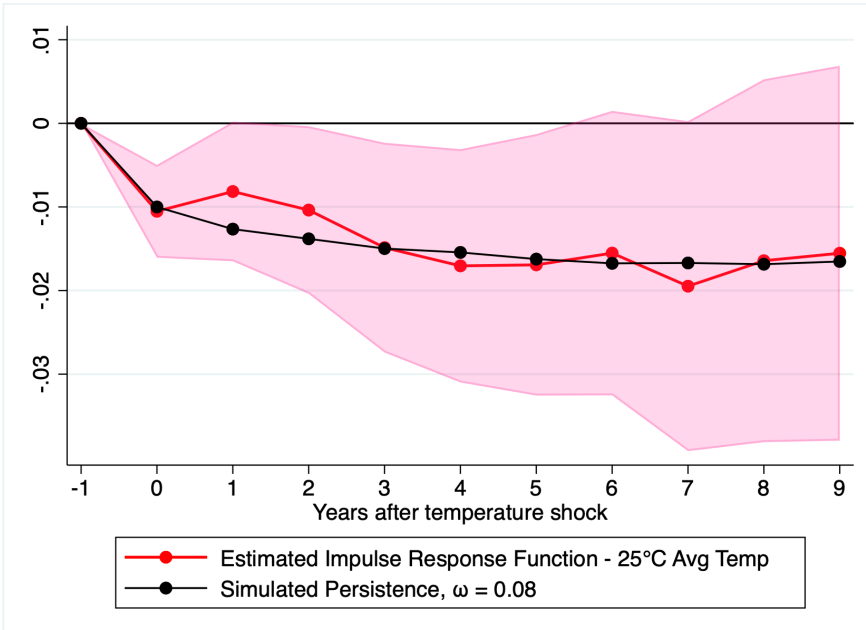
In order to interpret what the empirical estimates imply about long-run permanent changes in temperature, we estimate the value of ω consistent with the persistent GDP effects from the temperature shock process estimated in Section 4.2. While the historical record does not contain the ideal experiment of randomly-assigned large and permanent changes in temperature, the temperature shocks we identify do contain a mixture of transitory and permanent components. The degree to which the corresponding GDP effects from these shocks persist is informative about the value of ω, which also governs the persistence of growth effects from hypothetical permanent changes in temperature when viewed through the lens of the model.

We estimate the value of ω implied by the empirical estimates as follows. We start by constructing a model simulation of a temperature shock with persistence that matches the empirical temperature IRF. In the simulation, each year's temperature shock affects that year's value of μ_{it}, which we assume remains constant in the absence of temperature shocks. Following Appendix equation (1), each year's shock to μ_{it} affects productivity and output both contemporaneously and in future years, with the degree of persistence inversely related to ω.

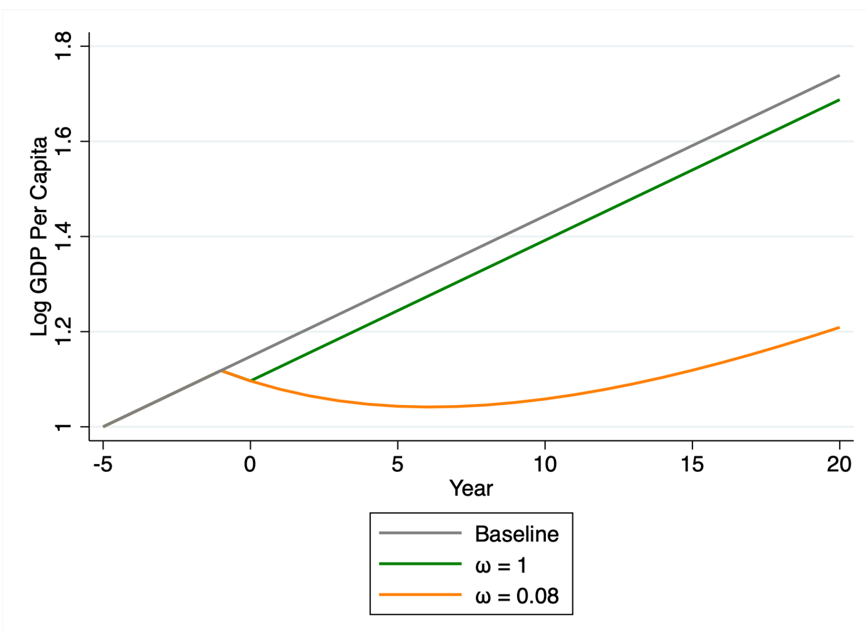
We calibrate the temperature effect on μ_{it} to match the contemporaneous impact of temperature on GDP in year 0 shown in Figure 5a for a 25°C country. We then calibrate the magnitude of each period's shock to match the value from the temperature impulse response function, again for a 25°C country. The combination of the simulated temperature shock process and the calibrated magnitude of each year's temperature effect provides us with a sequence of values for μ_{it}, beginning with the initial shock in year 0. When combined with a chosen value for ω and σ, equation (1) implies a sequence of values for Q_{it} that result from the sequence of shocks to μ_{it}. The simulated path of Q_{it} implies a corresponding impulse response function for GDP. We set $\sigma = 4$ and search for the value of ω that minimizes the sum of squared errors between the simulated and empirical impulse response functions over the 10-year horizon.

Figure 6: Model-Based Interpretation of Empirical Results

(a) Empirical vs. Simulated GDP Impulse Response Function
Year Fixed Effects Specification



(b) Transition Dynamics with $\omega = 0.08$



Notes: The red path in panel (a) shows the empirical impulse response function of the path of GDP following an unanticipated 1°C shock to temperature in year 0, estimated using Equation 6 with year fixed effects, with the 95% confidence interval shaded in pink. The black path shows a model simulation with $\omega = 0.08$ of the impulse response function following a shock with magnitude calibrated to match the contemporaneous effect in year 0, and persistence calibrated to match the impulse response function of temperature shown in Figure 5b. Panel (b) shows a model simulation of the medium-term growth trajectory following a permanent shock starting in year 0 with $\omega = 0.08$ in orange, and $\omega = 1$ in green for comparison.

Figure 6a displays an overlay of the empirical GDP impulse response function (in red) and its simulated counterpart (in black) for $\omega = 0.08$, the estimated value that most closely replicates the empirically estimated GDP persistence in the specification with year fixed effects. Figure 6b shows the implied long-run growth path following a permanent shock to μ_{it} starting in year 0 in a simulated economy with $\omega = 0.08$. The orange path shows that the growth effects of the hypothetical permanent shock to productivity (e.g. from temperature) would persist for well over a decade, and that the eventual long-run level effect would be many times larger than the level effect with no persistence (the green line with $\omega = 0$). Appendix Figure A-6 shows the corresponding results for the specification with global control variables instead of year FE, which implies an ω value of 0.21 and somewhat less persistence of growth effects. Overall, our estimates imply that hypothetical permanent changes in temperature are likely to have growth effects that persist in the medium term, though not indefinitely.

It is worth noting that $\omega = 0.08$ is remarkably close to the $\omega = 0.07$ estimate from Section 2.2 using indirect inference on historical growth patterns across countries. While we caution that it is possible for the persistence process of temperature shocks to differ from that of the more general drivers of growth, we take the striking similarity of these two very different methods of backing out ω as further support for a growth process in which country-specific growth effects can linger.

The simulated IRFs also demonstrate the importance of measuring the persistence in temperature itself. While the impulse response function for GDP shows no recovery during the 10-year window, one cannot conclude from this that a transitory shock to temperature causes a permanent level effect on GDP since the shock to temperature is not purely transitory. Thus, attributing the full path of the GDP effects to only the initial shock to temperature would overestimate the persistence of the effects. Instead, what we find through the model-based interpretation of the results is that the persistence in the GDP effects results from a combination of the lasting effects of the initial shock as well as the persistence of the temperature shock itself.

To recap, our estimated IRFs are most consistent with a permanent rise in temperature having long-lasting, but not permanent, effects on economic growth. While $\omega = 0.08$ represents the best estimate to match the empirical impulse response functions, however, the standard errors at the 10-year horizon are large enough that we cannot rule out a substantially larger value of ω nor the edge case of $\omega = 0$. The projections in the next section demonstrate that even the seemingly small distinction between medium-run growth effects with $\omega = 0.08$ and permanent growth effects with $\omega = 0$ constitutes an enormous difference over the time scale relevant to global warming. This underscores the importance of combining the empirical estimates with the indirect inference presented in Section 2.2 to more convincingly rule out the case of permanent growth divergence across countries. Put simply, historical growth rates have not diverged despite large and persistent differences in temperature across countries.

5 Climate change impact projections

5.1 Projection approach

In this section, we use our results from Section 4.2 to project the effects of global warming on the trajectory of GDP for 163 countries through the end of the 21st century. We take scientific projections of country-level population-weighted average temperature change directly from Burke, Hsiang and Miguel (2015), who use the Intergovernmental Panel on Climate Change's (IPCC) mean projected warming scenario, known as the Representative Concentration Pathway (RCP) 8.5, across all global climate models included in the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5 (CMIP5) (Tayler, Stouffer and Meehl, 2012). Following Burke et al. (2015), we use country-level projections for end-of-century warming and assume a linear increase in temperature from 2010 to 2099. The temperature projections from RCP 8.5 represent the median scenario from a warming trajectory with little emissions abatement and high fossil fuel use.

The population-weighted mean temperature increase across countries in Burke et al. (2015) is 4.3°C. This corresponds to about 3.7°C of global temperature change using the more widely-cited metric of global mean surface temperature, since land warms faster than the oceans. The projections imply that warming will be spatially heterogeneous, ranging from 2.7°C to 5.8°C across countries. Thus, a country's initial temperature is not a sufficient statistic for its vulnerability to global warming, as climate models imply that some parts of the world will heat up more than others. The hottest countries in the world had population-weighted average annual temperatures of about 28.6°C (Mauritania and Niger) in the historical period from 1980-2010. By 2099, that number rises to about 33.4°C for the hottest country in the projection. In this scenario, approximately 35% of the current global population lives in a country that will heat up to a level beyond the historical range of country-level temperatures. Thus projecting the effects of global warming necessarily requires out-of-sample extrapolation that is difficult to validate.

To project the effects of warming on country-level GDP, we rely on the cumulative response ratios (CRRs) from (7) and Figure 5c. The CRR takes the ratio of the integrals of the GDP response and temperature response over a 10-year horizon. These IRFs, shown in Figures 5a and 5b, are estimated using historical data on GDP and temperature from the 1960-2015 period as explained in Section 4. The CRRs represent the cumulative impact on GDP from a permanent pulse to temperature. We apply the CRR separately to the change in temperature in each future year relative to the 2010 baseline, which is equivalent to treating each realization as the new permanent level of temperature.

Using the CRRs to make climate change projections also requires incorporating the nonlinearity of the estimated effects. Recall from Section 4.2 that we allow the effects of temperature shocks to differ by average country temperature. The CRRs we estimate range from about a 6.0% loss per °C in the hottest parts of the world (28°C) to a roughly 4.8% gain per °C in the coldest parts of the world (5°C) in the specification with year fixed effects. We account for the nonlinear effects by applying the corresponding temperature-specific multiplier for each 0.1°C increment of warming that occurs in the projection. For instance, if a country warms from 25°C to 26°C, we apply the CRR for a 25°C country to the first 0.1°of warming, the CRR for a 25.1°C country to the next 0.1°, and so on.[19] For countries warming to temperatures outside the range of historical observation, the CRRs extrapolate the nonlinear effects of temperature on GDP beyond the range of the historical sample. For instance, at a country-level temperature of 32°C that is realized in the hottest places later in the century, our estimates imply that the long-run negative level effect on GDP per capita of an additional degree of warming is about 7.5%.

Given the challenge of using the estimates from historical data to project the effects of future warming, in Appendix E we show results from two alternative projection methods — one following Sims (1986), and one using the model from Section 2 directly. As we describe below, both alternative projection methods show somewhat larger average

[19]Note that this requires dividing the multiplier at each temperature by 10 to convert from the effects of a 1°C change to the effects of a 0.1°C change.

effects of warming than the CRR approach, though the contrast with the level effects and permanent growth effects in the literature remain stark, particularly at the regional level.

5.2 Projection results

Figure 7 displays the projected impact of warming on country level GDP by 2099, relative to a scenario with no warming. Panel (a) shows the estimates using the CRRs from the specification with year FE shown in Figure 5c. This projection allows for persistent, but not permanent, growth effects of a given temperature change. Panels (b) and (c) show projections that assume level effects and permanent growth effects, respectively. The level effect projections in panel (b) use only the contemporaneous effect of temperature on GDP shown in Figure 4, rather than the full effects of the temperature shock that accumulate over the 10-year horizon. This projection assumes that a permanent temperature change has no growth effects on GDP for any length of time, and that only contemporaneous temperature affects contemporaneous output. The permanent growth effect projections in panel (c) use the estimates from Burke, Hsiang and Miguel (2015), wherein rising temperatures permanently (and increasingly) alter each country's long-run growth rate.

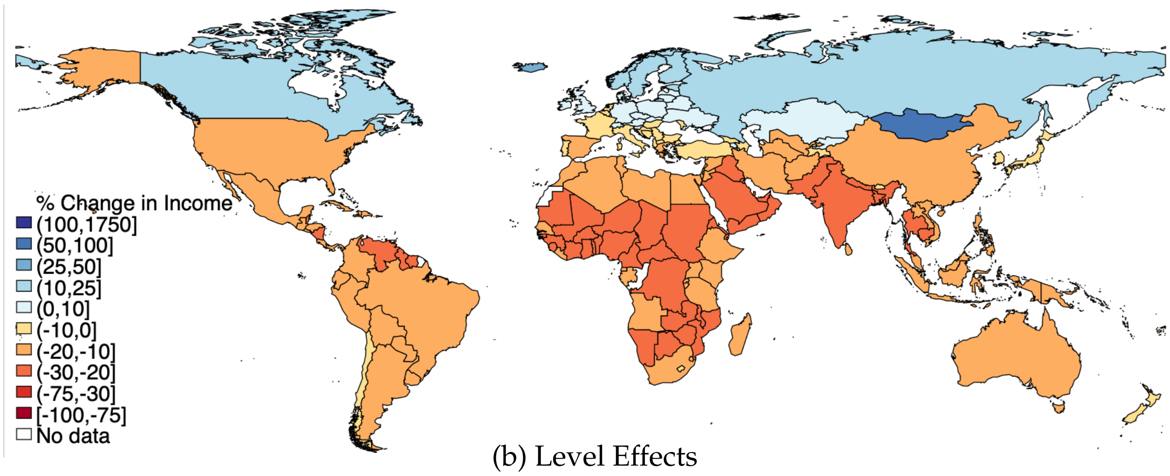
Figure 7a shows that projections with persistent, but not permanent, growth effects from global warming imply large effects in absolute terms. In panel (a), the hardest-hit countries in the world lose nearly 30% of their GDP to global warming on an annual basis by 2099. Warming reduces future income by at least 20% in 42 countries covering 33% of the present day global population, and by at least 15% in 93 countries covering 55% of the current global population. In total, 137 of the 163 countries — representing about 92% of the existing global population — lose income from warming. Meanwhile, just under 8% of the current population gains. The median person in today's population distribution loses about 16% of their income to warming by end-of-century in this scenario.[20]

Comparing our estimates in Figure 7a to those in Figure 7b underscores that our global warming impacts are markedly larger than the level effect estimates from previous work. The level effect projections shown in Figure 7b suggest that the hardest hit countries lose 7.3% of GDP from warming, approximately four times smaller than our persistent growth effect projections. The median person in today's global population loses only

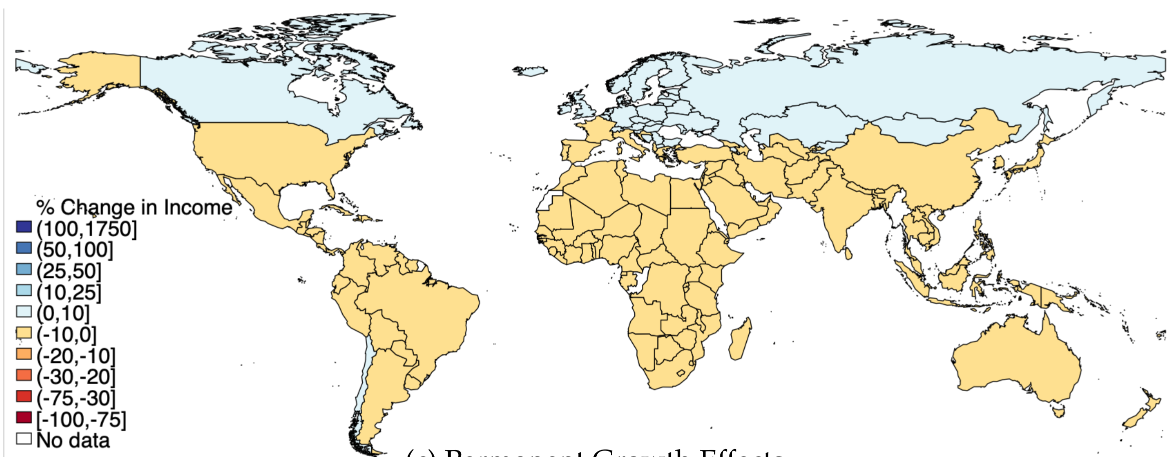
[20]This paragraph describes results from projections that use the empirical specification with year fixed effects. Appendix Figure A-8 and Table 4 below show the corresponding results for the specification with global control variables instead of year fixed effects.

Figure 7: Projected Impacts of Unabated Global Warming on Country-Level GDP

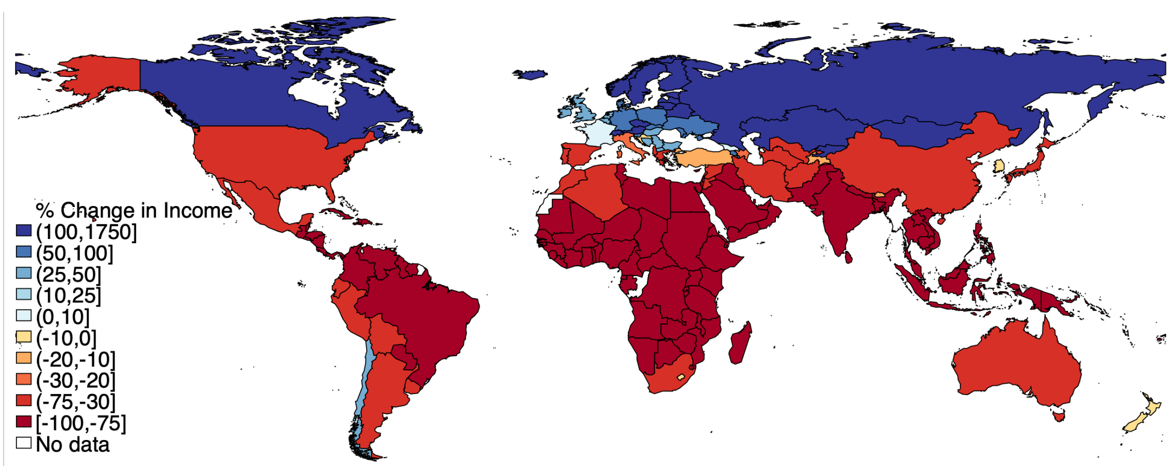
(a) Persistent Growth Effects



(b) Level Effects



(c) Permanent Growth Effects



Notes: Maps show the projected effects of unabated global warming on end-of-century country level GDP under different projection methods. "Persistent growth effects" estimates in panel (a) use the 10-year cumulative response ratio shown in Figure 5c, from the specification with year fixed effects, to calibrate the long-run level effect of each degree of projected warming. "Level effects" projections in panel (b) use only the estimated contemporaneous effect of a 1°C shock, and allow for no persistence or accumulating effects. "Permanent growth effects" use estimates from Burke, Hsiang and Miguel (2015), and allow for the effects of temperature to permanently alter country-level growth rates.

3.1% from warming under this assumption, about five times less than when we allow persistent effects of temperature to accumulate over the 10-year horizon. The level effect projections using our estimates are very similar to the projections from Casey, Fried and Goode (2023), who project 8% losses in countries like India and a 3.4% decline in global GDP in the same emissions scenario.

Conversely, the permanent growth effect projections from Burke, Hsiang and Miguel (2015) in Figure 7c suggest that the hardest hit countries will be about 94% poorer in 2099 than they would have been in the absence of warming, as economies in the hottest places shrink dramatically. The median person in today's global population would lose roughly 77% of their income to warming by 2099 under the Burke et al. (2015) projections. These estimates are much larger than our projections with only medium-run growth effects.

To illustrate more concretely why the panels in Figure 7 differ so sharply from each other, Figure 8 shows projected paths of income per capita over the 21st century in two example countries, India and Sweden. The blue paths represent the baseline trajectory of income in the absence of climate change for each country.[21] The green paths represents the modified trajectories using the level-effect estimate in which only current temperature affects current-year GDP. This level-effect estimate suggests that warming will have modest effects in both hot and cold countries.

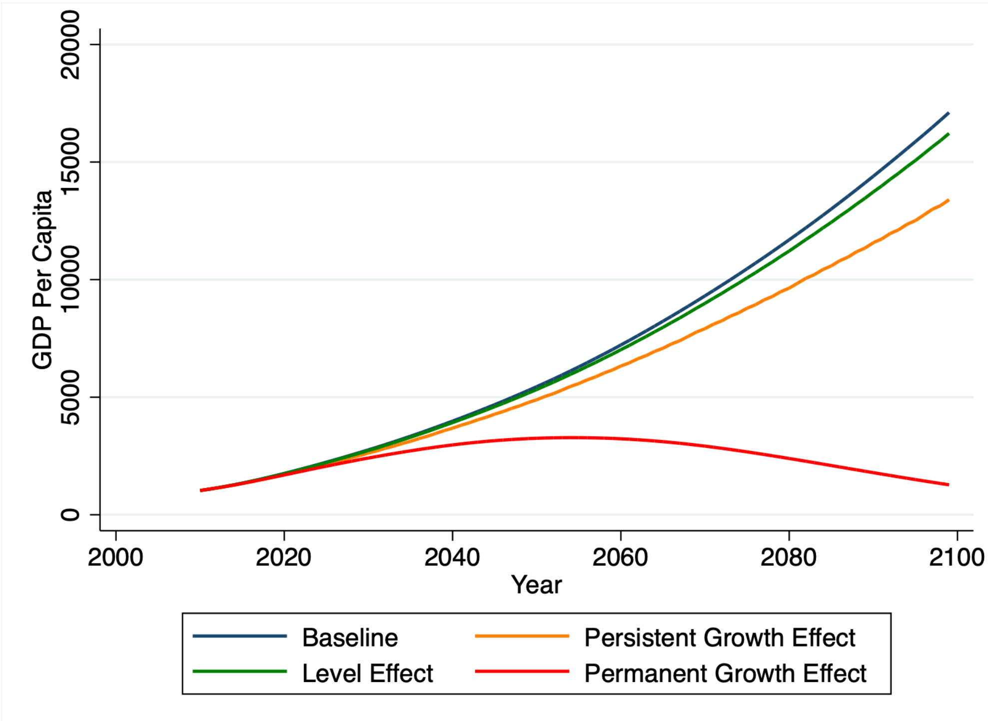
The red paths in Figure 8 represent the permanent growth effect projections in which hot and cold countries diverge permanently as the earth warms. Given that temperature is trending over the century, these projections imply accelerating growth in cold countries and ever-falling growth in hot countries, which accumulates to large effects by 2099.

Finally, the intermediate orange paths in Figure 8 show the projections that use the long-run level effects from our cumulative response ratios over the 10-year horizon. Our projections are consistent with persistent, but not permanent, growth effects from a given permanent change in temperature. Note that this actually implies permanent growth effects in our projections because temperatures are projected to keep increasing rather than level off.

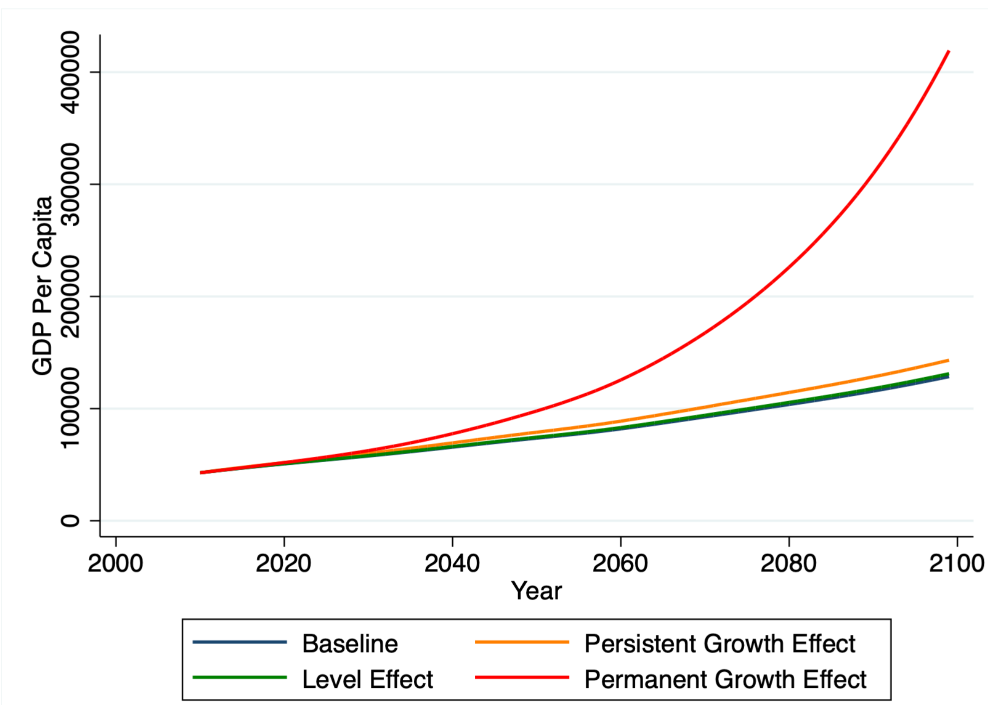
[21] The figure uses baseline estimates from Scenario Two of the Shared Socioeconomic Pathway economic growth projections (Dellink, Chateau, Lanzi and Magné, 2017) commonly used in climate change economics research. Müller, Stock and Watson (2022) provide a more comprehensive probabilistic set of projections of future baseline economic growth. The results in this paper are all percentage changes from the baseline, however, so the baseline trajectory used in the figure is only for illustration.

Figure 8: Projected Impacts of Unabated Global Warming in Example Countries

(a) India



(b) Sweden



Notes: Graphs show the projected effects of unabated global warming on the trajectory of GDP under different projection methods for two example countries, India and Sweden. "Persistent growth effects" projections in orange use the 10-year cumulative response ratio shown in Figure 5c, from the specification with year fixed effects, to calibrate the effect of each degree of projected warming. "Level effects" projections in green use only the estimated contemporaneous effect of a 1°C shock, and allow for no persistence or accumulating effects. "Permanent growth effects" projections in red use estimates from Burke, Hsiang and Miguel (2015), and allow for the effects of temperature to permanently alter country-level growth rates. Corresponding projections for the specification with global economic control variables instead of year fixed effects are shown in Appendix Figure A-7.

Table 4: Projected Effects of Unabated Global Warming on 2099 Income

	Persistent Growth Effects	Level Effects	Permanent Growth Effects
Panel A - Year Fixed Effect Specification			
Global Aggregates:			
Global GDP (no Q^* effect)	-11.5	-2.2	-26.6
Global Population Average	-16.4	-3.6	-58.7
Global Patent-Weighted Average Effect	-8.8	-1.1	-23.2
Global GDP (with Q^* effect, $\omega = 0.08$)	-12.2	-2.3	-26.6
Regional Summary:			
Sub-Saharan Africa	-20.6	-4.8	-86.1
Middle East & North Africa	-20.1	-4.3	-82.5
Asia	-18.0	-4.0	-73.3
South & Central America	-16.1	-3.3	-74.6
North America	-9.6	-1.4	-20.0
Europe	0.6	0.4	96.6
Panel B - Global Economic Controls Specification			
Global Aggregates:			
Global GDP (no Q^* effect)	-6.8	-1.9	-26.6
Global Population Average	-10.0	-3.1	-58.7
Global Patent-Weighted Average Effect	-4.3	-1.0	-23.2
Global GDP (with Q^* effect, $\omega = 0.21$)	-7.7	-2.1	-26.6
Regional Summary:			
Sub-Saharan Africa	-13.0	-4.2	-86.1
Middle East & North Africa	-12.1	-3.7	-82.5
Asia	-11.0	-3.4	-73.3
South & Central America	-9.5	-2.8	-74.6
North America	-4.8	-1.2	-20.0
Europe	0.2	0.4	96.6

Notes: Table show the projected effects, in percent changes, of unabated global warming on end-of-century GDP under different projection methods. Country level temperature projections come from Burke, Hsiang and Miguel (2015). "Persistent growth effects" projections use the 10-year cumulative response ratio shown in Figure 5c to calibrate the effect of each degree of projected warming. "Level effects" projections use only the estimated contemporaneous effect of a 1°C shock, and allow for no persistence or accumulating effects. "Permanent growth effects" projections use estimates from Burke, Hsiang and Miguel (2015), and allow for the effects of temperature to permanently alter country-level growth rates. Panel (a) shows results for the local projections specification with year fixed effects, and panel (b) shows results for the specification with global economic control variables instead.

Table 4 summarizes the projections from all three methods at the global and regional scale. Note that, while the country-level estimates are all expressed in percentage terms that do not depend on assumptions about baseline growth in the absence of climate change, summarizing the results at an aggregate level requires weighting countries by the size of their economies or populations. Rather than assuming that the current distribution of global GDP and population stays constant in the future, we aggregate to the global level using the average country-level baseline GDP and population projections from the five Shared Socioeconomic Pathway scenarios (Dellink et al., 2017) that forecast expected future trends under a range of assumptions about the speed of global growth and the rate of convergence in the absence of warming.

Using the weights from baseline growth projections, Table 4 shows that our estimates imply a decline in global GDP of 11.5% in the specification with year FE, which is over five times larger than the level-effect estimates and less than half as large as the permanent growth effect estimates. In the specification with global control variables, our estimates imply a decline in global GDP of 6.8%, which is over three times larger than the level-effect estimates, and nearly four times smaller than the estimates under permanent growth effects. As shown in Figure 5, the long-run level effect of temperature is smaller in the specification with global controls, which features modestly greater persistence of temperature and somewhat more rapid recovery of GDP to trend.

Regional comparisons of projected future climate damages reiterate that poorer and hotter regions suffer the greatest harm. Table 4 shows that the largest damages occur in Africa, the Middle East, and Asia, where lost income averages approximately 20% in the specification with year fixed effects. Due to the heavy concentration of losses in regions with large populations and relatively low incomes, the population-weighted average decline in income is substantially larger than the impact on world GDP. The persistent growth effect estimates with year fixed effects suggest that the median person in the 2099 global population suffers an 18% income loss from global warming. The corresponding loss for the median global agent in 2099 is 4% and 86% when assuming level effects and permanent growth effects, respectively.

Our persistent growth estimates in Figure 7 and Table 4 capture the direct effects of rising temperatures on each country, but do not incorporate any impact on the growth rate of global technology. Using the notation of the model described in Section 2, the projections shown thus far assume that each country's Q_{it} is affected, but that global warming has no impact on Q_t^*, the world technology frontier that all countries draw from. We can approximate the effects of warming on Q_t^* as the patent-weighted global average of the country-level effects on Q_{it}, consistent with the model in which countries contribute collectively to global innovation. We calculate that the implied decline in Q_t^* from the patent-weighted average effect is 8.8% and 4.3% in the specifications with and without year fixed effects, respectively.

The additional impact of global warming through Q_t^* depends on the diffusion parameter ω. Equation (1) shows that ω the governs the share of each country's productivity that depends on global technology relative to domestic technology, and consequently the share of the estimated Q^* effect that diffuses to losses in each country's GDP (in log terms). Given the ω estimates from Section 4.4 of 0.08 with year fixed effects and 0.21 with global controls, the patent-weighted global Q^* effect implied by Table 4 generates a further global GDP decline of 0.7% to 0.9% across specifications from reduced innovation by frontier countries. This additional effect takes the projected global GDP losses from 11.5% to 12.2% in the year FE specification, and from 6.8% to 7.7% in the global controls specification.

It is worth noting that the estimated effects on Q^* imply a permanent growth effect from a given permanent temperature change at the global level, but not at the country-level. Recall that we argued in Section 2.2 that global patterns of economic growth are not consistent with *country-specific* permanent growth effects, since technology spillovers tie growth together across countries in the long run. Appendix Figure A-9 shows that our persistent growth effect projections are consistent with historical patterns of growth convergence, whereas permanent growth effect projections imply a divergence in country growth trajectories that differs sharply from what has been previously observed.

The evidence on growth convergence presented in Section 2.2 does not rule out a slowdown in the global frontier growth rate that affects all countries, as we incorporate in the projection. The implied effects on Q^* suggest a 9 basis point permanent reduction in global frontier growth in the year FE specification, and 4 basis points in the global controls specification. We interpret these results with caution, however, as we lack any direct evidence on mechanisms through which the GDP effects of temperature estimated in this paper would affect the innovation channel specifically.

5.3 Alternative scenarios and projection methods

Appendix Table A-3 shows the estimated effects of the warming that has already occurred from the 1950s to the 2010s on the global economy. Depending on specification, our estimates suggest the global economy is about $400-$800 billion (0.4-0.8%) smaller in the present day than it would be in the absence of the past half century of warming, with damages averaging over 5% of GDP in Africa and the Middle East. These damages are exacerbated by the fact that hotter countries have warmed at a faster rate than cooler ones.

Appendix Table A-4 shows projections for a scenario in which global reductions in greenhouse gas emissions yield a global temperature increase of only 2°C (vs. 3.7°in our baseline). In this scenario, the decline in global GDP is 5.6% and 3.2% with year FE and global controls, respectively, and 5.9% and 3.6% when accounting for possible effects on Q^* as described above. The contrast between the persistent growth effect and level effect projection is similar to the high emissions scenario in Table 4, and the distinction relative to the permanent growth effect projection is even larger.

In Appendix E we show results for two alternative methods to translate the local projections into future projections. Appendix E.1 describes an approach following Sims (1986) and Metcalf and Stock (2023) that reconstructs the projected path of future temperatures as a sequence of annual shocks, each of which persists over the 10-year horizon according to the estimates from equation (5). The sequence of shocks then implies a long-run path of GDP based on the lagged effects of each temperature shock, as in equation (6). This approach is similar in spirit to that of the cumulative response ratios we used in our primary specification, but directly uses the full impulse response to each temperature shock rather than summing and dividing over the 10-year horizon. As with the CRRs, we use the estimated effects for $h = 0$ through $h = 9$.

In Appendix E.2 we describe a structural projection using the model in Section 2. This approach uses the contemporaneous ($h = 0$) estimated effect of temperature, the ω estimates inferred in Section 4.4, and the law of motion (1) for Q_{it} as a function of μ_{it} and ω. The strength of this approach is that the model allows for longer-run persistent growth effects beyond the empirically feasible 10-year horizon based on the level of persistence observed within that window. The primary drawback is that the model is fairly stylized, which suggests caution in interpreting these results.

Appendix Table A-5 shows the Sims (1986) and model projection methods alongside our baseline CRR projections, the level effects projections, and the permanent country-specific growth effects projections. The table shows that the Sims (1986) method produces moderately larger estimates for the effects of warming on global GDP. When accounting for the Q^* effect, the Sims (1986) estimates show global GDP losses of 15.3% in the year FE specification and 9.8% in the global economic controls specification, as compared to 12.2% and 7.7%, respectively, in the CRR projections.

Table A-5 also shows that directly using the model from Section 2 produces larger projected effects of warming on global GDP. In the global controls specification, the model projections imply global losses of 9.1%, versus 7.7% in the CRR projections. The year fixed effects specification shows an even larger difference, with a 20.0% global decline in GDP implied by the model projections, as compared to 12.2% with CRR projections. Intuitively, this is because the model allows for longer run effects beyond the 10-year window based on the ω parameter inferred from the impulse response functions. Figure 5c shows that, in the year fixed effects specification, the CRR is still increasing even by horizon $h = 9$. Thus, the model infers a level of persistence in this specification that implies substantial effects beyond the 10-year window, and incorporating these longer run effects raises the projected impact of warming substantially.

To summarize, alternative projection methods suggest the persistent growth effects in our main CRR specification may understate the contrast with level-effects damage estimates such as Barrage and Nordhaus (2023), and somewhat overstate the difference in global GDP effects from Burke, Hsiang and Miguel (2015). Still, across the range of projection methods and specifications in Table A-5 our estimates are four to ten times larger than those that use a level effects approach, and 25-70% smaller than the permanent growth effect projections. And the sharp contrast with Burke et al. (2015) at the regional level remains across all specifications. In hotter regions such as Africa and the Middle East, our estimates with persistent growth effects are at least two to three times smaller than the permanent growth effect estimates across all projection methods considered in Table A-5.

6 Conclusion

A critical question for assessing the potential damage from rising global temperatures is whether the result will be lower GDP per capita than otherwise, or instead a lower long-run growth rate of GDP per capita. Estimates in the literature vary widely on this point, from the contemporaneous level effects of Barrage and Nordhaus (2023) to the permanent growth effects of Burke, Hsiang and Miguel (2015). Their estimated losses in GDP per capita in 2099 differ by an order of magnitude as a result.

In this paper we estimate the dynamic effects of temperature on GDP and find that they build and persist, but eventually level off. Thus permanently higher temperatures in a country appear to hurt its long run level of GDP per capita but not its long run growth rate. Compared to the literature that estimates contemporaneous level effects only, we find it is crucial to allow lagged temperature to affect future GDP per capita in a given country. In contrast to the literature that estimates permanent growth effects, we incorporate the persistence of changes in temperature and project that temperature has an effect on GDP growth for years but eventually fades — leaving substantial long-run level effects but no long-run growth effects.

We emphasize that level (but not growth) effects are consistent with a large literature finding that country growth rates are tethered together by technology diffusion. And the estimates we obtain for the strength of knowledge spillovers based on GDP per capita alone are remarkably close to what is needed to rationalize the estimated dynamic effects of temperature on GDP in a given country. Levels can diverge, but growth rates converge back to the rate dictated by a common technological driver. We show that our estimates imply that warming will cause a modest slowdown in the rate of global technological progress that raises the implied by damages by a shade under one percentage point of global GDP in 2099.

Our estimates imply impacts in 2099 that are at least three to six times larger than contemporaneous level effect estimates, but 25-70% smaller than those estimates based on permanent country-specific growth effects, with especially stark differences for initially hot and cold countries. We leave it to future work to assess the implications of these climate damage estimates for cost-benefit analysis of climate change policies.

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A A Simple Model of Global Growth

Consider N economies (countries), indexed by i, with endogenous firm entry and endogenous process innovation upon entry each period. The final goods production function is:

$$Y_{it} = \left(\int_0^{M_{it}} y_{jit}^{\frac{\sigma-1}{\sigma}} \mathrm{d}j \right)^{\frac{\sigma}{\sigma-1}}.$$

M_{it} is the mass of intermediate goods, indexed by j, which are available in country i, and $\sigma > 1$ is the corresponding elasticity of substitution. Intermediate goods are produced by single-product monopolistically competitive firms with the following technology:

$$y_{jit} = q_{jit} \ell_{jit}$$

where q_{jit} is process efficiency and ℓ_{jit} is production labor. Importantly, each intermediate producer lives for a single year. In each year, a new set of intermediate producers choose the process efficiency with which they enter. Entrants are subject to the following entry cost, denominated in units of labor:

$$F \cdot \exp\left(\frac{q_{jit}}{\mu_{it} \overline{Q}_{it-1}} \right)$$

where $F > 0$ and $\mu_{it} > 0$ follows a time-varying process. μ_{it} can be thought of as the efficiency of technology adoption within a given country and year. Given the exponential form, the cost of entering is convex in the level of process efficiency chosen. $\overline{Q}_{it}$ is the geometric combination of domestic average process efficiency and that of technologically leading countries (e.g., OECD member countries), denoted as Q_t^*:

$$\overline{Q}_{it} = Q_{it}^{1-\omega} Q_t^{*\omega} \quad \text{where} \quad Q_{it} = \left(\int_0^{M_{it}} q_{jit}^{\sigma-1} \mathrm{d}j / M_{it} \right)^{\frac{1}{\sigma-1}} \quad \text{and} \quad Q_t^* = \prod_{k \in \text{oecd}} Q_{kt}^{\alpha_k}.$$

Here $\omega \in (0,1)$ so that entrants in a country build on a combination of domestic and foreign technologies. And $\alpha_k = L_{kt} / L_t^{\text{oecd}}$ and $L_t^{\text{oecd}} = \sum_{k \in \text{oecd}}^N L_{kt}$. The higher is the combination of domestic and foreign technology (process efficiency) last year, the lower the cost of entering with a given process efficiency this year.

Labor in each country is used in production and entry:

$$\int_0^{M_{it}} \ell_{jit} \mathrm{d}j + \int_0^{M_{it}} F \cdot \exp\left(\frac{q_{jit}}{\mu_{it}\overline{Q}_{it-1}}\right) \mathrm{d}j = L_{it}.$$

L_{it} denotes the employment of country i in year t, which grows at the common exogenous rate n in each country:

$$L_{it} = (1+n)L_{it-1}.$$

A.1 Equilibrium allocation

The final sector's problem delivers the usual demand functions for each variety:

$$y_{jit} = Y_{it}\left(\frac{P_{it}}{p_{jit}}\right)^{\sigma} \quad \text{where} \quad P_{it} \equiv \left(\int_0^{M_{it}} p_{jit}^{1-\sigma} \mathrm{d}j\right)^{\frac{1}{1-\sigma}}.$$

Given the demand for its variety and the wage, the intermediate firm's problem delivers the usual pricing functions:

$$p_{jit} = \frac{\sigma}{\sigma-1} \times \frac{w_{it}}{q_{jit}}.$$

Substituting this in the intermediate firm's profit function, we have:

$$\pi_{jit} = \frac{P_{it}Y_{it}q_{jit}^{\sigma-1}}{\sigma M_{it}Q_{it}^{\sigma-1}} - w_{it}F\exp\left(\frac{q_{jit}}{\mu_{it}\overline{Q}_{it-1}}\right)$$

where the free-entry condition implies:

$$\frac{P_{it}Y_{it}q_{jit}^{\sigma-1}}{\sigma M_{it}Q_{it}^{\sigma-1}} = w_{it}F\exp\left(\frac{q_{jit}}{\mu_{it}\overline{Q}_{it-1}}\right).$$

Taking the first-order condition of profits with respect to q_{jit}:

$$\mu_{it}\overline{Q}_{it-1} \times \frac{(\sigma-1)P_{it}Y_{it}q_{jit}^{\sigma-2}}{\sigma M_{it}Q_{it}^{\sigma-1}} = w_{it}F\exp\left(\frac{q_{jit}}{\mu_{it}\overline{Q}_{it-1}}\right).$$

Substituting in the free-entry condition in this previous expression, we obtain the intermediate firm's choice of process efficiency:

$$q_{jit} = Q_{it} = (\sigma - 1)\mu_{it}\overline{Q}_{it-1} \quad \forall j. \tag{8}$$

Thus entrants choose higher process efficiency the higher is μ_{it} and the taller the shoulders they are building upon $\overline{Q}_{it-1}$. Note that, by symmetry, all j intermediate good producers choose the same process efficiency within a given country and year.

Integrating the free-entry condition over all firms and substituting in the choice of process efficiency as well as the aggregate budget constraint ($w_{it}L_{it} = P_{it}Y_{it}$), we obtain the equilibrium measure of varieties:

$$M_{it} = \frac{L_{it}}{\sigma F \exp(\sigma - 1)}.$$

This then implies that income per person is given by:

$$\frac{Y_{it}}{L_{it}} = \frac{w_{it}}{P_{it}} = (\sigma - 1)^2 \cdot \mu_{it} \cdot \overline{Q}_{it-1} \cdot \left[\frac{L_{it}}{\sigma^{\sigma} F \exp(\sigma - 1)}\right]^{\frac{1}{\sigma - 1}}.$$

A.2 Balanced growth path

Given firm choices, the growth rate g_{it} of domestic process efficiency in country i is

$$1 + g_{it} = (\sigma - 1) \cdot \mu_{it} \cdot \left(\frac{Q^*_{t-1}}{Q_{it-1}}\right)^{\omega}.$$

If $\mu_{it} = \overline{\mu}_i \forall t$, including in the frontier countries, then it is easy to show that the growth rate of Q_{it} settles down to the constant growth rate of Q^*_t. That is, $g_i = g^*$.

The path of average process efficiency in country i along its balanced growth path is

$$Q_{it} = \left[\frac{(\sigma - 1) \cdot \overline{\mu}_i}{1 + g^*}\right]^{\frac{1}{\omega}} Q^*_t$$

Substituting this into the definition of Q^*_t for OECD countries, we find that:

$$1 + g^* = (\sigma - 1) \cdot \overline{\mu}^* \quad \text{where} \quad \overline{\mu}^* \equiv \prod_{k \in \text{oecd}} \overline{\mu}_k^{\alpha_k},$$

which can be substituted in the previous equation to obtain:

$$Q_{it} = (\overline{\mu}_i / \overline{\mu}^*)^{\frac{1}{\omega}} Q_t^*.$$

Note that $Q_{it}/Q_t^* \propto \overline{\mu}_i{}^{\frac{1}{\omega}}$ on the steady state growth path. A country's process efficiency relative to the frontier countries is increasing in its $\overline{\mu}^i$.

A country's income per capita can be expressed as:

$$Y_{it}/L_{it} = \frac{\sigma - 1}{\sigma} \cdot M_{it}^{\frac{1}{\sigma-1}} \cdot Q_{it}.$$

A country is richer the higher its mass of varieties and the higher its process efficiency. This can be translated in terms of exogenous variables as

$$Y_{it}/L_{it} = \frac{\sigma - 1}{\sigma} \cdot \left[\frac{L_{it}}{\sigma F \exp(\sigma - 1)} \right]^{\frac{1}{\sigma-1}} (\overline{\mu}_i / \overline{\mu}^*)^{\frac{1}{\omega}} Q_t^*. \tag{9}$$

Countries with more employment will generate more varieties because entry costs are denominated in terms of domestic labor.[22] And, as mentioned, countries who are better at building on the previous year's technology (i.e., with higher $\overline{\mu}_i$) will tend to be richer.

Income per worker grows at the rate:

$$(1+n)^{\frac{1}{\sigma-1}} (1 + g^*) - 1.$$

Using log first differences, the approximate growth rate is:

$$g_{Y/L} \approx \frac{1}{1-\sigma} \cdot n + g^*$$

Thus all countries will grow at the same rate (in terms of both GDP and GDP per worker) in the long run if they have the same long run employment growth rate.

This model provides a stark point of contrast to "AK" models in which countries grow at permanently different rates if they have different investment rates in K and/or

[22]This is an example of a weak scale effect: the level of employment raises the *level* of income. In terms of varieties the model is in the spirit of the semi-endogenous growth models of Jones (1995) and Peretto (1998). It does not have the strong scale effect of the Romer (1990) model in which a higher level of employment raises the growth rate.

have different A levels (say due to differences in their climate). Here we could add A differences in the final goods production function and they would affect levels but not the growth rate of income per worker.

A.3 Transition Dynamics

Along a transition path, income per capita is given by:

$$Y_{it}/L_{it} = \frac{\sigma-1}{\sigma} \cdot M_{it}^{\frac{1}{\sigma-1}} Q_{it} \quad \text{where} \quad Q_{it} = (\sigma-1) \cdot \mu_{it} \cdot Q_{it-1}^{1-\omega} Q_{t-1}^{*\omega}.$$

So the transition dynamics for average process efficiency for non-OECD country i and for the OECD countries, respectively, is:

$$Q_{it+1} = (\sigma-1) \cdot \mu_{it+1} \cdot Q_{it}^{1-\omega} Q_t^{*\omega} \quad \text{and} \quad Q_{t+1}^* = (\sigma-1) \cdot \mu_t^* \cdot Q_t^*. \tag{10}$$

To characterize the speed at which countries converge to the common stationary growth rate g^*, once their μ_i settles down, one needs an estimate for ω. So suppose that we can proxy process efficiency Q_{it} by a country i's TFP (in labor augmenting form) net of its "love of variety" component M_{it} (which is proportional to employment in country i). Then one could estimate equation (1) in logarithms by OLS with country fixed effects β_i:

$$\log(Q_{it+1}) = \beta_i + (1-\omega)\log(Q_{it}) + \omega \log(Q_t^*) + u_{it} \tag{11}$$

However, the serial correlation coming from the unobserved μ_{it} could potentially bias an OLS estimate of ω. Therefore, we instead estimate ω by indirect inference. More precisely, we proceed in 6 steps:

1. We first obtain the biased OLS estimate $\widehat{\omega}_{\text{empirical}}$ by estimating equation (11).

2. Then, given a value of σ, we choose a value of ω_0 and use it together with data on Q_{it} and equation (1) to obtain country-specific time series for μ_{it}.

3. With these μ_{it} series we estimate the AR(1) parameters μ_i, ρ_i and ς_i for each country separately by OLS.

4. We draw shocks ϵ_{it} to μ_{it} from the normal distribution $\mathcal{N}(0, \varsigma_i)$ to simulate the μ_{it} process for T periods (matching the length of our time series for Q_{it}), starting the

simulation with a random draw from the stationary distribution of μ_{it}: $\log(\mu_{i0}) \sim \mathcal{N}(\frac{\log(\mu_i)}{1-\rho_i}, \frac{\varsigma_i^2}{1-\rho_i^2})$.

5. With the simulated time series of μ_{it}, we use equation (1) together with the empirical starting value Q_{i0} and our chosen value ω_0 to simulate the path of Q_{it} for T periods.

6. Finally, we estimate equation (11) with simulated data and compare the simulated and empirical estimates $\widehat{\omega}_{\text{simulation}}$ and $\widehat{\omega}_{\text{empirical}}$. To elicit the true value of ω, we iterate on our initial chosen value of ω_0 until the distance between $\widehat{\omega}_{\text{simulation}}$ and $\widehat{\omega}_{\text{empirical}}$ goes to zero (within a tolerance).

Assuming that Q_t^* is U.S. TFP in year t, we estimate ω according to this algorithm. We restrict our sample to countries with complete data between 1980 and 2019 and for which data quality is not an issue.[23] Overall, we are left with a balanced panel of 103 countries. Finally, when estimating equation (11), we (a) use weights that correspond to each country's global employment share in a given year, (b) apply the Cochrane-Orcutt estimation procedure to adjust for serial correlation, and (c) either do or do not impose the constraint that the exponents on own and foreign technologies add up to 1.

With this strategy, the biased OLS estimate $\hat{\omega}$ we obtain is equal to 0.076 (0.006). And we find that this is generated by a *true* ω of 0.069. Thus, at least in our simulation, the bias is small and the OLS ω is not far from the true ω. The true ω of 0.07, combined with $\rho > 0$, implies that shocks to country technology adoption will have effects on GDP that will build and persist for a number of years before fading.

As a validation exercise, we use the simulated data produced in step 4 of the algorithm to calculate two cross-sectional moments (across 103 countries): (A) the standard deviation of average annual TFP growth and (B) the correlation of the logarithm of TFP between the beginning and ending periods of our simulation. Those moments are respectively equal to 1.95% and 0.898 when calculated on simulated data. If we instead compute these moments using real world data, we get values of 1.89% and 0.707, respectively.

[23]The Penn World Tables classifies some countries as "outliers" because their data is of poor quality in some year. We exclude those countries from our sample, in addition to five other countries for which data quality is also an issue. The five other countries are Kuwait, the Central African Republic, Angola, Mongolia and Qatar.

B Literature on Globally-Interconnected Growth

The evidence we present in Section 2 of this paper adds to an already-established body of evidence that has led to a consensus among growth economists that country growth rates are tethered together in the long run (i.e., $\omega > 0$). In this section, we summarize the three strands of literature that underlie this consensus.

Conditional convergence

The consistent finding in the cross-country growth regression literature is that per capita incomes tend to converge to parallel growth paths (or sometimes even the same growth path). That is, countries converge towards relative steady state income levels determined by persistent fundamentals affecting their long run investment rates in physical capital, human capital, and technology. Classic cites in this regard include Barro and Sala-i Martin (1992), Mankiw, Romer and Weil (1992), and Easterly, Kremer, Pritchett and Summers (1993). Their findings hold up in more recent studies such as Pritchett and Summers (2014), Barro (2015), and Kremer, Willis and You (2022).

The dominant explanation for this pattern is that technology diffuses across countries, so that countries experience the same long run growth rate if they are sufficiently open to the international flow of ideas. This view is advocated by Mankiw et al. (1992), Barro (1995), Parente and Prescott (1994, 2005), Grossman and Helpman (1995), Sachs and Warner (1995), Klenow and Rodriguez-Clare (2005), Acemoglu, Aghion and Zilibotti (2006), Acemoglu (2008), Lucas (2009), Alvarez, Buera and Lucas (2013), Buera and Oberfield (2020), Cai, Li and Santacreu (2022), Lind and Ramondo (2022b), Hsieh, Klenow and Nath (2022), and many others.

Development accounting

A large literature estimates *level* effects of country differences in investment rates in human and physical capital. That is, such differences help account for differences in levels of development rather than generating persistent differences in country growth rates.

One of the first and most influential in this vein was Mankiw et al. (1992). Klenow and Rodriguez-Clare (1997) and Hall and Jones (1999) homed in on how schooling contributed to income differences. Erosa et al. (2010), Schoellman (2012), and Manuelli and Seshadri (2014) emphasized differences in the quality of schooling across countries. Weil

(2014) examined the role of health differences, and Lagakos et al. (2018) human capital accumulated on the job.

Caselli (2005), Hsieh and Klenow (2010), and Jones (2016) provide surveys of this literature. Again, these studies provide evidence that investment rate differences have level effects on country incomes, rather than causing country growth rates to diverge.

Technology diffusion

Many studies provide direct or at least indirect evidence of technology diffusing across countries. The evidence covers categories like patents, trade, foreign direct investment (FDI), hybrid seeds, and generic drugs:

Eaton and Kortum (1996, 1999) show that firms frequently patented the same invention in many different OECD countries at once in the era before the European Patent Office. Patenting is costly, so this indicates that firms routinely tried to protect their intellectual property from being used by competitors selling in foreign markets. More recently, Jones (2016) stresses that over half of patents in the United States are filed by companies and individuals based outside the U.S. Akcigit, Ates and Impullitti (2018) use this data to estimate the joint contribution of research in the U.S. and Europe to their common growth rate.

Eaton and Kortum (2001) document that all but a few countries import most of their equipment from other countries. Since Greenwood et al. (1997) much of U.S. growth has been traced to equipment-embodied technical change. Grossman, Helpman, Oberfield and Sampson (2017) is a recent paper in the same spirit. Coe, Helpman and Hoffmaister (1997, 2009) find that importing goods from R&D-intensive economies is associated with higher productivity, consistent with technology embodied in rich-country exports. See also Keller (2002), and Keller (2004) for a survey.

Firms can also transfer technology through FDI, i.e., operating plants in other countries. Natalia Ramondo provides some of the best evidence in a series of papers with collaborators: Ramondo and Rodríguez-Clare (2013), Arkolakis, Ramondo, Rodríguez-Clare and Yeaple (2018), Alviarez, Cravino and Ramondo (2020), and Lind and Ramondo (2022a,b).

The use of hybrid seeds, with substantial impact on agricultural productivity, can be traced directly to foreign genetic ancestors in many countries. Foster and Rosenzweig

(1995, 1996) study India in particular, and they provide a survey in Foster and Rosenzweig (2010). Evenson and Gollin (2003) and Gollin, Hansen and Wingender (2021) provide evidence for many countries.

Alfonso-Cristancho et al. (2015) compile statistics on generic drug production across the world. The World Trade Organization Trade-Related Aspects of Intellectual Property Rights (TRIPS) agreement aimed to deal with generic drugs and other flows of intellectual property. See Chaudhuri, Goldberg and Jia (2006) for how TRIPS impacted the generic drug industry in India.

Some papers analyze ways in which technology developed in advanced economies may not be appropriate for emerging economies. Still, they obtain that a fraction of technologies flow, resulting in level differences rather than growth rate differences across countries. Examples include Basu and Weil (1998), Acemoglu and Zilibotti (2001), Alviarez et al. (2020), and Moscona and Sastry (2022).

C Additional Exercises Illustrating Econometric Challenges

C.1 Monte Carlo Evidence on Growth vs. Level Effects

This section reports the details and results of the Monte Carlo investigation of biases in estimating levels versus growth effects. Recall the equations from the main text:

$$\Delta y_{it} = \rho \Delta y_{it-1} + \beta T_{it} + \theta_1 T_{i,t-1} + \theta_2 T_{i,t-2} + \mu_i + \mu_t + \eta_{it}.$$

$$T_{it} = \gamma T_{it-1} + \lambda_i + \lambda_t + \zeta_{it}, \quad \zeta_{it} \sim \mathcal{N}(0, \sigma^2)\,.$$

Δy_{it} is GDP growth (based on log differences of GDP and stated in percent) in country i in year t, T_{it} is temperature in country i in year t, and the μ's and λ's represent country and year fixed effects. We are implicitly assuming that the log level of GDP is driven by a unit root permanent component as well as a component that is related to temperature.[24]

Simple algebra shows that if temperature has only a transitory, one-period effect on the log level of GDP it must be the case that $\theta_1 = -\beta(1+\rho)$ and $\theta_2 = \beta\rho$. That is, the coefficients on the lagged values of temperature in the GDP growth equation must reverse the previous effect on GDP growth. This algebra clarifies what Newell et al. (2021) mean by *sign reversal* when discussing their estimates that include lags of temperature (e.g. p. 4-5). In the special case in which there is no serial correlation of GDP growth ($\rho = 0$), temperature must enter as a first difference, i.e. $\theta_1 = -\beta$ and $\theta_2 = 0$. However, GDP growth is serially correlated in the data, so a more general formula is needed.

What happens if one estimates the model with the lagged temperature terms omitted, as in the baseline model on which BHM base their projections?

To answer this question, we conduct some simple Monte Carlo simulations. We create a panel of 150 countries, each with 60 years of data. We calibrate the model so that temperature has a temporary, contemporaneous effect on the level of GDP. We set β to -1 and the autocorrelation parameter for GDP growth, ρ, to 0.2 based on regressions on

[24] The nonstationarity of GDP does not imply that all shocks to GDP have permanent level effects. GDP is likely affected by both permanent and temporary driving forces. For example, a permanent change in technology likely leads to a permanent change in GDP and its gradual diffusion could lead to serial correlation in GDP growth rates. Monetary policy shocks are examples of driving forces that have temporary effects.

our data set.[25]

Table A-1 shows the results of estimating several specifications on the simulated data. We begin by considering the case in which γ=0, so that there is no serial correlation in temperature. The first column shows the result of estimating the BHM model with no lags. Interestingly, even when no lags of temperature (or GDP growth) are included, the estimates of β are centered around the true value of -1. There is no bias in this case because the omitted lagged temperature variables are uncorrelated with current temperature since deviations from mean are i.i.d. However, this contemporaneous estimated growth effect tells us *nothing* about how GDP growth will respond in the future, so one cannot infer permanent growth effects. In fact, the temperature results completely reverse if we include lagged temperature in the regression. Column 2 shows that the parameter on the first lag of temperature reverses the effect of contemporaneous temperature, such that the sum of the parameters on the three temperature variables is zero, implying no lasting effects. However, Column 2, which does not control for lagged GDP growth, recovers biased coefficients for the first and second lags of temperature. Column 3 shows that only with an additional control for lagged GDP growth can the regression recover estimates close to the true coefficients for both contemporaneous and lagged temperature.[26]

Columns 4 through 6 of Table A-1 estimate the same regressions as Columns 1 through 3, but on simulated data in which temperature follows a first-order autoregressive process (AR(1)). The primary difference here is that the regression of GDP growth on contemporaneous temperature with no lags included is downward biased by 50 percent (Column 4). The bias occurs in this case because the omitted lags of temperature are correlated with contemporaneous temperature. Once the two temperature lags and the one lag of GDP growth are included, as in Column 6, the coefficient on temperature is unbiased, as are the coefficients on lagged temperature.

This Monte Carlo experiment illustrates two main points. First, even without serial correlation of GDP or temperature, the BHM baseline specification constrains temperature to have a growth effect because it rules out reversals that turn the effect into a temporary effect on GDP levels. Lagged values of temperature must be included in order

[25]Note that we measure GDP growth as a percent, so our coefficients on temperature are typically 100 times those of most others in the literature.

[26]The estimate of ρ on lagged GDP growth displays the well-known downward bias of autoregressive parameters in finite samples. The bias is approximately -(1 + 3 ρ)/(# of observations in the time dimension). Our simulations have 60 years for each country, so the bias is predicted to be 0.027.

Table A-1: Monte Carlo Illustration of Bias from Omitting Temperature Lags

	Dependent Variable: GDP Growth in year t					
	(1)	(2)	(3)	(4)	(5)	(6)
	$\gamma = 0$	$\gamma = 0$	$\gamma = 0$	$\gamma = 0.5$	$\gamma = 0.5$	$\gamma = 0.5$
Temperature$_{it}$	-0.995	-0.995	-0.996	-0.517	-0.995	-0.996
	(0.128)	(0.130)	(0.128)	(0.113)	(0.131)	(0.128)
Temperature$_{i,t-1}$		1.003	1.177		1.00	1.175
		(0.130)	(0.129)		(0.145)	(0.143)
Temperature$_{i,t-2}$		-0.0028	-0.182		-0.0029	-0.180
		(0.132)	(0.130)		(0.132)	(0.130)
GDP Growth$_{i,t-1}$			0.179			0.179
			(0.011)			(0.011)

Notes: Simulated data for 150 countries with 60 years of data each. The true parameter on contemporaneous temperature, β, is -1. The true parameters on the two lags of temperature are 1.2 and -0.2, respectively. γ is the autocorrelation coefficient on temperature and varies across specifications. The true parameter on lagged GDP growth is 0.2. Standard errors in parentheses. The downward bias in the estimate of this latter parameter is well-known for finite samples.

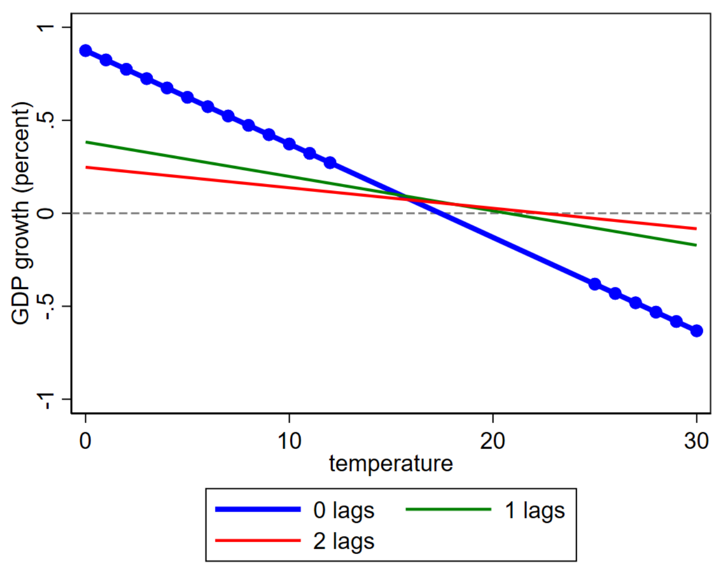
to detect the reversal effect. Second, the presence of serial correlation of GDP growth and temperature implies that simple first-difference versus levels specifications are not appropriate, so more lags are likely to be necessary. How many lags should be included depends on the serial correlation properties of GDP growth and temperature and whether there are lagged effects of temperature.

C.2 Illustrating the Importance of Lagged Temperature

Section 3.1.1 and the Appendix section above show the importance of controlling for lagged temperature and GDP both algebraically and in Monte Carlo simulations. To show the importance in practice, we estimate the Burke, Hsiang and Miguel (2015) (BHM) baseline model using our data set described in Section 4.1. The model we estimate follows the main specification in BHM in regressing GDP growth on a quadratic in temperature, a quadratic in precipitation, and country and year fixed effects. It omits BHM's country-specific quadratic trends since they remove useful variation in persistent temperature shocks that differ across countries.

Appendix Figure A-1 below shows the estimated cumulative marginal effects of temperature on GDP by temperature level when zero, one, and two lags of the polynomial in temperature are included. The specifications with temperature lags also include one lag of GDP growth. The version with no temperature lags implies that the effects of temperature on GDP growth vary with temperature itself, with positive effects for colder countries and negative effects for warmer countries. The slope of the line is statistically different from zero at many points. However, when one or two lags of temperature are included, the relationship flattens and weakens the negative effects.

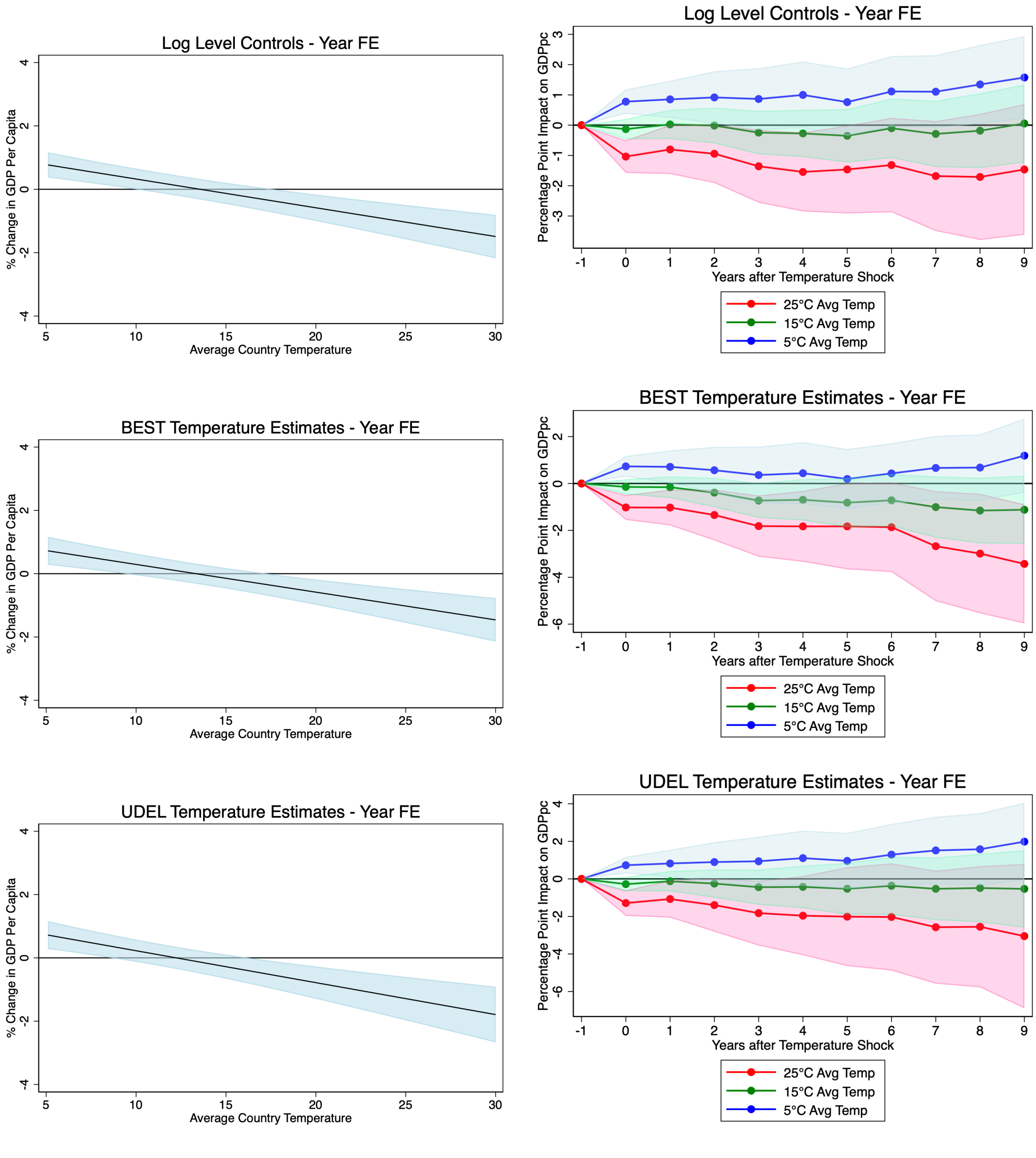
Figure A-1: Estimated Cumulative Marginal Effects in a Simplified BHM Model
Effects of Adding Lags of Temperature



Notes: Estimates from regressions of GDP growth on a quadratic in temperature and precipitation, as well as country- and year-fixed effects in our new dataset. One lag of GDP growth is included in the specifications that have temperature lags. The estimates shown are for the marginal effects and are summed over current and lagged temperature. The solid dots denote estimates that are statistically different from zero at the 90 % level. GDP data are from the World Development Indicators, and temperature data is from the Global Meteorological Forcing Dataset. We describe the sample in more detail in Section 4.1.

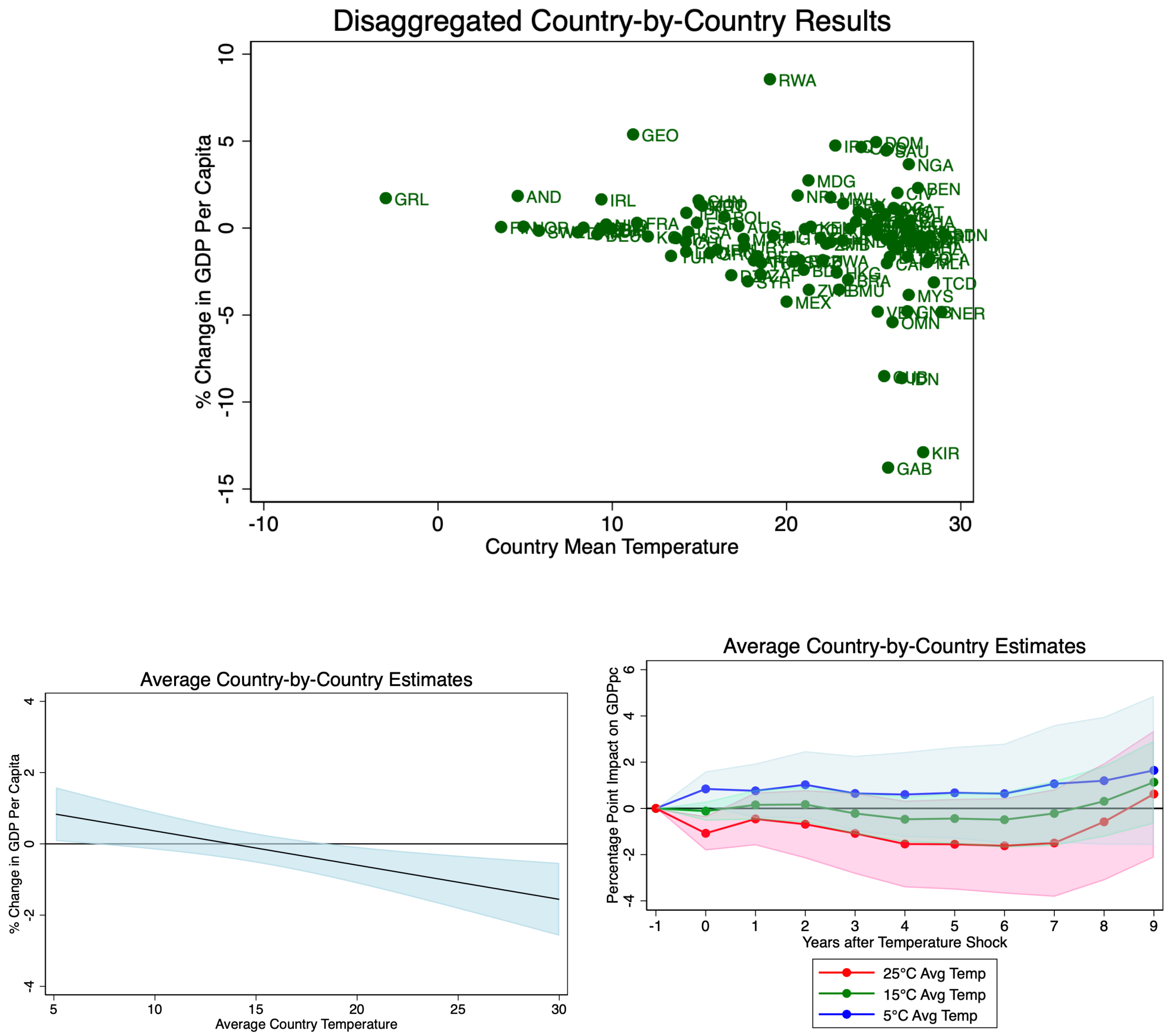
D Empirical and Projection Robustness Results

Figure A-2: Robustness Results



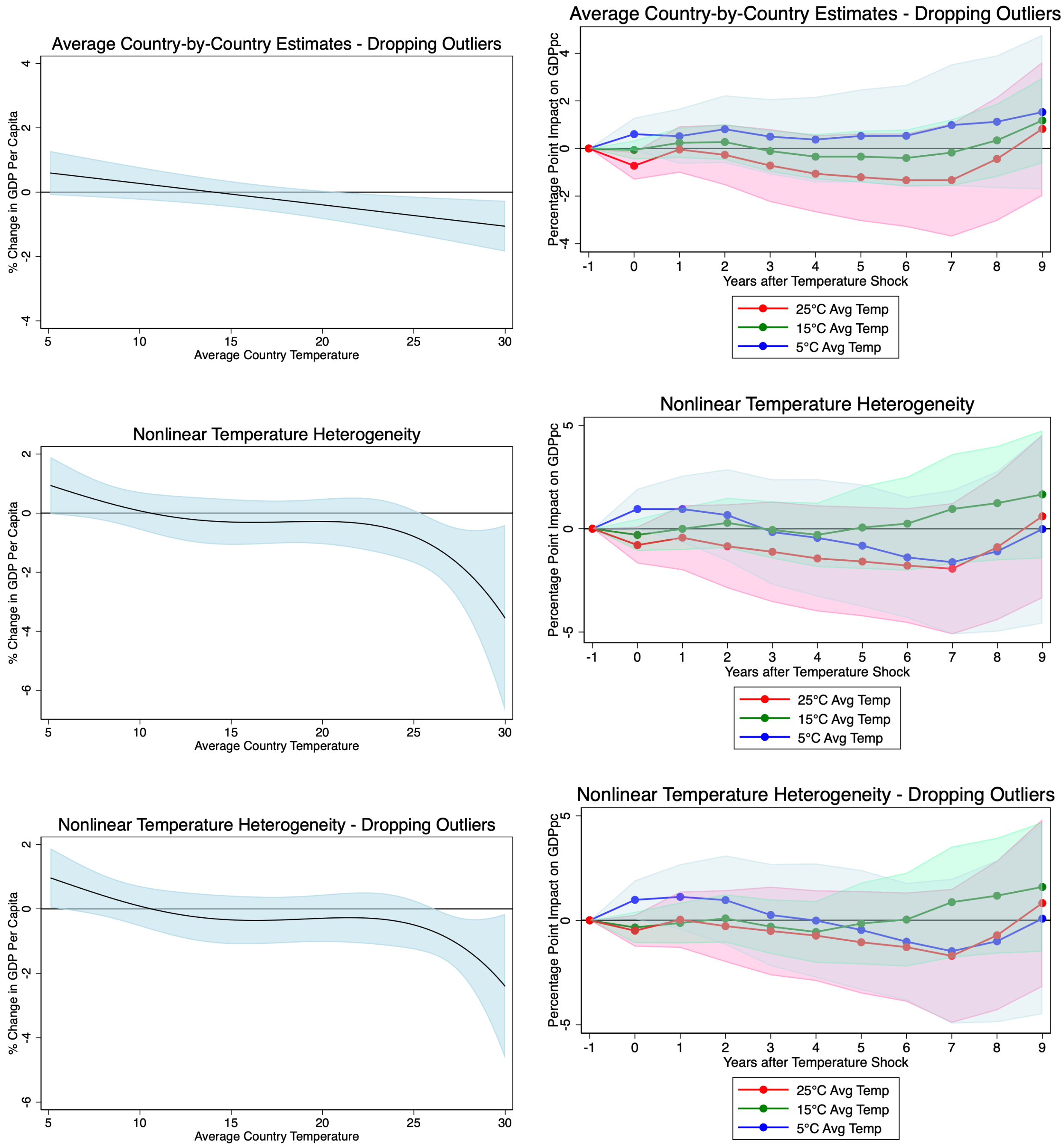
Notes: Graphs show local projections estimates of the persistent effects of an unanticipated 1°C temperature shock on GDP using Equation 6. Each graph on the left shows the contemporaneous effects of a 1°C temperature shock on GDP. The effect is allowed to vary with long-run average historical country temperature, which is shown on the x-axis. Each graph on the right shows the impulse response function of GDP to the initial shock to a 10-year horizon. Panel (a) shows estimates that use log levels of the lagged control variables rather than first-differences. Panels (b) and (c) show estimates using the Berkeley Earth Surface Temperature dataset and University of Delaware Temperature dataset, respectively, each with year fixed effects. In each impulse response function, the blue, green, and red lines represent cold (5°C), moderate (15°C), and hot (25 °C) countries, respectively, and the 95% confidence intervals are shown with corresponding color shading. GDP data are from the World Development Indicators.

Figure A-3: Country-by-Country Local Projections Results



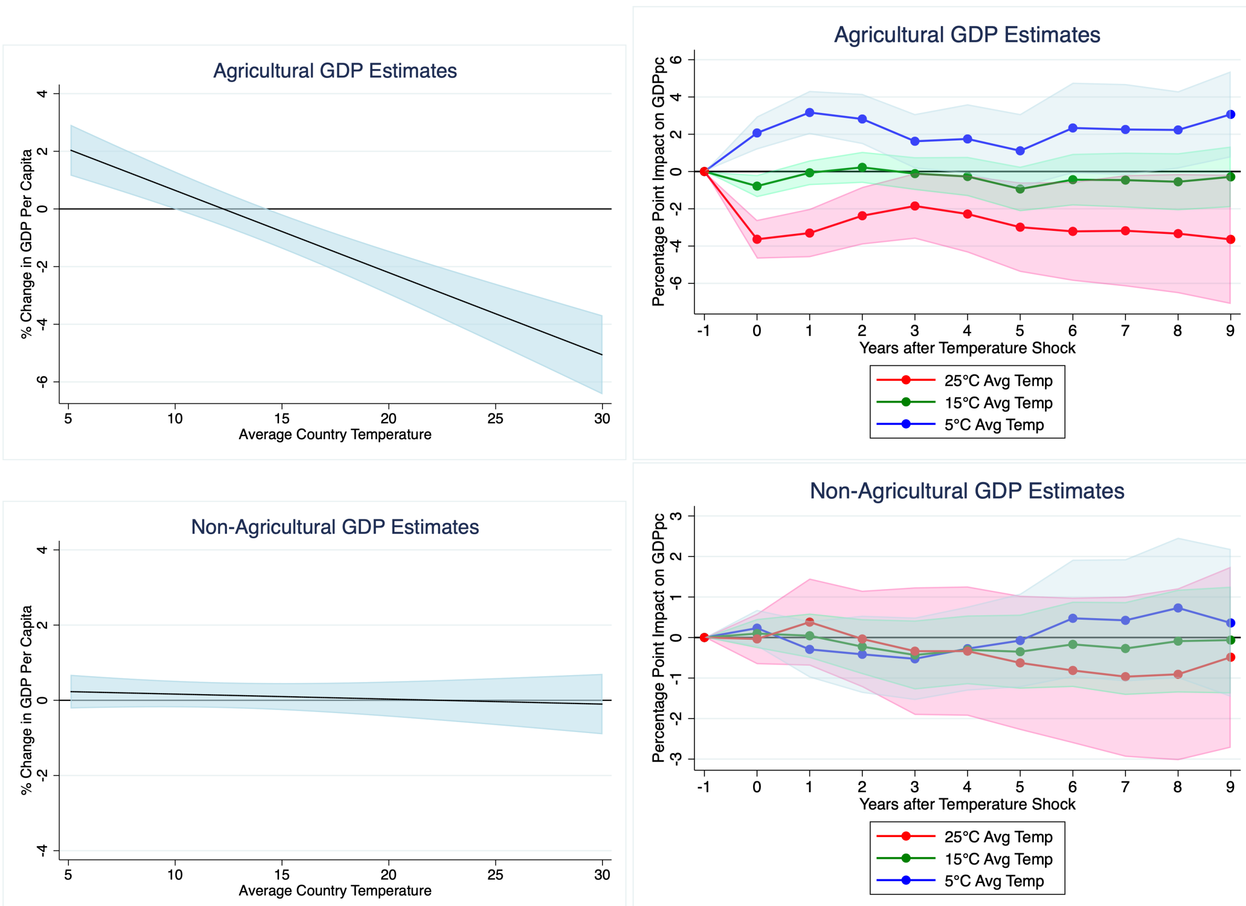
Notes: Panel (a) shows local projections estimates of the contemporaneous effects of an unanticipated 1°C temperature shock on GDP using Equation 6, estimated one country at a time for all 112 countries with at least 50 years of data in the sample. In panel (b), the graph on the left shows the average effects across the range of long-run average temperatures experienced throughout the world, which is shown on the x-axis. The 95% confidence interval is shaded in blue. The graph on the right of panel (b) shows the impulse response function of GDP to the initial shock to a 10-year horizon. In each impulse response function, the blue, green, and red lines represent cold (5°C), moderate (15°C), and hot (25 °C) countries, respectively, and the 95% confidence intervals are shown with corresponding color shading. Temperature data are from the Global Meteorological Forcing Dataset. GDP data are from the World Development Indicators.

Figure A-4: Country-by-Country Local Projections Robustness Checks



Notes: Panel (a) shows local projections estimates of the contemporaneous effects of an unanticipated 1°C temperature shock on GDP using Equation 6, estimated one country at a time for all 112 countries with at least 50 years of data in the sample. In panel (b), the graph on the left shows the average effects across the range of long-run average temperatures experienced throughout the world, which is shown on the x-axis. The 95% confidence interval is shaded in blue. The graph on the right of panel (b) shows the impulse response function of GDP to the initial shock to a 10-year horizon. In each impulse response function, the blue, green, and red lines represent cold (5°C), moderate (15°C), and hot (25 °C) countries, respectively, and the 95% confidence intervals are shown with corresponding color shading. Temperature data are from the Global Meteorological Forcing Dataset. GDP data are from the World Development Indicators.

Figure A-5: Agricultural and Non-Agricultural GDP



Notes: Graphs show local projections estimates of the persistent effects of an unanticipated 1°C temperature shock on GDP using Equation 6. Each graph on the left shows the contemporaneous effects of a 1°C temperature shock on GDP. The effect is allowed to vary with long-run average historical country temperature, which is shown on the x-axis. Each graph on the right shows the impulse response function of GDP to the initial shock to a 10-year horizon. Panel (a) shows the effects for agricultural GDP, and panel (b) shows the effects for nonagricultural GDP. Data on agricultural and nonagricultural GDP is compiled from Herrendorf, Rogerson and Valentinyi (2014), the UN National Accounts database, and the University of Groningen 10-Sector Database (Timmer, de Vries and De Vries, 2015). In each impulse response function, the blue, green, and red lines represent cold (5°C), moderate (15°C), and hot (25 °C) countries, respectively, and the 95% confidence intervals are shown with corresponding color shading. Temperature data are from GMFD, and GDP data are from the World Development Indicators.

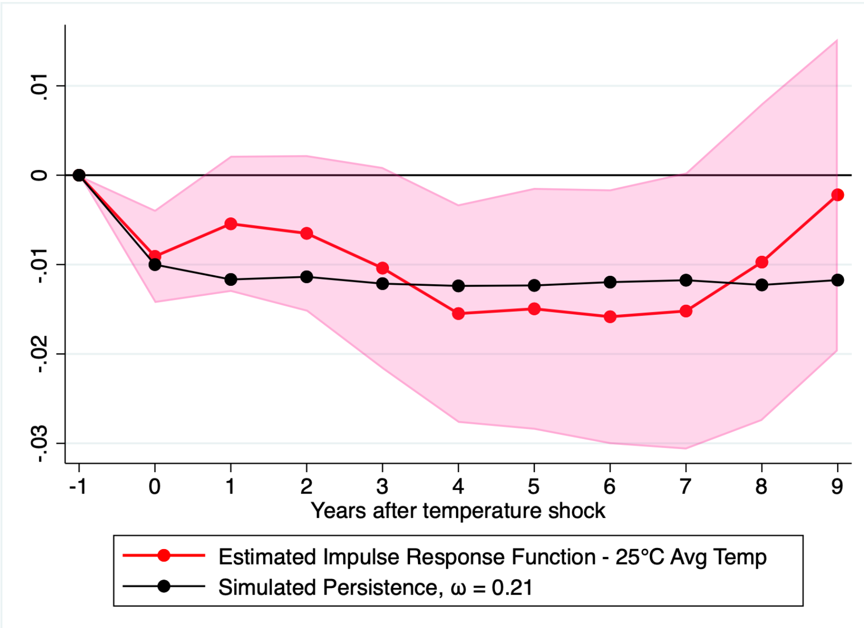
Table A-2: Heterogeneous Effects of Temperature Shock on GDP
Country-by-Country Local Projections Estimates

	Dependent Variable: $\beta_{GDP}^{h=0}$			
	(1)	(2)	(3)	(4)
Country Mean Temperature	-0.096**	-0.12**	-0.13**	-0.14**
	(0.032)	(0.044)	(0.046)	(0.048)
Dummy for Original OECD		-0.61		
		(0.54)		
Mean Agricultural Share of GDP			4.02	
			(2.77)	
Dummy for Poor Country in 1980				1.27
				(0.74)
Constant	1.32*	1.91*	1.36*	1.53*
	(0.53)	(0.93)	(0.56)	(0.59)
N	112	112	111	112

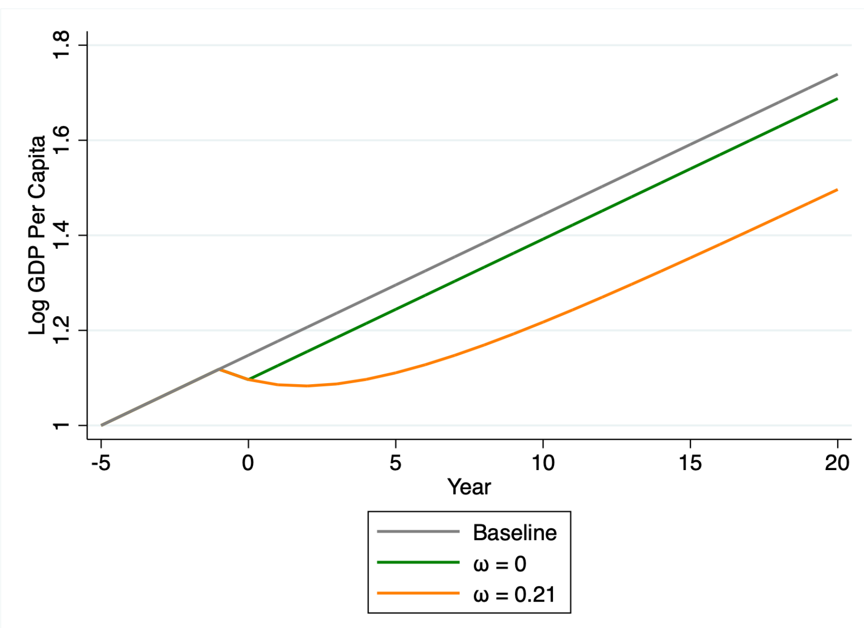
Notes: Table show how the effects of a 1°C temperature shock on contemporaneous GDP vary with country characteristics. The dependent variable in each regression is the coefficient $\beta_{GDP}^{h=0}$ estimated using Equation 6 for one country at a time. The independent variables in each regression include long-run average temperature in each country, and a variety of measures of levels of development and agricultural specialization.

Figure A-6: Model-Based Interpretation of Empirical Results
Global Economic Controls Specification

(a) Empirical vs. Simulated GDP Impulse Response Function



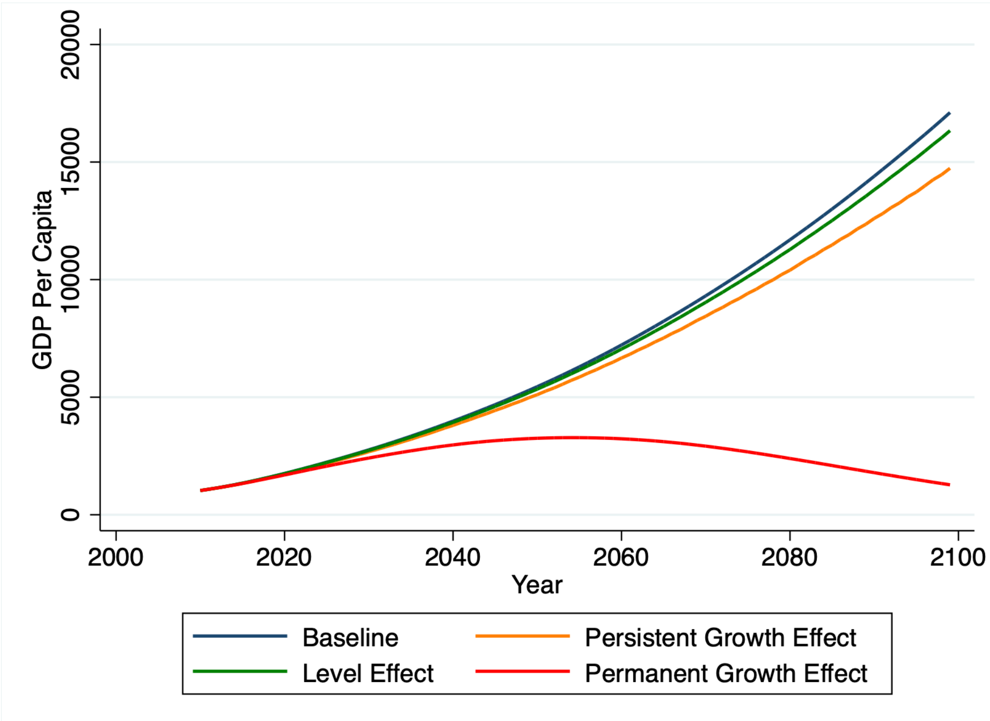
(b) Transition Dynamics with $\omega = 0.08$



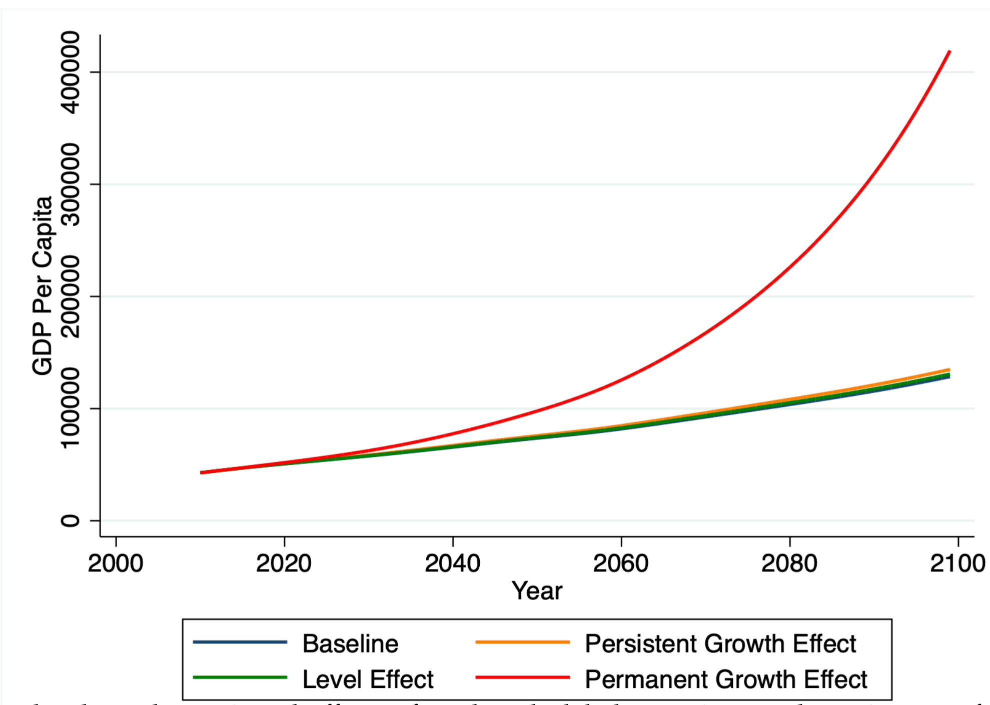
Notes: The red line in panel (a) shows the empirical impulse response function of the path of GDP following an unanticipated 1°C shock to temperature in year 0, estimated using Equation 6 with current and lagged U.S. TFP and lags of global GDP as controls instead of year fixed effects, with the 95% confidence interval shaded in pink. The black line shows a model simulation with $\omega = 0.21$ of the impulse response function following a shock with magnitude calibrated to match the contemporaneous effect in year 0, and persistence calibrated to match the impulse response function of temperature shown in Figure 5b. Panel (b) shows a model simulation of the medium-term growth trajectory following a permanent shock starting in year 0 with $\omega = 0.21$ in orange, and $\omega = 0$ for comparison in green.

Figure A-7: Projected Impacts of Unabated Global Warming in Example Countries - Global Economic Controls Specification

(a) India



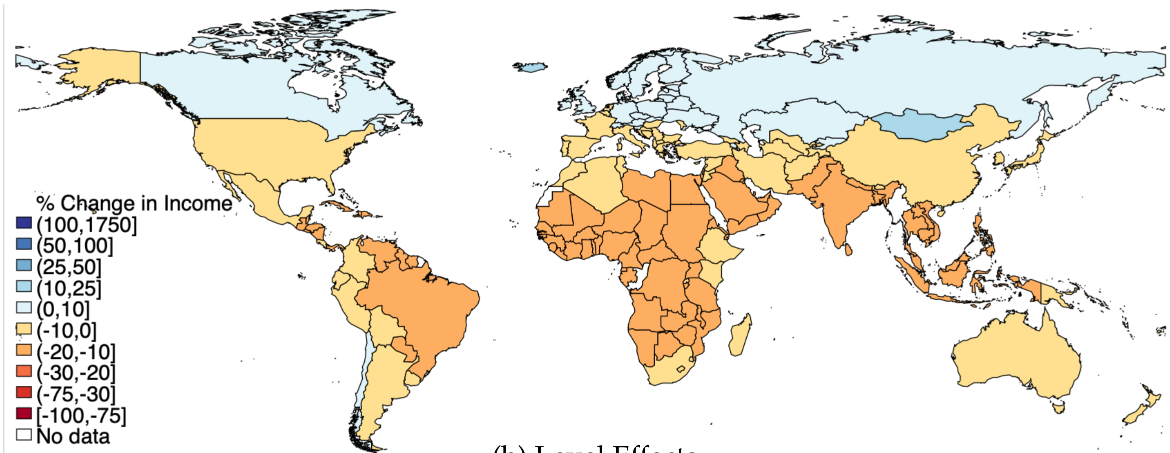
(b) Sweden



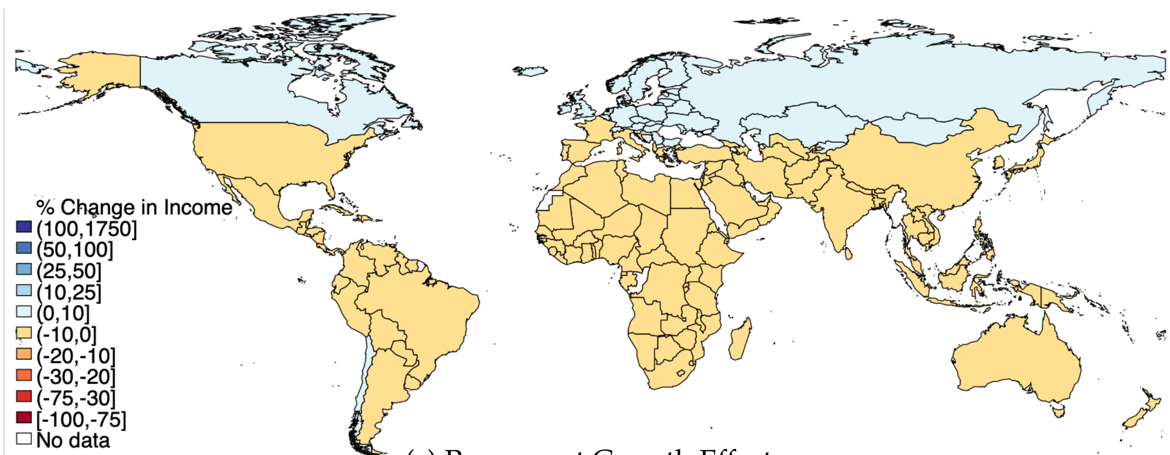
Notes: Graphs show the projected effects of unabated global warming on the trajectory of GDP under different projection methods for two example countries, India and Sweden. "Persistent growth effects" projections in orange use the 10-year cumulative response ratio shown in Figure 5c, from the specification with global economic control variables instead of year fixed effects, to calibrate the effect of each degree of projected warming. "Level effects" projections in green use only the estimated contemporaneous effect of a 1°C shock, and allow for no persistence or accumulating effects. "Permanent growth effects" projections in red use estimates from Burke, Hsiang and Miguel (2015), and allow for the effects of temperature to permanently alter country-level growth rates. Corresponding projections for the specification with year fixed effects are shown in Figure 8.

Figure A-8: Projected Impacts of Unabated Global Warming on Country-Level GDP

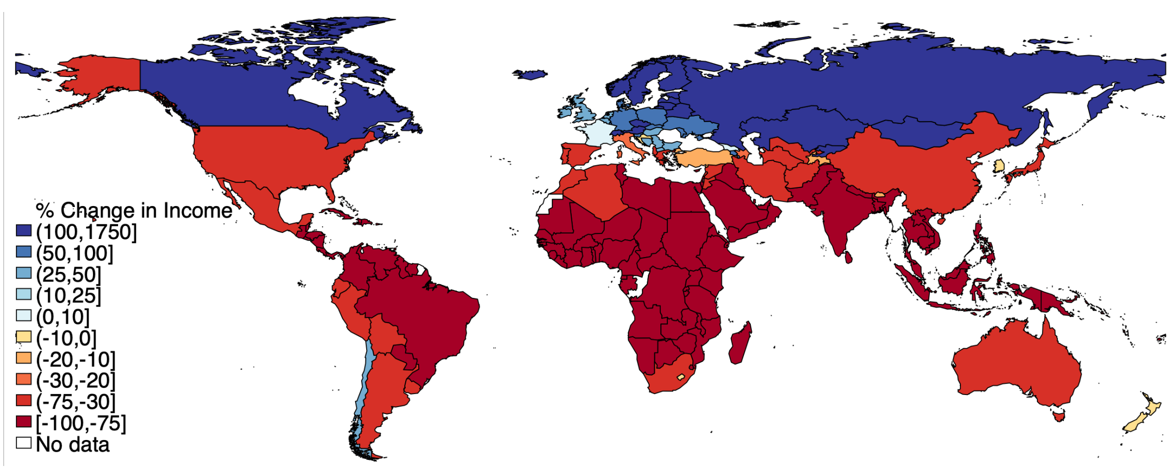
(a) Persistent Growth Effects - Global Economic Controls Specification



(b) Level Effects

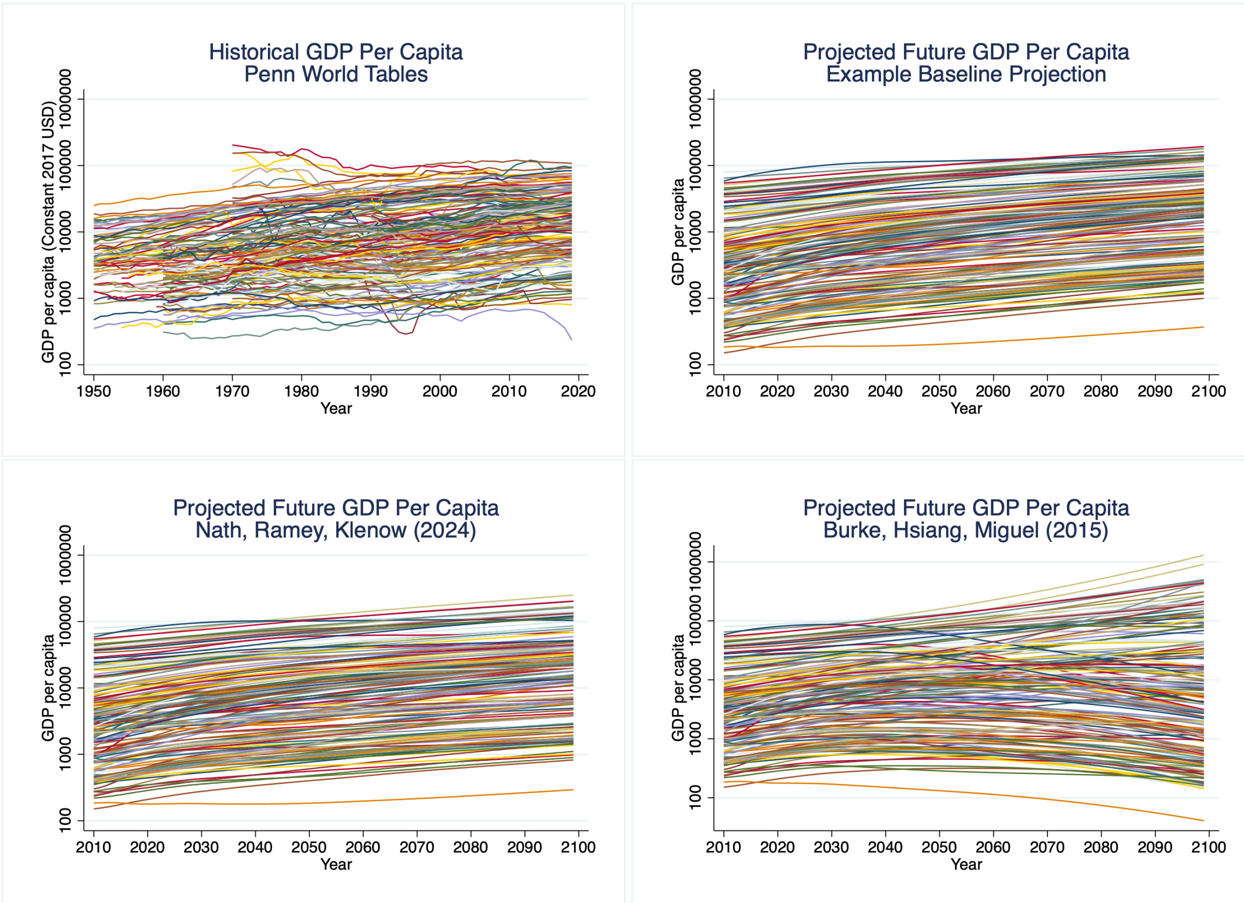


(c) Permanent Growth Effects



Notes: Maps show the projected effects of unabated global warming on end-of-century country level GDP under different projection methods. "Persistent growth effects" estimates in panel (a) use the 10-year cumulative response ratio shown in Figure 5c, from the specification with global economic control variables instead of year fixed effects, to calibrate the long-run level effect of each degree of projected warming. "Level effects" projections in panel (b) use only the estimated contemporaneous effect of a 1°C shock, and allow for no persistence or accumulating effects. "Permanent growth effects" use estimates from Burke, Hsiang and Miguel (2015), and allow for the effects of temperature to permanently alter country-level growth rates.

Figure A-9: Visualizing Income Level Differences and Growth Convergence



Notes: Top left panel shows historical GDP per capita across the world from 1950 to 2019, as measured by the Penn World Tables. Top right panel shows an example future projection of global incomes in the 21st century from Dellink et al. (2017). The projection is from Shared Socioeconomic Pathway (SSP) Four, which is labeled "Moderate Growth, Low Convergence." The bottom left panel shows a version of the SSP 4 projections that incorporate estimated climate damages from this paper, and the bottom right panel shows a version of the SSP 4 projections that incorporate estimated climate damages from Burke, Hsiang and Miguel (2015).

Table A-3: Estimated Effects of Historical Warming
From 1950s to 2010s

	Year FE	Global Economic Controls
Global GDP	-0.8	-0.4
Global Population Average	-2.9	-1.6
Middle East & North Africa	-5.4	-2.8
Sub-Saharan Africa	-5.3	-3.1
South & Central America	-4.7	-2.6
Asia	-3.2	-1.8
North America	-0.3	-0.1
Europe	2.1	0.9

Notes: Table show the estimated effects, in percent changes, of the global warming that has occurred between 1950 and 2019. Projections are made using the average country-level decadal temperature from 1950 to 1959 as the starting period and 2010 to 2019 as the ending period. Temperature data is from the Berkeley Earth Surface Temperature dataset. Projections use the 10-year cumulative response ratio shown in Figure 5c to calibrate the effect of each degree of observed warming. Column 1 shows results for the local projections specification with year fixed effects, and Column 2 shows results for the specification with a contemporaneous control for US TFP instead.

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Table A-4: Projected Effects of Global Warming
Moderate Emissions Scenario

Region	Persistent Growth Effects	Level Effects	Permanent Growth Effects
Panel A - Year Fixed Effect Specification			
Global Aggregates:			
Global GDP (no Q^* effect)	-5.6	-1.0	-22.5
Global Population Average	-8.6	-1.8	-46.6
Global Patent-Weighted Average Effect	-3.8	-0.4	-10.1
Global GDP (with Q^* effect, $\omega = 0.08$)	-5.9	-1.8	-22.5
Regional Summary:			
Sub-Saharan Africa	-11.3	-2.4	-67.4
Middle East & North Africa	-10.8	-2.1	-60.6
Asia	-9.5	-1.9	-55.1
South & Central America	-8.5	-1.6	-52.7
North America	-4.1	-0.5	-10.8
Europe	1.8	0.5	45.3
Panel B - Global Economic Controls Specification			
Global Aggregates:			
Global GDP (no Q^* effect)	-3.2	-0.9	-22.5
Global Population Average	-5.1	-1.5	-46.6
Global Patent-Weighted Average Effect	-1.7	-0.3	-10.1
Global GDP (with Q^* effect, $\omega = 0.21$)	-3.6	-1.0	-22.5
Regional Summary:			
Sub-Saharan Africa	-6.9	-2.1	-67.4
Middle East & North Africa	-6.2	-1.8	-60.6
Asia	-5.6	-1.7	-55.1
South & Central America	-4.9	-1.4	-52.7
North America	-2.0	-0.4	-10.8
Europe	0.8	0.4	45.3

Notes: Table show the projected effects, in percent changes, of 2°C global warming on end-of-century GDP under different projection methods. The 2°C approximately corresponds to Representative Concentration Pathway 4.5. Country level temperature projections come from Burke et al. (2015), and are proportionately scaled down from the 3.7°C global average temperature increase in RCP 8.5. "Persistent growth effects" projections use the 10-year cumulative response ratio shown in Figure 5c to calibrate the effect of each degree of projected warming. "Level effects" projections use only the estimated contemporaneous effect of a 1°C shock, and allow for no persistence or accumulating effects. "Permanent growth effects" projections use estimates from Burke, Hsiang and Miguel (2015), and allow for the effects of temperature to permanently alter country-level growth rates. Panel (a) shows results for the local projections specification with year fixed effects, and panel (b) shows results for the specification with a contemporaneous control for US TFP instead.

E Projection Method Sensitivity

E.1 Sims (1986) Method

Let P_{it} be the projected change in future temperatures in country i in year t, which we take from Burke, Hsiang and Miguel (2015) in the baseline specification. We construct a sequence of shocks, denoted $\tilde{T}_{it}$, which reproduces the projected temperature path, given the estimated persistent effects of each year's shock. This follows directly from the method of Sims (1986) as implemented by Metcalf and Stock (2023).

Specifically, using the estimated coefficients governing the persistence of temperature shocks at horizon h, α_0^h and α_1^h from Equation 5, we construct the sequence of shocks as follows:

$$\tilde{T}_{it} = P_{it} - \sum_{j=1}^{9} \tilde{T}_{i,t-j}(\hat{\alpha}_0^j + \hat{\alpha}_1^j T_{i,t-j}) \tag{12}$$

Intuitively, each year's shock is the residual necessary to match the projected temperature path in that year, once the cumulative persistent temperature effects from each previous year's shock have been accounted for. Note that the estimates allow the temperature persistence process to depend on the level of temperature itself, T_{it}, in order to capture the nonlinearities documented in Figure 5.

Given the sequence of shocks, $\tilde{T}_{it}$, that we infer in Equation 12, we can then use the estimates from the GDP local projections to calculate the GDP effects in each future year. Specifically, the implementation is as follows with the estimated coefficients governing the GDP effects of temperature shocks, β_0^h and β_1^h from Equation 6:

$$\log \text{GDP Climate Change}_{it} - \log \text{GDP Baseline}_{it} = \sum_{j=0}^{9} \tilde{T}_{i,t-j}(\hat{\beta}_0^j + \hat{\beta}_1^j T_{i,t-j}) \tag{13}$$

Intuitively, each future year has a contemporaneous shock, $\tilde{T}_{it}$, that affects GDP, and the projection also must account for the persistent effects of each previous year's shock, $\tilde{T}_{i,t-j}$. As with the cumulative response ratio, our implementation accounts for ten years of persistent effects (the contemporaneous effect of temperature, and nine lags).

E.2 Model Projection

This projection starts from assuming that temperature affects GDP per capita through the parameter governing the ability of a country to adopt technology, μ_{it}. We calculate the effects of climate change as a combination of the contemporaneous effect estimated in the local projections estimates in Equation 6 and the persistence implied by the ω parameter inferred to match the impulse response functions in Section 4.4. We use $\omega = 0.08$ for the specification with year fixed effects, and $\omega = 0.21$ for the specification with global economic controls.

Specifically, the projection proceeds as follows. We start with any given example baseline (no climate change) projected future path of productivity, Q_{it}. We then calculate the path of μ_{it} consistent with the baseline Q_{it} projections using Equation 8. Note that the effects are independent of the choice of baseline. To account for the effects of temperature on μ_{it}, we apply the estimated contemporaneous effects of temperature change from the no climate change baseline temperature, T_{i0}, to the projected future year's temperature, T_{it}. This calculation uses the coefficients β_0^h and β_1^h from Equation 6 with $h = 0$, accounting for the nonlinearity with respect to temperature in the same way as with the cumulative response ratio approach described in Section 5.1.

Given the path of μ_{it} implied by temperature change, we then calculate the path of Q_{it} using Equation 1, which we reproduce here for convenience:

$$Q_{it+1} = (\sigma - 1) \cdot \mu_{it+1} \cdot Q_{it}^{1-\omega} Q_t^{*\omega}$$

The implementation of the equation of motion above accounts for the persistent long-run effect of the temperature impacts on μ_{it}. We use the ω parameter implied by the simulation exercise in Section 4.4, as described above. The projected losses from climate change consist of the difference between the new path of Q_{it} and the assumed baseline. Note that these estimates are independent not only of the assumed baseline path of Q_{it}, but also of the assumed path of Q_t^*. Until this point, we have assumed no climate change effects on Q_t^*.

Table A-5: Projected Effects of Global Warming
Alternative Projection Methods

Region	Cumulative Response Ratio	Sims (1986) Method	Model Projection	Level Effects	Permanent Growth Effects
Panel A - Year Fixed Effect Specification					
Global Aggregates:					
Global GDP (no Q* effect)	-11.5	-14.3	-19.1	-2.2	-26.6
Global Population Average	-16.4	-18.4	-30.8	-3.6	-58.7
Global Patent-Weighted Average	-8.8	-12.1	-10.5	-1.1	-23.2
Global GDP (with Q* effect, $\omega = 0.08$)	-12.2	-15.3	-20.0	-2.3	-26.6
Regional Summary:					
Sub-Saharan Africa	-20.6	-21.6	-41.2	-4.8	-86.1
Middle East & North Africa	-20.1	-22.1	-37.2	-4.3	-82.5
Asia	-18	-19.9	-34.3	-4	-73.3
South & Central America	-16.1	-17.5	-30.3	-3.3	-74.6
North America	-9.6	-13	-12.2	-1.4	-20
Europe	.6	-4.5	6.9	.4	96.6
Panel B - Global Economic Controls Specification					
Global Aggregates:					
Global GDP (no Q* effect)	-6.8	-8.5	-8.2	-1.9	-26.6
Global Population Average	-10	-11.6	-13.3	-3.1	-58.7
Global Patent-Weighted Average	-4.3	-6.3	-4.2	-1	-23.2
Global GDP (with Q* effect, $\omega = 0.21$)	-7.7	-9.8	-9.1	-2.1	-26.6
Regional Summary:					
Sub-Saharan Africa	-13	-14.1	-17.8	-4.2	-86.1
Middle East & North Africa	-12.1	-13.9	-16	-3.7	-82.5
Asia	-11	-12.6	-14.7	-3.4	-73.3
South & Central America	-9.5	-10.7	-12.5	-2.8	-74.6
North America	-4.8	-7	-4.9	-1.2	-20
Europe	.2	-2.2	2	.4	96.6

Notes: To be written.