Projecting the impact of rising temperatures: The role of macroeconomic dynamics

Gregory Casey[a], Stephie Fried[b], and Ethan Goode[b]

[a]Williams College

[b]Federal Reserve Bank of San Francisco

August 2022

Abstract

We use theory and empirics to distinguish between the impact of temperature on transition (temporary) and steady state (permanent) growth in output per capita. Standard economic theory suggests that the long-run growth rate of output per capita is determined entirely by the growth rate of total factor productivity (TFP). We find evidence suggesting that the level of temperature affects the level of TFP, but not the growth rate of TFP. This implies that a change in temperature will have a temporary, but not a permanent, impact on growth in output per capita. To highlight the quantitative importance of distinguishing between permanent and temporary changes in economic growth, we use our empirical estimates and theoretical framework to project the impacts of future increases in temperature from climate change. We find losses that are substantial, but smaller than those in the existing empirical literature that assumes a change in temperature permanently affects economic growth.

Preliminary version of a paper prepared for the Conference on Transformational Recovery: Seizing Opportunities from the Crisis and the IMF Economic Review. Email: gpc2@williams.edu, stephie.fried@sf.frb.org, ethan.goode@sf.frb.org. We are grateful to Laura Bakkensen, Peter Pedroni, Dan Wilson, and Nick Wilson, as well as seminar participants at the Federal Reserve Board of Governors, Williams College, and participants in the IMF/BAM/IMFER conference on Transformational Recovery, for helpful comments. The views expressed in this paper are our own and do not reflect the views of the Federal Reserve System or its staff.

1 Introduction

Understanding the relationship between temperature and economic output is critical for designing climate change mitigation and adaptation policies. Our paper theoretically and empirically differentiates between two different approaches to modeling this relationship. The first approach assumes that a one time, permanent change in temperature affects the long-run level of output, but not the long-run growth rate of output. We call this a *level effect*. The second approach assumes that a one time change in temperature affects the long-run growth rate of output. We call this a *growth effect*.

Macroeconomic climate-economy models almost always assume that temperature has a level effect (e.g., Nordhaus and Boyer, 2003; Golosov et al., 2014; Barrage, 2020; Hassler et al., 2021). For example, the damage functions in these models imply that a 3°C increase in global average temperature will decrease economic output by approximately 2 percent (Nordhaus and Moffat, 2017).[1] In contrast, an empirical literature, beginning with Dell et al. (2012), argues that temperature has a growth effect. In an influential study, Burke et al. (2015) project the reduced-form estimates of the growth effect forward and find future climate damages that are an order of magnitude larger than suggested by the macroeconomic climate-economy models.[2]

The difference in outcomes between these two approaches has important policy implications. If temperature has a growth effect, rather than a level effect, then optimal carbon taxes are likely to be much higher (Moore and Diaz, 2015; Dietz and Stern, 2015). For example, a recent report by the Intergovernmental Panel on Climate Change (IPCC) uses evidence from Burke et al. (2015, 2018) on growth effects to suggest that policy should be aimed at keeping global average temperature change below 1.5°C, well below the 'optimal' level of approximately 3.5°C in the climate-economy models (Masson-Delmotte et al., 2018; Golosov et al., 2014). Understanding the impacts of climate change is also essential for designing government policies that

[1]The 2 percent decrease in output does not account for the endogenous response of capital accumulation to the change in productivity caused by the climate damage.

[2]This comparison understates the quantitative difference between the two approaches, because climate-economy models use global average temperature as a sufficient statistic for a wide range of climate impacts, while the econometric literature focuses only on changes in local ambient temperature and abstracts from other impacts like natural disasters and sea level rise. In this paper, we follow the econometric literature and focus only on changes in ambient temperature.

assist adaptation (Fankhauser, 2017).

In this paper, we revisit the level versus growth effects debate while paying special attention to the distinction between permanent and temporary changes in economic growth following a productivity shock. As in the existing empirical literature, we focus on temperature shocks and abstract from other climate impacts. Our analysis has four steps. First, we present a simple model that we use to study the different dynamic implications of growth and level effects. Second, drawing on intuition from the model, we empirically investigate the impact of temperature on TFP. Third, we combine our empirical results with the model to project the impacts of the temperature increases from climate change. Fourth, we compare our findings to the influential empirical literature that uses reduced-form estimates to project the impacts of rising temperatures from climate change.

The simple model integrates level and growth effects of temperature into an otherwise standard Solow (1956) model. We use the model to show that an increase in climate damage – say, from an increase in temperature – always reduces economic growth in the short run, regardless of its long-run impact. Economic growth always falls in the short run because capital gradually transitions to a lower balanced growth path in response to the shock (Fankhauser and Tol, 2005; Moore and Diaz, 2015; Letta and Tol, 2019). In the level-effects case, capital grows at its original rate once it reaches the new balanced growth path, and economic growth also returns to its original rate. In the growth-effects case, the increase in climate damage permanently slows the growth rate TFP, which in turn permanently slows the growth rate of capital and output. The fact that both level and growth effects imply that growth in output per capita will slow down for several periods makes it hard to distinguish between them in annual panel data on GDP and temperature. However, once capital dynamics die out, the growth rate of output per capita depends only on the growth rate of TFP. Thus, the short-run behavior of TFP is informative about the long-run relationship between temperature and GDP per capita.

Building on this insight, we empirically investigate whether temperature affects the level or growth rate of TFP in a country-year panel. Our analysis is similar to Dell et al. (2012) who use the methodology developed by Bond et al. (2010) to study growth and level effects of temperature. We build on their work in two ways. First, drawing on the insights from the simple model, we use TFP as our dependent variable, instead of GDP per capita. Second, we incorporate non-linear impacts of temperature following Burke et al. (2015). Overall, the evidence suggests that temperature affects the level of TFP, but not the growth rate of TFP. Thus, the historical data suggest that temperature has a level effect on GDP per capita, but not a growth effect.[3]

To understand the quantitative importance of distinguishing between level and growth effects, we use our estimates and model to project the impact of rising temperatures from climate change on GDP per capita around the world. We compare our projections to the results of similar analyses from the existing literature that assume only growth effects (Burke et al., 2015). To perform the analysis, we combine projections of future temperature under a commonly studied carbon-emissions scenario, Representative Concentration Pathway (RCP) 8.5 (Meinshausen et al., 2011), with our regression estimates to construct reduced-form projections for TFP in scenarios with and without climate change. To capture capital dynamics, we simulate our simple model under our projected climate-change and no-climate-change time paths of TFP. In our exercise, future changes in temperature reduce global GDP by 3.4 percent with a 95 percent confidence interval of (-6.71, -0.05), relative to a simulation without climate change.[4,5] In contrast, Burke et al. (2015) assume only growth effects and find that increases in temperature consistent with RCP 8.5 would decrease world GDP by approximately 20 percent.[6]

It is important to acknowledge the limited scope of analyses that use historical relationships between annual average temperature and economic growth to project the

[3]We do find evidence of growth effects in some specifications that use region-by-year fixed effects or allow country fixed effects to differ before and after 1990. However, even when the growth effects coefficients are statistically significant, the signs of the growth effects differ across these specifications and almost all of the estimated country-period interactions or region-by-year fixed effects are statistically insignificant.

[4]If we instead include both growth and level effects, our projections imply that future temperature changes increase global GDP per capita by 14.9 percent with a large confidence interval of (-56.4, 300.9).

[5]This aggregate number masks considerable heterogeneity. Given the non-linear impact of temperature on TFP growth, hotter countries are more negatively impacted by climate change. For example, GDP per capita falls by 8.5 percent in India, a relatively hot country, but only by 2.3 percent in the US, a comparatively colder country.

[6]To be more precise, they assume only growth effects in their main analyses, which are cited in policy reports. Importantly, the underlying papers also include specifications that allow for both growth and level effects in robustness analyses.

impacts of climate change. As in many of these studies, our projections do not include (i) non-market impacts of changes in annual temperatures, (ii) other climate impacts like sea level rise and natural disasters (e.g., Hsiang and Jina, 2014; Bakkensen and Barrage, 2018; Bernstein et al., 2019), (iii) the impacts daily or seasonal temperature fluctuations (e.g., Schlenker and Roberts, 2009; Colacito et al., 2019), or (iv) the distributional impacts of temperature within countries. Moreover, by following the existing literature and using our regression estimates to project forward, we assume that the reduced-form relationship between temperature and TFP is stable over time. Thus, we abstract from changes in adaptation technology, which weaken the link between temperature and TFP (Pindyck, 2013), global tipping points (e.g., Lemoine and Traeger, 2016; Cai and Lontzek, 2019; Dietz et al., 2021), and spatial interactions between countries (Costinot et al., 2016; Nath, 2022; Cruz Álvarez and Rossi-Hansberg, 2021). These limitations are important caveats to our work and also to the existing analyses that are widely used in the policy sphere. Our goal is to use macroeconomic theory to provide new insights on the estimates used in policy reports. As a result, we focus on how estimates of climate impacts differ between level and growth effects, rather than the scale of the projected impacts.

Related Literature. Our paper is related to several important strands of the existing literature. Our econometric methodology builds closely off of Bond et al. (2010), Dell et al. (2012), and Burke et al. (2015, 2018); Diffenbaugh and Burke (2019). There is also a wider literature looking at the impact of temperature on economic output (e.g., Deryugina and Hsiang, 2017; Colacito et al., 2019; Kiley, 2021).[7] Our paper is closely related to a subset of this literature focusing on growth versus level effects. Newell et al. (2021) conduct sensitivity analyses based on the regression specification from Burke et al. (2015) and show that the estimates of the growth effects are sensitive to the particular specification. They focus on GDP, rather than TFP. Bastien-Olvera et al. (2022) estimate level versus growth effects with low frequency temperature variation and find evidence for growth effects. A key focus of our paper is estimating the impacts of temperature in a manner that accounts for capital dynamics. Kahn et al. (2021) account for capital dynamics in a setting that assumes

[7]See Auffhammer (2018) for a review of the empirical literature on the broader impacts of climate change.

that deviations from average temperature have a level effect. Relatedly, Letta and Tol (2019) estimate the impact of temperature on TFP assuming only level effects, and Henseler and Schumacher (2019) estimate the impact of temperature on TFP assuming only growth effects.[8]

Second our projections of the impacts of future changes in temperature update the approach of Burke et al. (2015, 2018) to account for differences between permanent and temporary impacts of temperature on growth. Like our paper, other work has projected the impacts of future changes in temperature based on regression estimates. In particular, Newell et al. (2021) study how the sensitivity of the impact of temperature on GDP per capita contributes to uncertainty in climate impact projections. Letta and Tol (2019) project the impacts of temperature on TFP assuming only level effects. The 2017 World Economic Outlook report from the IMF projects the impact of temperature change on GDP per capita, assuming that temperature affects the level of TFP (Acevedo et al., 2017).

More generally, our approach is related to integrated assessment models that capture the impact of 'business as usual' climate scenarios. Traditionally, such models have assumed only level effects (e.g., Nordhaus and Boyer, 2003; Golosov et al., 2014). Some studies have included growth effects in these models, which considerably increases the impact of climate change (e.g., Moore and Diaz, 2015; Dietz and Stern, 2015). The spirit of our paper also mirrors Bakkensen and Barrage (2018), who demonstrate how theory can be used to inform analyses of the impacts of natural disasters. They focus on the difference between expectations and realizations of natural disasters and do not consider level versus growth effects.

The remainder of the paper proceeds as follows. In Section 2, we present and analyze the simple model and discuss its implications for our approach and the existing literature. In Section 3, we examine the relationship between average annual temperature and TFP in a country-year panel. In Section 4, we project the impacts of future increases in temperature from climate change. Section 5 concludes.

[8] In a presentation to the Federal Reserve Bank of San Francisco and the Climate Impact Lab, Klenow (2020) also stresses the importance of distinguishing between temporary and permanent growth effects of climate change.

2 Background and Motivation

We discuss a simple model to highlight the importance of macroeconomic dynamics for understanding the effects of temperature on the level and growth rate of output per capita.[9] We use the model to derive theoretically consistent equations that can separate these growth and level effects in historical data. Finally, we discuss the connections between our approach and the influential existing literature on the growth effects of temperature. Throughout the paper, we use the term climate change to refer to changes in temperature that result from global warming. Our analysis abstracts from all other aspects of climate change and climate damage, such as sea level rise, biodiveristy loss, and changes in the severity and frequency of natural disasters.

2.1 Simple Model

A one-time permanent change in temperature could have temporary or permanent effects on the growth rate of output per capita. We say that temperature has a *level effect* on output per capita when a one-time permanent change in temperature has a temporary effect on the growth rate of output. We say that temperature has a *growth effect* on output per capita when a one-time permanent change in temperature has a permanent effect on the growth rate of output.[10]

Definition 1. *Climate change has a* level effect *on variable X if a one-time, permanent change in the level of temperature affects the long-run level of X, but not the long-run growth rate of X.*

[9] Our simple model abstracts from the distinction between weather and climate. *Weather* refers to specific outcomes (e.g., temperature and precipitation) in a unit of space (e.g., country) over a specific time (year). *Climate* refers the distribution of potential weather outcomes. Since our simple model has a fixed saving rate and no forward looking behavior, climate has no impact on the economic dynamics conditional on weather.

[10] Since we are focused on long-run increases in temperature from climate change, we define growth and level effects in terms of permanent changes in temperature. However, we can also consider how a temporary change in temperature would affect the level and growth rate of GDP in both cases. A temporary change in temperature will have a temporary impact on the growth rate of output, regardless of whether there are level or growth effects. A temporary change in temperature will have a permanent effect on the level of GDP per capita if there are growth effects and no impact on the long-run level of GDP per capita if there are level effects. While we focus on the long-run trends, the short-run volatility of temperature could be important for designing stabilization policy (Kiley, 2021).

Definition 2. *Climate change has a* growth effect *on variable X if a one-time, permanent change in the level of temperature affects the long-run growth rate of X.*

To theoretically distinguish between these two possibilities, we consider an extension of the Solow (1956) growth model that incorporates the impacts of climate change. We focus on the Solow model because it is the simplest, most well-known model that maintains the distinction between transition and steady state economic growth.

Output, Y_{it}, in country i in period t is given by the Cobb-Douglas production function:

$$Y_{it} = A_{it} K_{it}^{\alpha} N_i^{1-\alpha}, \tag{1}$$

where K_{it} is capital, A_{it} is total factor productivity and N_i is population. Investment is a constant fraction $s_i \in (0, 1)$ of output. A constant fraction $\delta_i \in (0, 1)$ of capital depreciates every period. The law of motion for capital is

$$K_{it+1} = s_i Y_{it} + (1 - \delta_i) K_{it}. \tag{2}$$

We specify the following process for TFP that incorporates both level and growth effects from climate change:

$$A_{it} = D_l(T_{it}) \tilde{A}_{it} \quad \text{and} \quad \tilde{A}_{it+1} = (1 + g + D_g(T_{it+1})) \tilde{A}_{it}. \tag{3}$$

Variable T_{it} is average temperature in country i in year t. Climate change alters the temperature sequence, $\{T_{it}\}_{t=0}^{\infty}$, in each country. The variable $\tilde{A}$ is the component of TFP that carries over from period to period. Function $D_g : \mathbb{R}_+ \to (-\infty, \infty)$ describes the relationship between climate in period $t + 1$ and the growth rate of of TFP from period t to period $t + 1$. We refer to D_g as the growth-effect damage function. Function $D_l : \mathbb{R}_+ \to [0, 1]$ describes the relationship between climate in period t and the level of TFP in period t, conditional on $\tilde{A}_t$. We refer to D_l as the level-effect damage function.

To compare the implications of the level- and growth-effect damage functions, we use the simple model to analyze a one-time, permanent increase in temperature. For this discussion, we focus on the case where both damage functions have weakly negative first derivatives. We relax this assumption later in the paper. We study the two extreme cases: (1) climate change only affects the level of TFP, implying that $D_g = 0 \; \forall T$, and (2) climate change only affects the growth rate of TFP, implying that $D_l = 1 \; \forall T$.

The solid, dark blue line in Figure 1 sketches the dynamics following a one-time increase in temperature in period $t^\star$ for the level-effects-only case. For comparison, the dashed black line sketches the dynamics if there is no shock to temperature. Starting with the top left panel, TFP grows at constant rate before the shock. In period t^*, there is a permanent, one-time drop in the level of TFP from the increase in temperature. After the period of the shock, TFP grows at its original rate in all subsequent periods. The one-time fall in TFP triggers the usual transition dynamics in the Solow model. The lower level of productivity causes capital to transition to a new, lower balanced growth path (BGP). After it reaches the BGP, it continues to grow at its original rate. The path of output incorporates the changes in both TFP and capital. Output drops in period t^* due to the fall in TFP, and then continues to grow more slowly than the baseline case while capital transitions to the new BGP. Once capital reaches the new BGP, output growth returns to its original level. The bottom right panel summarizes these dynamics and shows that the increase in temperature leads to a temporary decrease in growth (i.e., over the transition), but not a permanent decrease in growth (i.e., steady state growth is unchanged). Thus, when climate change has a level effect on TFP, the model implies that climate change also has a level effect on output per capita.

The dotted light blue line in Figure 1 sketches the dynamics following a one-time increase in temperature in period $t^\star$ for the growth-effects-only case. Again beginning with the top panel, TFP grows at a constant rate before the change in temperature. Starting in period t^*, TFP grows at a new lower rate in all subsequent periods. As in the level-effects-only case, the fall in the growth rate of TFP leads to an immediate decrease in the growth rate of capital and output per capita. However, unlike in the level-effects-only case, the growth rates of output and capital per capita never return to their original levels. Instead, as highlighted in the bottom right panel, the economy transitions to a new steady state in which output per capita grows at a permanently lower rate. Thus, when climate change has a growth effect on TFP, the model implies that climate change also has a growth effect on output per capita.

In sum, the level- and growth-effect damage functions both imply that an increase in climate damage will decrease economic growth for several periods because of the gradual endogenous response of capital to a change in temperature. This similarity makes it difficult to distinguish between level and growth effects in annual panel data on GDP per capita and temperature. In contrast, the response of TFP to temperature differs between the level- and growth-effect cases. After the initial period, the change in temperature has no subsequent impact on the growth rate of TFP in the level-effects case, but the change in temperature permanently reduces the growth rate of TFP in the growth-effects case. These observations suggest that estimating the effects of temperature on TFP, instead of on GDP per capita, can circumvent the issues posed by endogenous capital dynamics and better distinguish between level and growth effects in panel data. Figure 1 shows that distinguishing between these cases is important because of their different implications for economic growth in the long run.

2.2 Empirical Strategy

We draw on the simple model to discuss empirical methods for distinguishing between level and growth effects of temperature on TFP. Our methods build closely on the work of Bond et al. (2010) and Dell et al. (2012). For expositional simplicity, we derive the estimating equation for an economy with full depreciation of capital ($\delta = 1$), and we assume that the level- and growth-effect damage functions have the following functional forms: $D_l(T_{it}) = e^{\beta T_{it}}$, and $D_g(T_{it}) = \gamma T_{it}$. We relax these assumptions later in the text.

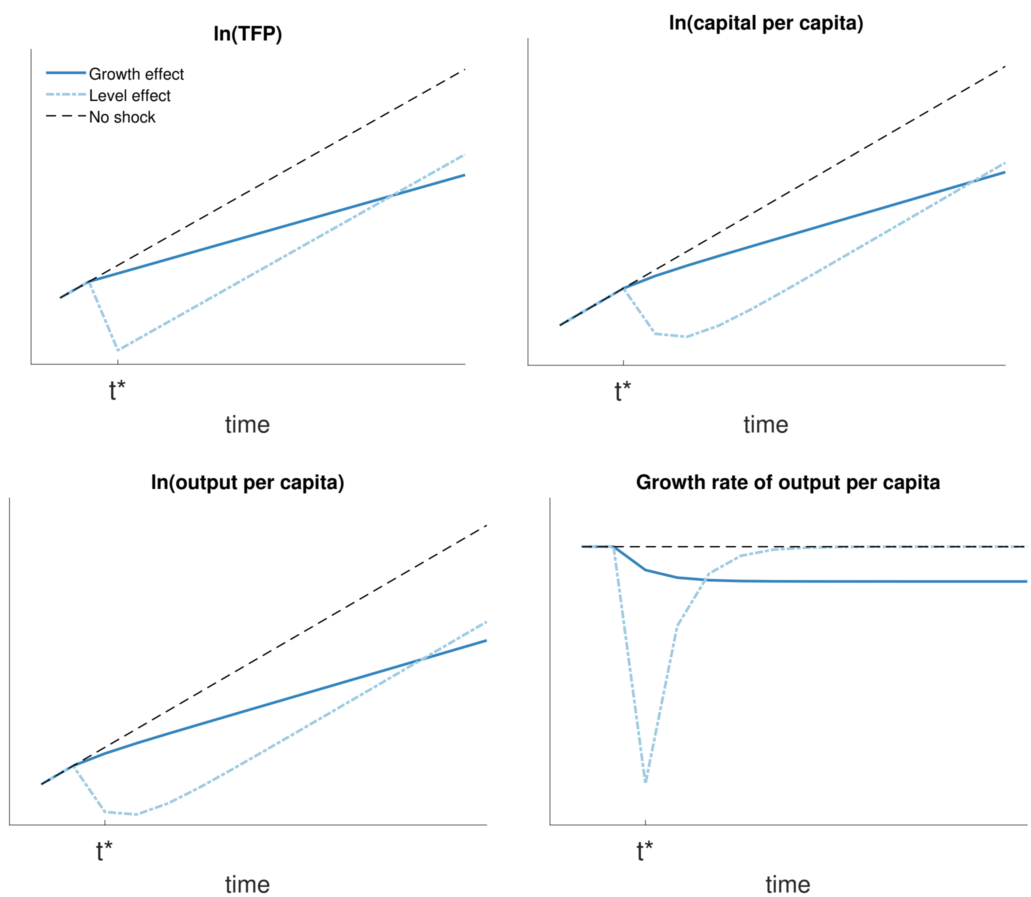
In this setting, $Y_{it} = e^{\beta T_{it}} \tilde{A}_{it} \left(s_i Y_{it-1}\right)^{\alpha} N_i^{1-\alpha}$. Taking logs yields

$$y_{it} = \alpha \ln(s_i) + \alpha s_i y_{it-1} + (1-\alpha)\beta T_{it} + \tilde{a}_{it} + (1-\alpha) n_i,$$

where $z_{it} = \ln Z_{it}$ for any variable Z. Noting that this expression holds for all periods and subtracting y_{it-1} from both sides yields

$$\Delta y_{it} = \alpha s_i \Delta y_{it-1} + (1-\alpha)\beta \Delta T_{it} + \Delta \tilde{a}_{it},$$

Figure 1: Impact of a One-Time Increase in Temperature



Note: This figure shows the consequences from a one-time increase in temperature in period $t\star$. It plots the evolution of TFP (top left panel), the log of capital per capita (top right panel), the log of output per capita (bottom left panel), and the growth rate of output per capita (bottom right panel) in the simple model when there is (1) no shock (dashed black line), (2) a one-time decrease in the level of TFP in period $t^{\star}$ (dashed-dotted light blue line), and (3) a one-time decrease in the growth rate of TFP in period $t^{\star}$ (solid dark blue line).

where $\Delta Z_{it} = Z_{it} - Z_{it-1}$ for any variable Z. In addition,

$$\Delta\tilde{a}_{it} = 1 + g + \gamma T_{it}.$$

Putting these together yields,

$$\Delta y_{it} = \alpha s \Delta y_{it-1} + \beta \Delta T_{it} + \gamma T_{it} + 1 + g_i. \tag{4}$$

Equation (4) suggests a straightforward way to use historical data to separately estimate β (the level effect) and γ (the growth effect): regress the growth rate of GDP per capita on its lagged value, the level of temperature, and the difference in temperature (or, equivalently, the level of temperature and its first lagged value). Importantly, adding the lagged dependent variable will only isolate the impacts of temperature on TFP for the special case of full depreciation of capital, $\delta = 1$. In a more realistic setting, with less than full depreciation, $\delta < 1$, it would be necessary to include the full sequence of past GDP in equation (4), making it impractical to estimate.

A more feasible approach is to estimate the historical impacts of temperature directly on TFP, instead of on GDP per capita. As discussed above, understanding the short-run behavior of TFP following a change in temperature allows us to distinguish between level and growth effects, and therefore understand the long-run impact of temperature on output per capita. Following the same steps as above, the analogous estimating equation for TFP is

$$\Delta a_{it} = \beta \Delta T_{it} + \gamma T_{it} + 1 + g_i. \tag{5}$$

The key intuition still applies when TFP is the dependent variable, but without the complications caused by capital. We will estimate an equation similar to equation (5) in our main analysis, but allow for non-linearites in the temperature-TFP relationship and a more general process for the dynamics of TFP.

2.3 Projected Impacts in the Existing Literature

The standard approach in macroeconomic climate models is to assume that temperature effects the level of TFP, but not the growth rate of TFP (e.g., Nordhaus, 1992; Golosov et al., 2014; Barrage, 2020; Hassler et al., 2021). Consequently, these models assume that changes in climate will affect the long-run level of GDP, but not the long-run growth rate of GDP. This assumption has been called into question by an empirical literature which shows that temperature affects the growth rate of GDP per capita over short periods of time (Dell et al., 2012; Burke et al., 2015, 2018). This empirical work is not as directly at odds with the modelling literature as it initially appears. As the analysis of the simple model highlights, the dynamics of capital imply that even a level effect of climate on TFP will generate short-run changes in economic growth, as found in the empirical literature.[11]

The empirical growth-effects literature often focuses on the results of the following regression:

$$\Delta y_{it} = \gamma_1 T_{it} + \gamma_2 T_{it}^2 + \text{controls} + \epsilon_{it}. \tag{6}$$

This regression estimates the contemporaneous relationship between temperature and growth in GDP per capita. The standard approach is to project the future impacts of climate change according to:

$$\Delta y_{it} = 1 + g_i^Y + \gamma_1 T_{it} + \gamma_2 T_{it}^2, \tag{7}$$

given a sequence $\{T_{it}\}_{t=0}^{t_{max}}$ of exogenous future values of temperature and a level of growth, g_i^Y, in the absence of climate change. This projection assumes that a one-time change in temperature will permanently affect the growth rate of income per capita. Focusing on long-term outcomes, this assumption implies that the historical relationship between temperature and growth arises solely from the growth-effects damage function, D_g. Yet, as the simple model demonstrates, temperature will affect the short-run growth rate of GDP per capita in equation (6) regardless of whether temperature affects output through the level-effects or the growth-effects damage

[11] There is also some evidence that the approach used in macroeconomic models is consistent with the implicit theoretical framework underlying the empirical analyses that focus on growth effects. For example, the dynamics of GDP in a world with only level effects (Figure 1) are quite similar to those labeled as a "permanent growth effect" in Burke et al. (2015) (see panel a of figure ED2).

function. Thus, the estimation results from equation (6) do not, in isolation, imply that projections of future climate damage should be based entirely on growth effects, as equation (7) assumes.

Importantly, the existing literature often does include specifications that distinguish between level and growth effects in robustness analyses and appendices (Burke et al., 2015, 2018). However, these results are generally not emphasized in the main text or in prominent policy outlets like the IPCC reports (Masson-Delmotte et al., 2018). Even so, these robustness analyses do not account for capital dynamics, one of the main contributions of our paper.

3 Analysis of Historical Data

3.1 Data

Our data are a country-year panel. We use data on annual average temperature (measured in degrees Celsius) and precipitation (measured in millimeters) in each country from 1960-2010 compiled by Burke et al. (2015). The underlying data are from Matsuura and Willmott (2018). We use data on capital (K_{it}), output (Y_{it}), and population (N_{it}) from the Penn World Tables 10.0 (Feenstra et al., 2015) to calculate TFP in each country over this same time period.[12] Drawing on the Cobb-Douglas production function from the simple model, we calculate TFP in country i in year t as:

$$TFP_{it} = \frac{Y_{it}}{K_{it}^{\alpha} N_{it}^{1-\alpha}},$$

where $\alpha = 0.33$ for all countries (Gollin, 2002). The resulting data set is an unbalanced panel with 155 countries and 6,654 country-year observations. Summary statistics are provided in Appendix Table A1.

[12]We use variables rgdpna, rrna, and pop to measure output, capital, and population, respectively.

3.2 Empirical Specification

We model the dynamics of TFP as

$$A_{it} = \exp\left(\beta_1 T_{i,t} + \beta_2 T_{i,t}^2 + \xi_1 P_{it} + \xi_2 P_{it}^2 + \eta_t + \epsilon_{it}\right) A_{it-1}^{\rho} \tilde{A}_{it} \tag{8}$$

$$\tilde{A}_{i,t+1} = (1 + g_i + \gamma_1 T_{i,t+1} + \gamma_2 T_{i,t+1}^2 + \kappa_t + \nu_{it})\tilde{A}_{i,t}, \tag{9}$$

where P_{it} is precipitation. The TFP process includes four generalizations relative equation (3) in the simple model. First, both damage functions have quadratic components: $D_g = \gamma_1 T_{it} + \gamma_2 T_{it}^2$ and $D_l = \exp\left(\beta_1 T_{it} + \beta_2 T_{it}^2\right)$. Burke et al. (2015) show that these non-linearities are important for capturing the different marginal effects of temperature change in hot and cold countries. Second, we allow for time-specific shocks that are common to all countries (η_t, κ_t), as well as country-by-time specific shocks $(\epsilon_{it}, \nu_{it})$. Third, as in much of the existing empirical research, we include precipitation as a control. Fourth, we include the term A_{it-1}^{ρ}, which accounts for the fact that shocks to the level of TFP – including those induced by temperature – might not die out immediately. In other words, it allows for a one-time, permanent change in temperature to affect the level of TFP for several periods without permanently affecting the growth rate of TFP.

To derive our estimating equation, we follow the process from Section 2.2. Once again, we use lower-case variables to denote the natural logs of variables. Taking logs and first differences of (8) yields

$$\Delta a_{it} = \beta_1 \Delta T_{i,t} + \beta_2 \Delta T_{i,t}^2 + \xi_1 \Delta P_{i,t} + \xi_2 \Delta P_{i,t}^2 + \rho \Delta a_{it-1} + \Delta \tilde{a}_{i,t} + \Delta \eta_t + \Delta \epsilon_{it}. \tag{10}$$

Taking logs and first differences of (9), evaluating at time t and applying the small value approximation $\ln(1+x) \approx x$ for growth rates yields

$$\Delta \tilde{a}_{it} = g_i + \gamma_1 T_{it} + \gamma_2 T_{it}^2 + \kappa_t + \nu_{it}. \tag{11}$$

Substituting (11) into (10) yields our main estimating equation:

$$\Delta a_{it} = \gamma_1 T_{i,t} + \gamma_2 T_{i,t}^2 + \beta_1 \Delta T_{i,t} + \beta_2 \Delta T_{i,t}^2 + \xi_1 \Delta P_{i,t} + \xi_2 \Delta P_{i,t}^2 + \rho \Delta a_{it-1} + g_i + b_t + u_{it}, \tag{12}$$

where g_i is a country fixed effect, $b_t = \kappa_t + \Delta\nu_t$ is a time fixed effect, and $u_{it} = \nu_{it} + \Delta\epsilon_{it}$ is the composite error term. Note that the our estimating equation still includes a lagged dependent variable, even though we estimate the results for TFP instead of GDP per capita. The lagged dependent variable stems from our generalization that allows shocks to TFP to be persistent.

We estimate equation (12) via ordinary least squares (OLS). The results allow us to separately determine the effect of temperature on the level of TFP and on the growth rate of TFP. Rejecting the null that $\gamma_1 = \gamma_2 = 0$ would imply that temperature affects the growth rate of TFP, while rejecting the null that $\beta_1 = \beta_2 = 0$ would imply that temperature affects the level of TFP. Additionally, we estimate variants of equation (12) in which we impose that there are only level effects ($\gamma_1 = \gamma_2 = 0$) or that there are only growth effects ($\beta_1 = \beta_2 = 0$). We consider several robustness analyses that address concerns surrounding the inclusion of the lagged dependent variable, the treatment of long-run trends in TFP growth, the number of temperature lags, and heterogeneous effects across countries.

The identifying variation in regression equation (12) comes from two sources. The first source is country-specific deviations of temperature from its mean growth rate, including short-run shocks to temperature as well as country-specific trends in the growth rate of temperature. The second source is cross-sectional variation. As Auffhammer (2018) explains, the quadratic terms are partially identified from variation in the marginal effects of temperature across locations with different mean temperatures. Importantly, since the regression includes time fixed effects, global trends in temperature are not a source of identifying variation. Similarly, since the regression includes country fixed effects, mean changes in temperature within a country are also not a source of identifying variation.

3.3 Results

We discuss the results from our main specification and several robustness analyses.

3.3.1 Main Specification

Table 1 presents our analysis of historical data. Column 1 assumes that there are only growth effects ($\beta_1 = \beta_2 = 0$) as in the regressions used to inform policy. We find the inverted-U relationship emphasized by Burke et al. (2015) with a positive linear term and a negative squared term. The optimal temperature is slightly above 11°C, which is slightly lower than findings in the existing literature. The test for joint significance of the temperature coefficients is borderline significant at conventional levels ($p = 0.09$). The coefficient on the lagged dependent variable is highly statistically significant, implying that $\rho \neq 0$ and thus that it is important to allow for the possibility that shocks to TFP could persist for multiple periods. When ignoring level effects, the data can support the assumption that the level of temperature affects the growth rate of TFP.

In column 2, we estimate the specification that instead assumes that there are only level effects ($\gamma_1 = \gamma_2 = 0$). We once again find evidence for the inverted-U relationship. The optimal temperature is slightly higher in this specification equal to approximately 13°C. The joint significance test strongly rejects the null that there is no effect of temperature on TFP ($p < 0.01$), and the coefficient on the lagged dependent variable is virtually unchanged from the first column. Thus, when ignoring growth effects, we find that the data can support the assumption that the level of temperature affects the level of TFP.

In column 3, we estimate equation (12), allowing for both growth and level effects. The level effect coefficients (βs) are hardly affected by the inclusion of the growth-effect terms and the joint significance test strongly rejects the null of no level effects ($p < 0.01$). In contrast, the growth effect coefficients (γs), change considerably when we allow for the possibility of level effects. The linear term (γ_1) decreases by one-third and the quadratic term (γ_2) decreases by an order of magnitude. The joint significance test fails to reject the null that there are no growth effects ($p = 0.50$).

Overall, we interpret these results as providing evidence that there is a level effect of temperature on TFP, but not a growth effect of temperature on TFP. A key implication of the non-linear relationship between temperature and TFP is that the impact of future changes in temperature will differ across countries. To show these differential effects, Figure 2 plots the relationship between temperature and TFP estimated from panel data with the specification from column 2. The vertical lines in Figure 2 indicate the 2010 temperatures for a select group of countries, a measure of their vulnerability to future changes in temperature. The relatively wealthy coun-

Table 1: Main Results

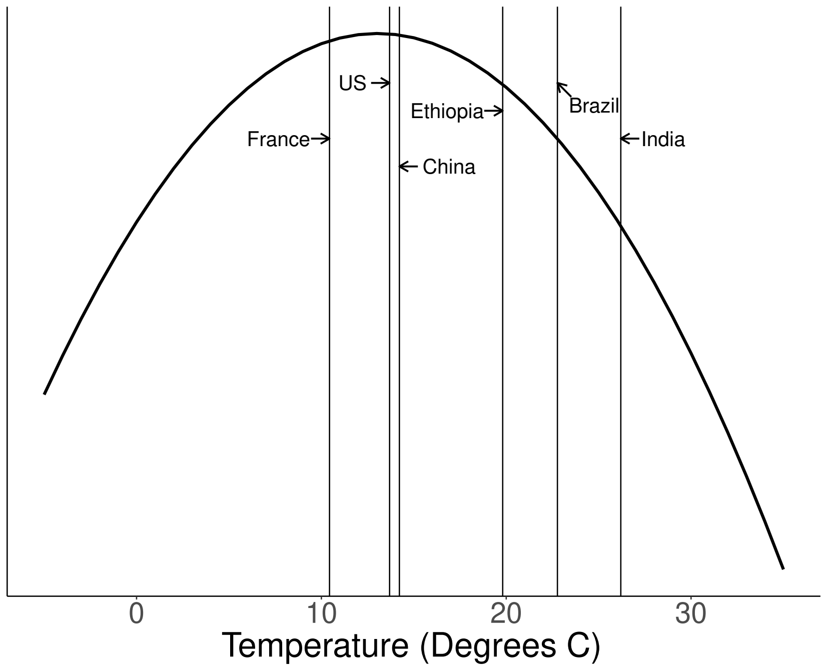
Dep. Var.: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp. : \gamma_1$	0.0036*		0.0015
	(0.0017)		(0.0018)
$Temp.^2 : \gamma_2$	-0.0002		-0.0000
	(0.0001)		(0.0001)
$\Delta Temp. : \beta_1$		0.0104***	0.0095**
		(0.0032)	(0.0033)
$\Delta Temp.^2 : \beta_2$		-0.0004***	-0.0004***
		(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	0.0082	0.0052	0.0051
	(0.0080)	(0.0080)	(0.0080)
$\Delta Precip.^2 : \xi_2$	-0.0008	-0.0004	-0.0004
	(0.0019)	(0.0019)	(0.0019)
$\Delta LnTFP_{t-1} : \rho$	0.1882***	0.1904***	0.1898***
	(0.0386)	(0.0386)	(0.0385)
N	6,654	6,654	6,654
Adj. R-squared	0.12	0.12	0.12
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.0919		0.5018
$\beta_1 = \beta_2 = 0$ (p-value)		0.0003	0.0015
Optimal Temperature	11.06	13.09	

Note: All specifications include country- and year-fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects, and column 3 is the specification with both growth and level effects. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

tries tend to be near the optimum, implying that the marginal impact of changes in temperature will be close to zero. Meanwhile, countries in poorer parts of the world, including South Asia, South America and Africa, tend to be to the right of the optimum, implying that the marginal impact of changes in temperature will be negative.

Of course, there is considerable uncertainty in the regressions, and it is impor-

Figure 2: Non-Linear Impacts of Temperature Change



Note: The figure plots the non-linear relationship between temperature anf output: $\hat{\beta}_1 T + \hat{\beta}_2 T^2$ where $\hat{\beta}_1$ and $\hat{\beta}_2$ are the coefficient estimates from column 2 in Table 1. The vertical lines denote the average annual temperature for selected countries in 2010, indicating their vulnerability to future changes in temperature.

tant not to conflate the statistical insignificance of growth effects with zero impact of temperature on long-run economic growth. The estimated growth effects could be insignificant, for example, because of imprecise measurement of TFP. To aid in the interpretation of the results, Appendix Figure C1 takes the results from column 3 and plots the marginal level effects ($\partial a_{it}/\partial T_{it} = \beta_1 + 2\beta_2 T_{it}$) and marginal growth effects ($\partial \Delta a_{it}/\partial T_{it} = \gamma_1 + 2\gamma_2 T_{it}$) for different temperatures. Strikingly, the marginal growth effects are positive until 26.7°C. Thus, for most countries in the world, the (statistically insignificant) growth effects would imply a positive impact of temperature on GDP growth.

3.3.2 Robustness of the Main Results

The inclusion of lagged dependent variables can cause problems in panel regressions with fixed effects (e.g., Nickell, 1981; Pesaran and Smith, 1995). We take two approaches to address this issue. First, Appendix Table B1 re-estimates the specifications from Table 1 after dropping the lagged dependent variable. The qualitative pattern of the results is unchanged. Quantitatively, removing the lagged dependent variable increases the magnitude of the growth effect coefficients and decreases the magnitude of the level effect coefficients. This pattern is consistent with the original motivation for including the lagged dependent variable in the main specification. The lagged dependent variable allows the effect of temperature on the level of TFP to last for several periods. Without the lagged dependent variable, any persistent impact of lagged temperature will show up as a permanent growth effect.

For our second approach to addressing potential concerns from the lagged dependent variable, we re-estimate the specifications from Table 1 using innovations in TFP growth as the dependent variable. We measure TFP innovations as the residuals from a regression of the difference in log TFP on its first lagged value. The results reported in Appendix Table B2 show that this alternative specification has no impact on the qualitative takeaways. Quantitatively, using TFP innovations increases the magnitude of the level effect coefficients and shrinks the magnitude of the growth effect coefficients. Together, the robustness results from Appendix Tables B1 and B2 suggest that our main results in Table 1 are not driven by biases introduced by the lagged dependent variable.

We next examine alternative ways to account for long-run trends in TFP growth rates. Focusing on GDP per capita growth, Burke et al. (2015, 2018) include country-specific quadratic time trends in their regression specification. Newell et al. (2021) highlight that these trends are important for whether the regressions suggest the existence of growth effects. Intuitively, such trends capture the convergence of income per capita to its steady state level. This convergence process results from capital accumulation and is therefore unlikely to be important for TFP dynamics. Nevertheless, it is still important to understand the sensitivity of our results to different ways of accounting for long-run trends.[13]

[13] Allowing for country-specific trends implies that the impacts of temperature on TFP are no

Appendix Table B3 adds country-specific linear trends to the main specification. Again, the qualitative patterns are unchanged. As shown in Appendix Figure C4, none of the country-specific trends are significant in columns 2 or 3, motivating our decision to exclude them from the main specification. Table B3 includes country-specific quadratic trends. In this specification, both the level and growth effects of temperature are statistically insignificant, but only 6 percent of the trend coefficients are significant in any specification (see Appendix Figure C4). Appendix Table B5 follows Dell et al. (2012) and adds region-by-year fixed effects to the main specification, another way of capturing long-run trends. Burke et al. (2015) argue against using such fixed effects, because most of the relevant year-to-year variation in temperature comes from shocks that affect multiple countries in a region. Interestingly, this specification supports the existence of both level and growth effects in column 3. However, marginal growth effects are positive for $T < 27.2$°C, an even more extreme version of the findings from column 3 in the main regression. Approximately 30 percent of the region-by-year fixed effects are statistically significant (see Appendix Figure C5). Finally, Appendix Table B6 follows Kiley (2021) and interacts country fixed effects with a post-1990 dummy. Here, there are strong growth effects even in column 3, suggesting that increases in temperature reduce the growth rate of TFP whenever $T > 9.4$°C. Importantly, none of the interaction terms are statistically significant (see Appendix Figure C5). It is important to stress, however, that it is possible to find support for the existence of growth effects depending on how long-run trends are modeled.

Our baseline specification includes the contemporary level of temperature and the first difference, which is equivalent to using the contemporary level of temperature and its first lag. Dell et al. (2012) show that, when multiple lags are included in the regression, testing for the significance of the sum of all the temperature coefficients is equivalent to testing for growth effects. In a world with only level effects, all of the coefficients should add to zero. In Appendix Table B7, we re-estimate column 3 from Table 1 with up to five lags of temperature. In all cases, we fail to reject the null hypothesis that the sum of the coefficients is equal to zero, implying that we find

longer identified from country-specific trends in the growth rate of temperature (e.g. as a result of climate change).

evidence for level effects but not growth effects.[14]

The existing literature has emphasized that the effects of climate change could differ by level of development (e.g., Dell et al., 2012; Letta and Tol, 2019). In Appendix Table B8, we re-estimate the specifications from Table 1 when interacting all of the temperature variables with dummies that capture whether a country has above-median GDP/capita in 2010 (‘$Rich_i$’) or below-median GDP/capita in 2010 (‘$Poor_i$’). We find that the data continue to support the existence of level effects after allowing for heterogeneity in the temperature coefficients. In particular, column 3 rejects the null hypothesis of no level effects for both rich and poor countries, but fails to reject the null of no growth effects for either group. For all coefficients, we cannot reject the null hypothesis of no difference between rich and poor countries.[15] Appendix Table B9 presents a closely related analyses that splits the sample into ‘agricultural’ and ‘non-agricultural’ economies, where an economy is labeled as ‘agricultural’ if the ratio of value added in agriculture to GDP is above the sample median in 2010. Once again, we find no evidence of heterogeneity, and the results continue to suggest that the level of temperature affects the level of TFP and not the growth rate of TFP.

3.3.3 Estimated Effects of Temperature on GDP, Capital, and Labor

We use TFP as the dependent variable in our main regressions to help distinguish between growth effects and level effects. In this section, we briefly examine the impact of temperature on GDP per capita, capital per capita, and employment. We focus on whether the results of these analyses are consistent with the assumptions of our theoretical framework and the finding of only level effects in Table 1.

Table 2 re-estimates specifications from Tables 1 and B1 with GDP per capita, instead of TFP, as the dependent variable. Following these earlier tables, columns 1–4 report estimates with only level effects or only growth effects. As before, we find evidence for either effect when they are considered separately.

[14] We performed this test separately for the linear and quadratic terms. We also performed a test with ten lags and arrived at the same result. We excluded this specification from the table due to space constraints.

[15] In Appendix Table B11, we interact temperature with lagged temperature to determine whether the impact of temperature in a given year depends on recent temperature shocks. We do not find evidence for this interaction.

Columns 5 and 6 present the key results. As discussed in Section 2.2, it is possible to test for level and growth effects with GDP per capita as the dependent variable, at least for the special case of full depreciation of capital. To do this, we must include the level of temperature, the change in temperature, and the lagged value of GDP per capita as explanatory variables in the same regression. Without accounting for capital accumulation, we would expect the γ coefficients to be statistically significant, even when there are only level effects. This is because a one-time, permanent change in temperature affects the growth rate of output for several periods, even though it only affects the growth rate of TFP for a single period (see Figure 1).

The results from columns 5 and 6 align with this intuition. Column 5 allows for both growth and level effects and does not include a lagged dependent variable. The joint significance test rejects the null hypothesis of no level effects ($p < 0.05$) and only barely fails to reject the null of no growth effects at standard levels ($p = 0.11$). Column 6 allows for both growth and level effects while controlling for capital dynamics with the lagged dependent variable. As expected, accounting for capital dynamics increases the magnitude of the level effect coefficients and shrinks the magnitude of the growth effect coefficients. Moreover, the joint significance test still rejects the null hypothesis of no level effects (p <0.01), but fails to reject the null of no growth effects (p=0.30).

Taken together, the results from Tables 1 and 2 and the intuition from the simple model in Figure 1 suggest that the impact of temperature on short-run economic growth identified in the existing literature – and, correspondingly, column 5 of Table 2 – were actually picking up capital dynamics induced by level effects, which only affect growth in output per person temporarily. Appendix Table B12 directly examines the impact of temperature on capital per capita. Consistent with the predictions of the simple model, we find evidence that the level of temperature does not affect the contemporaneous level of capital, but it does affect the growth rate of capital.[16]

[16] To be consistent with the existing literature and columns 1 and 5 of Table 2, we do not include the lagged dependent variable in the specification with capital as the dependent variable. If we do include the lagged dependent variable in this specification, then both the level and growth effect coefficients are insignificant. Also, it is important to note that these regressions do not control for how close capital is to its balanced growth level and should therefore be interpreted with caution. Still, it is reassuring that the results are consistent with theory and with Tables 1 and 2.

Table 2: GDP per capita Results

	(1)	(2)	(3)	(4)	(5)	(6)
Dep. Var.: $\Delta LnGDPPC$	Growth	Growth	Level	Level	Both	Both
$Temp.:\gamma_1$	0.0049**	0.0044**			0.0032	0.0022
	(0.0017)	(0.0017)			(0.0019)	(0.0018)
$Temp.^2:\gamma_2$	-0.0002*	-0.0002*			-0.0001	-0.0001
	(0.0001)	(0.0001)			(0.0001)	(0.0001)
$\Delta Temp.:\beta_1$			0.0103**	0.0112***	0.0084*	0.0099**
			(0.0033)	(0.0032)	(0.0034)	(0.0033)
$\Delta Temp.^2:\beta_2$			-0.0004***	-0.0004***	-0.0003**	-0.0004***
			(0.0001)	(0.0001)	(0.0001)	(0.0001)
$\Delta Precip.:\xi_1$	0.0063	0.0078	0.0042	0.0048	0.0041	0.0047
	(0.0084)	(0.0082)	(0.0081)	(0.0082)	(0.0081)	(0.0081)
$\Delta Precip.^2:\xi_2$	-0.0004	-0.0008	-0.0001	-0.0004	-0.0001	-0.0003
	(0.0021)	(0.0020)	(0.0019)	(0.0020)	(0.0019)	(0.0020)
$\Delta LnGDPPC_{t-1}:\rho$		0.2118***		0.2144***		0.2134***
		(0.0436)		(0.0381)		(0.0381)
N	6,654	6,654	6,654	6,654	6,654	6,654
Adj. R-squared	0.14	0.18	0.14	0.18	0.14	0.18
$\gamma_1=\gamma_2=0$ (p-value)	0.0104	0.0303			0.1072	0.2972
$\beta_1=\beta_2=0$ (p-value)			0.0023	0.0002	0.0182	0.0015
Optimal Temperature	14.22	11.65	14.49	13.39		

Note: All specifications include country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Columns 1-2 are the specifications with only growth effects, column 3-4 are the specifications with only level effects and columns 5-6 are the specifications with both growth and level effects. $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.10$.

3.3.4 Summary of Historical Evidence

The above evidence generally supports the existence of level effects, but not growth effects. This can be seen most directly in Table 1, where we use the method of Bond et al. (2010) and find evidence that the level of temperature affects the level of TFP and not the growth rate of TFP. This result is robust to considering alternate lag lengths (Appendix Table B7) and allowing for heterogeneity across countries (Appendix Tables B8 and B9). We also find support for this result using GDP as the dependent variable (Table 2). Taken as a whole, our findings suggest that previous studies may have identified growth effects because of capital accumulation or persistent TFP shocks, both of which cause changes in temperature to temporarily affect the growth of GDP per capita.

It is important to acknowledge, however, that there is uncertainty surrounding the finding of only level effects, even within the subset of possible specifications that we investigate.[17] While all specifications support the existence of level effects, the specifications with region-by-year fixed effects and with post-1990 dummies also support the existence of growth effects, but with opposite implications. Increases in temperature increase GDP growth for most countries in the specification with region-by-year fixed effects and decrease GDP growth for most countries in the specification with post-1990 dummies. Moreover, more than half of the region-by-year fixed effects and all of the post-1990 dummies are statistically insignificant. Given the sensitivity of the growth effect results, we focus on level effects in the subsequent analysis.

4 Projections of Future Climate Damages

To show the quantitative importance of distinguishing between growth and level effects, we project the impact of future changes in temperature from climate change on GDP per capita around the world. Our projected impacts rely on reduced-form projections for TFP and only capture a subset of the impacts of climate change. In light of these concerns, we focus on comparing our results to the results in the existing literature, which is subject to the same caveats. The results should be interpreted

[17] Newell et al. (2021) undertake a large-scale sensitivity analysis focusing on GDP per capita regressions without lagged dependent variables.

with these caveats in mind.

4.1 Data

We use country-specific projections of the change in temperature in each year from 2010 to 2100 consistent with the RCP 8.5 emissions scenario.[18] RCP 8.5 was originally developed to project global emissions in the absence of wide-spread climate policy. Figure 3 shows the temperature in each country around the world in 2010, the starting point of our projection period. Countries in white, like the United States, have temperature near the optimum of 11°C identified in Figure 2, implying that small changes in temperature will have approximately no impact on TFP. Countries in red are hotter than the optimum, implying that small increases in temperature decrease the level of TFP, and countries in blue are colder than the optimum, implying that small increases in temperature increase the level of TFP. Unsurprisingly, the map demonstrates that poorer countries tend to be more vulnerable to increases in temperature. Figure 4 shows the change in temperature in each country between the two end points of our analysis, 2010 and 2100.

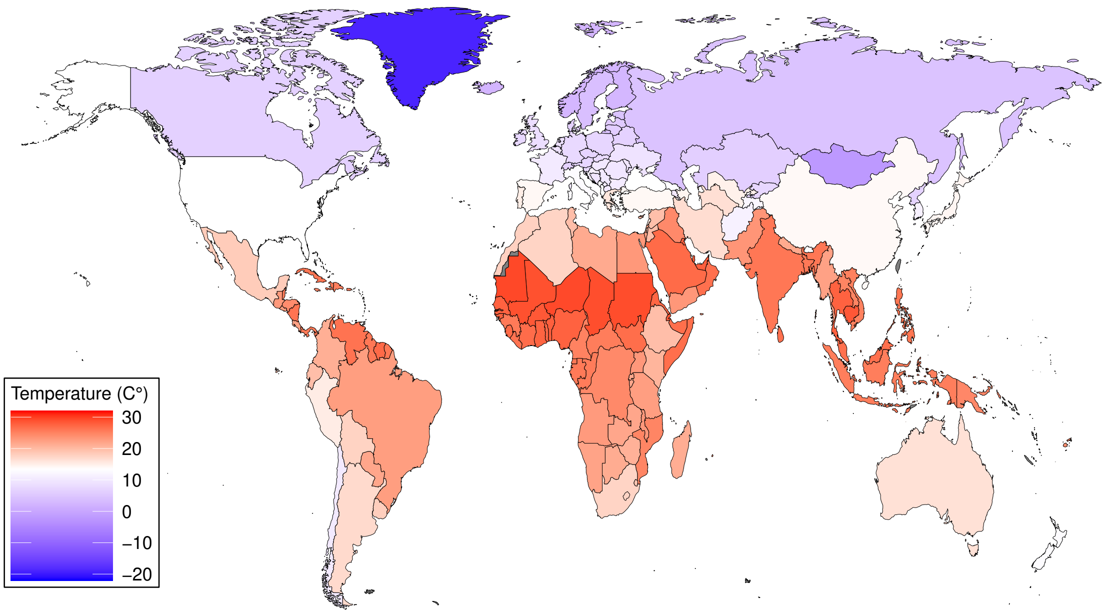
We calibrate the parameters of the simple model directly from the available data. We set the savings rate, s_i, and the depreciation rate, δ_i, equal to their average values from the Penn World Tables (Feenstra et al., 2015) in each country. We set $\alpha = 0.33$ in all countries, consistent with the cross-country evidence on the capital share of income (Gollin, 2002). Additionally, we assume that the population in each country grows at a constant country-specific rate, equal to the average population growth rate from the Penn World Tables (Feenstra et al., 2015).

4.2 Method

We use the estimates from the level-effects-only specification in column 2 of Table 1 to project the impacts of future changes in temperature on TFP. We iterate the

[18] The projections are from the World Meteorological Organization and can be downloaded from https://climexp.knmi.nl/start.cgi. To calculate the projected temperature for each country-year, we add the projected change in temperature from 2010 to the observed value of the 2010 temperature. Note that for a small set of countries, we only have the projected change in temperature from 2010 to 2100 rather than yearly projections. For these countries, we linearly interpolate the temperature change in each year based on the projected temperature change from 2010 to 2100.

Figure 3: Average Annual Temperature in 2010



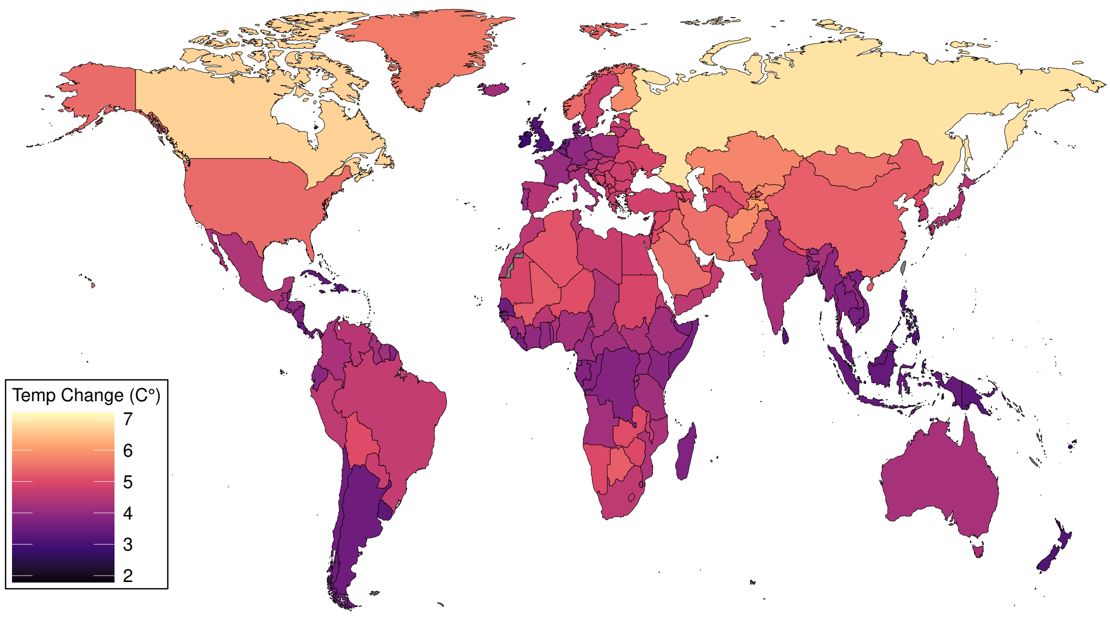
Note: The map shows the annual average temperature in each country in 2010. The lightest color corresponds to the optimal temperature from column 2 of Table 1.

following equation forward,

$$\Delta a_{it} = \hat{\beta}_1 \Delta T_{it} + \hat{\beta}_2 \Delta T_{it}^2 + \hat{\xi}_1 \overline{\Delta P}_i + \hat{\xi}_2 \overline{\Delta P}_i^2 + \hat{\rho} \Delta a_{it-1} + \hat{g}_i + \hat{\bar{u}}, \tag{13}$$

where 'hat' denotes the point estimates from column 2 of Table 1. There is no trend in the estimated time fixed effects (see Appendix Figure C2), and we set the time fixed effect in the projection equal the average of the estimated time fixed effects, $\hat{\bar{u}}$. We set the change in precipitation in each country equal to its historical mean, denoted by the bars in equation (13). To project the impacts of climate change on GDP per capita in each country, we compare a climate-change and a no-climate-change simulation of the simple model augmented with the richer TFP specifications from equations (8) and (9). In the climate-change simulation, we feed in the projected time path of TFP from equation (13), using the temperature projections consistent with RCP 8.5. In the no-climate change simulation, we feed in the projected time path of

Figure 4: Change in Temperature under RCP 8.5 between 2010-2100



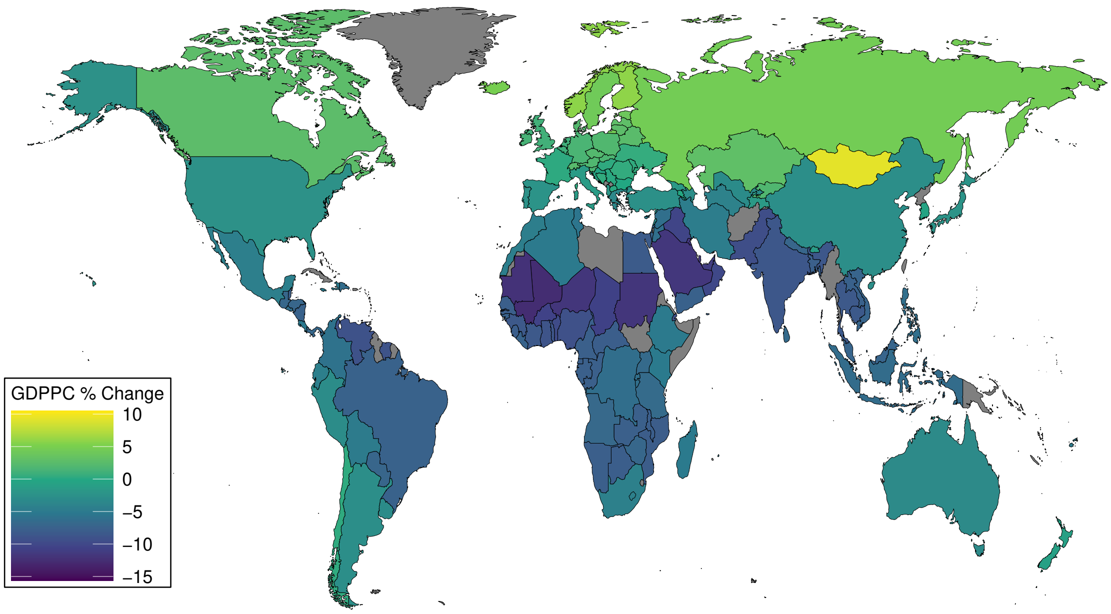
Note: The map shows the projected increase in the annual average temperature between 2010 and 2100 under RCP 8.5.

TFP from equation (13) when we set the ΔT_{it} and ΔT_{it}^2 equal to zero, which implies that future temperatures in each country are constant at their values in 2010. We measure the impact of climate change as the percent difference in output between the no-climate-change and climate-change simulations.

4.3 Results

Figure 5 shows the impact of climate change on 2100 GDP per capita in each country. Countries close to the equator with high initial temperatures suffer the largest losses. For example, in this exercise, climate change reduces output by 7.3 percent in Brazil and by 8.5 percent in India. These results are consistent with the findings of Acevedo et al. (2017) who use a model to project the impacts of temperature change and assume that the level temperature affects the level of TFP. They find that in low-income economies 2100 GDP per capita would be approximately 8 percent lower

Figure 5: Impact of Climate Change on GDP per Capita in 2100



Note: The map shows the impact of the increase in temperature from climate change on GDP per capita in 2100. The projection is calculated using the level-effects specification in column 2 of Table 1.

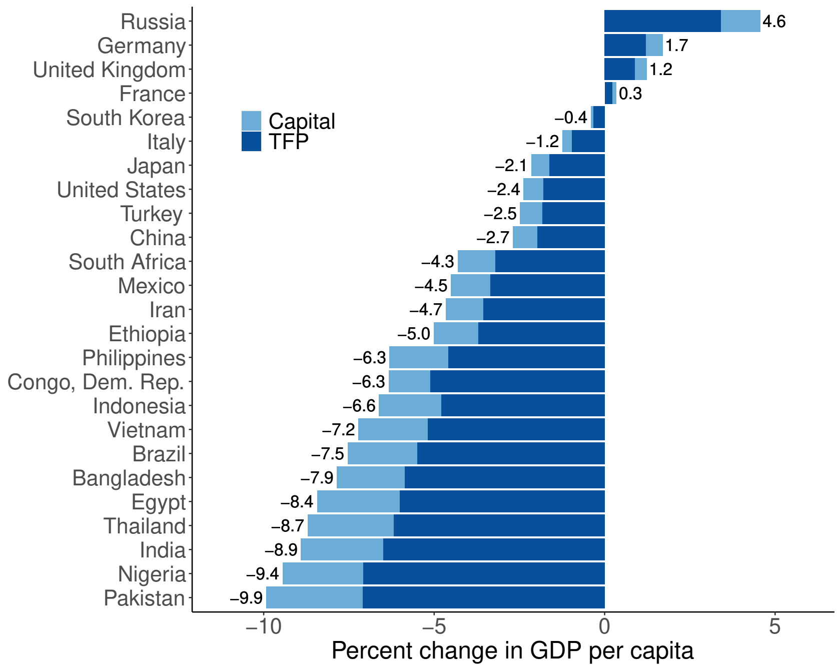
under RCP 8.5, compared to a future without any additional temperature change.

Countries at higher absolute latitudes with low initial temperatures experience benefits from climate change.[19] In the analysis, climate change increases output per person in Canada by 2.8 percent and in Russia by 4.7 percent. Countries in the mid-latitudes with 2010 temperatures close to the optimum experience the smallest effects. For example, climate change reduces output per capita by 2.3 percent in the US and increases output per capita by 0.4 percent in France.

Figure 6 decomposes the simulated impact of climate change on GDP per capita into the impact on capital per capita and TFP for the 25 most populous countries. We use the identity that $\Delta \ln(Y_{it}/N_{it}) = \Delta \ln A_{it} + \alpha \Delta \ln(K_{it}/N_{it})$ to calculate the decomposition. In all the countries, changes in both capital and TFP account for

[19] Mongolia is the coldest country in our data with an annual average temperature in 2010 of -1.7°C. It is far north, has average elevation of over 5000 feet and is completely landlocked. Starting from such a low temperature implies that Mongolia experiences considerable gains.

Figure 6: Decomposition of Climate Impacts

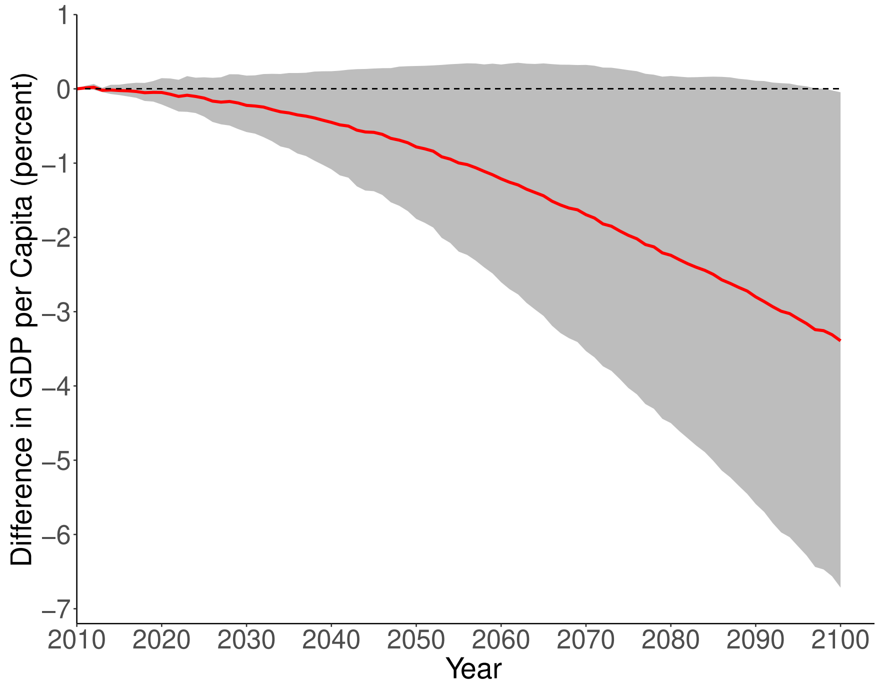


Note: This figure decomposes the impact of climate change between TFP and capital per person for the 25 most populous countries. The projection is calculated using the level-effects specification in column 2 of Table 1.

substantial portions of the impact of climate change on GDP per capita. However, changes in TFP account for more of the climate change impacts than changes in capital. This difference is at least partially due to the fact that the capital stock does not have time to fully react to the temperature increases near year 2100.

Figure 7 plots the aggregate effects of temperature change on world GDP per capita from 2010-2100. The projections imply that temperature change reduces GDP per capita by approximately 0.78 percent in 2050 and by approximately 3.4 percent in 2100. To provide a sense of the uncertainty surrounding these projections, we follow Burke et al. (2015) and bootstrap the regression estimates 1000 times, sampling countries with replacement. We simulate the model for each bootstrap, using the same procedure as we did for the main specification. The grey area in Figure 7 plots the resulting 95 percent confidence interval. The confidence interval in 2100 spans a range from virtually no impact to a 6.5 percent decrease in global GDP.

Figure 7: Impact of Climate Change on World GDP per Capita

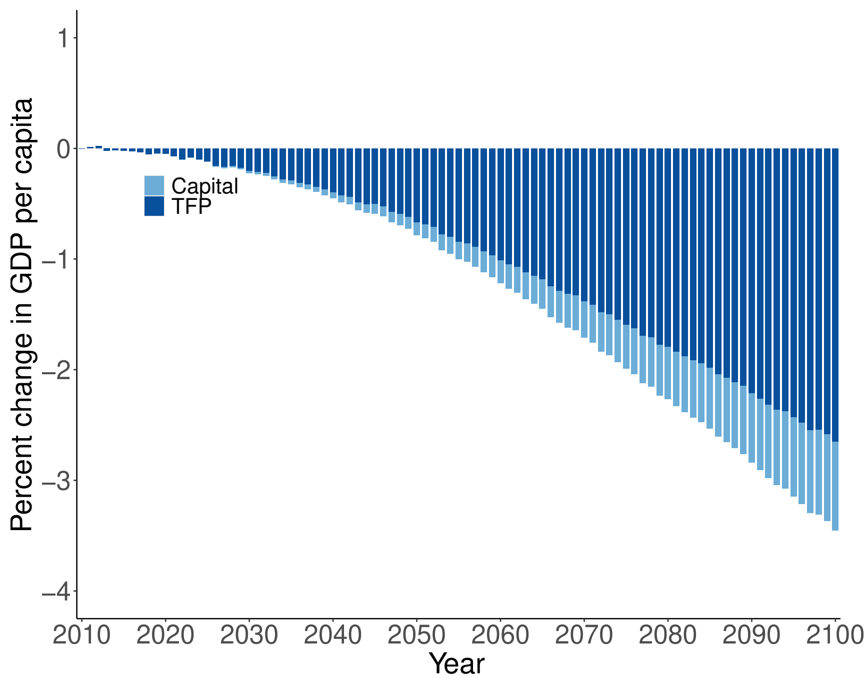


Note: The solid red line plots the impact of the temperature increase caused by climate change on global GDP per capita in each year from 2010-2100. The projection is calculated using the level-effects specification from column 2 of Table 1. The shaded gray region marks the boot-strapped 95 percent confidence interval, which captures sampling uncertainty in the regression.

Figure 8 decomposes the effects of temperature on world GDP into impacts on capital and TFP. As in the country-level breakdown, the direct impact of temperature on TFP explains most of the overall impact of changing temperatures. Capital takes time to adjust to the increase in temperature each period. Consequently, the fraction of the loss in GDP per capita from capital increases over time from near zero in 2010 to 22 percent in 2100.

So far, the projected effects we have presented assume that there are only level effects. While the bulk of the empirical evidence points in this direction, we cannot rule out the existence of growth effects. Figure 9 compares the projections using the estimates from columns 2 of Table 1 (only level effects) with the projections using the estimates from column 3 in Table 1 (both growth and level effects). Somewhat

Figure 8: Decomposition of Climate Impacts



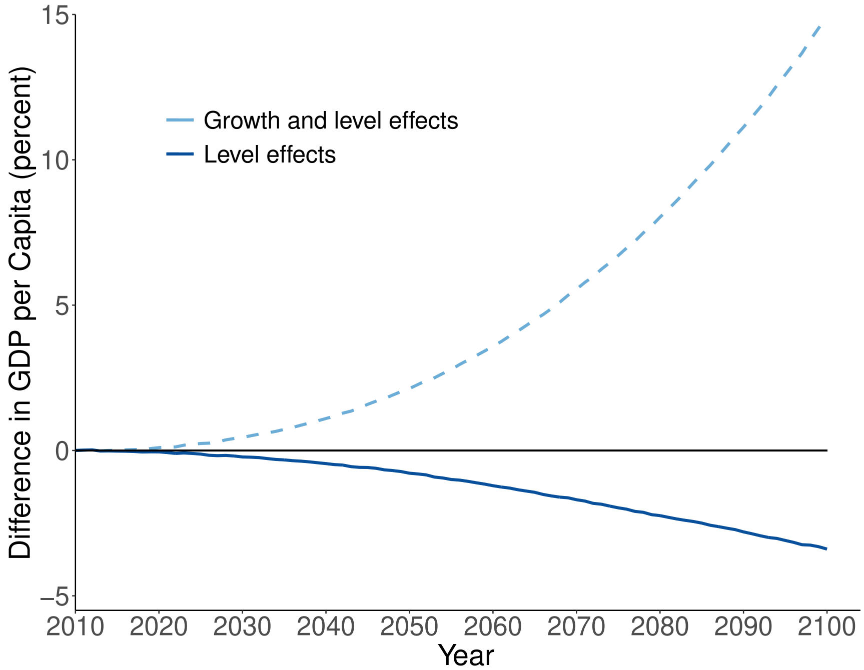
Note: This figure decomposes the impact of climate change between TFP and capital per person for the 25 most populous countries. The projection is calculated using the level-effects specification in column 2 of Table 1.

surprisingly, the projected effect of temperature on world GDP with both level and growth effects is positive. This is because the growth effect coefficients from column 3 imply that increases in temperature increase TFP growth when temperature is less than 26.7°C, which encompasses the majority of countries in world in 2010.

4.4 Reduced-form Growth Effects

We compare our projection results to those from the existing literature. Burke et al. (2015) project the impacts of temperature increases under RCP 8.5 assuming that there are only growth effects of temperature and no level effects. Relative to our results, they find much larger output losses from future changes in climate. However, their analysis also differs from ours along other dimensions. They (i) assume a constant growth rate of income per capita in the absence of climate change, (ii) use a different data source (World Bank instead of Penn World Tables), (iii) cap the

Figure 9: Comparison of the Impact of Climate Change on World GDP per Capita



Note: The solid dark blue line plots the impact of the temperature increase caused by climate change on world GDP per capita for the level-effects specification from column 2 of Table 1. The dashed light blue line plots the impact of the temperature increase caused by climate change on world GDP per capita for the specification with both growth and level effects from column 3 of Table 1.

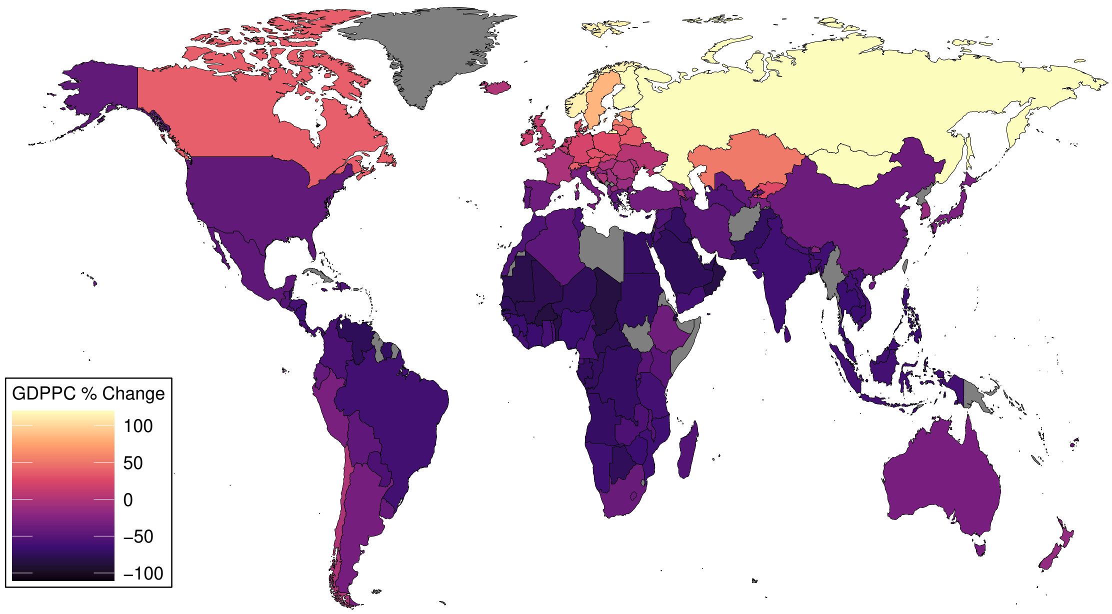
impacts of climate change at 30°C, (iv) and do not allow for dynamic impacts from a lagged dependent variable.

To understand whether the differences between our results and Burke et al. (2015) are driven by growth versus level effects or these other factors, we conduct a reduced-form projection of the future impacts of climate change using column 2 from Table 2. This projection captures the spirit of the existing analyses that use GDP as the dependent variable. The projection equation is

$$\Delta y_{it} = \hat{\gamma}_1 T_{it} + \hat{\gamma}_2 T_{it}^2 + \xi_1 \overline{\Delta P}_i + \xi_2 \overline{\Delta P}_i^2 + \hat{\rho} \Delta y_{it-1} + \hat{\bar{u}} + \hat{g}_i. \tag{14}$$

The results, presented in Figure 10, reveal much larger climate change impacts

Figure 10: Results with Reduced-Form Growth Effects



Note: The map shows the impact of the increase in temperature from climate change on GDP per capita in 2100. The projection is calculated using the growth-effects specification from column 2 of Table 2. The projected changes in GDP per capita in Mongolia, 263 percent, and Finland, 177 percent, exceed the color scale on the map.

than the baseline results in Figure 5. For example, US GDP per capita drops by 43 percent, compared to just over 2 percent in our model-based results. Similarly, GDP per capita in India drops by over 61 percent compared to approximately 8.5 percent in the model-based results. These results support the notion that the main reason our findings differ from those of Burke et al. (2015) is because of the distinction between level and growth effects.

5 Conclusion

Our paper combines theory with empirics to study the economic impact of climate change. There is an ongoing debate about whether a one-time change in temperature will affect the growth rate of output per capita permanently or temporarily. Standard economic theory suggests that long-run growth in output per capita is determined entirely by growth in TFP. We examine the relationship between temperature and TFP and find evidence that the level of temperature affects the level of TFP, but not the growth rate of TFP. Consequently, our results suggest that the level of temperature only affects the growth rate of output per capita temporarily. We then show that this finding has important implications for the literature that uses historical relationships to project the future impacts of climate change. This literature generally assumes that a one-time change in temperature permanently alters the growth rate of output per capita. We find that the projected impacts of future rising temperatures from climate change are smaller, but still substantial, when the impacts on growth are temporary, rather than permanent.

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Appendices

A Data

Table A1: Summary Statistics

Statistic	N	Mean	St. Dev.	Min	Max
$\Delta LnTFP$	6,654	0.010	0.065	-1.091	0.667
$\Delta LnGDPPC$	6,654	0.017	0.067	-1.109	0.664
$Temp.$	6,654	19.063	7.216	-2.370	29.610
$\Delta Temp.$	6,654	0.018	0.538	-2.950	2.460
$\Delta Precip.$	6,654	0.001	0.230	-2.515	1.978

Note: Summary statistics for regression sample in Tables 1 and 2.

B Sensitivity

Table B1: Results Without the Lagged Dependent Variable

Dep. Var.: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp.:\gamma_1$	0.0039*		0.0021
	(0.0018)		(0.0019)
$Temp.^2:\gamma_2$	-0.0001		-0.0000
	(0.0001)		(0.0001)
$\Delta Temp.:\beta_1$		0.0095**	0.0082*
		(0.0032)	(0.0033)
$\Delta Temp.^2:\beta_2$		-0.0003***	-0.0003**
		(0.0001)	(0.0001)
$\Delta Precip.:\xi_1$	0.0070	0.0047	0.0045
	(0.0080)	(0.0079)	(0.0079)
$\Delta Precip.^2:\xi_2$	-0.0005	-0.0002	-0.0002
	(0.0019)	(0.0019)	(0.0019)
N	6,654	6,654	6,654
Adj. R-squared	0.08	0.09	0.09
$\gamma_1=\gamma_2=0$ (p-value)	0.0833		0.2796
$\beta_1=\beta_2=0$ (p-value)		0.0030	0.0142
Optimal Temperature	13.41	13.95	

Note: The table reports the results when we exclude the lagged dependent variable. All specifications include country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects and column 3 is the specification with both growth and level effects. $^{***}p<0.01$, $^{**}p<0.05$, $^{*}p<0.10$.

Table B2: Results With TFP Innovations

Dep. Var.: $\Delta LnTFP$ innovations	(1) Growth	(2) Level	(3) Both
$Temp. : \gamma_1$	0.0028		0.0005
	(0.0016)		(0.0017)
$Temp.^2 : \gamma_2$	-0.0002		-0.0000
	(0.0001)		(0.0001)
$\Delta Temp. : \beta_1$		0.0107***	0.0104**
		(0.0031)	(0.0032)
$\Delta Temp.^2 : \beta_2$		-0.0004***	-0.0004***
		(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	0.0085	0.0053	0.0053
	(0.0081)	(0.0081)	(0.0080)
$\Delta Precip.^2 : \xi_2$	-0.0009	-0.0005	-0.0005
	(0.0019)	(0.0019)	(0.0019)
N	6,654	6,654	6,654
Adj. R-squared	0.03	0.04	0.04
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.1803		0.9194
$\beta_1 = \beta_2 = 0$ (p-value)		0.0002	0.0006
Optimal Temperature	8.98	12.84	

Note: The table reports the results when we exclude the lagged dependent variable and use TFP innovations as the dependent variable. All specifications include country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects and column 3 is the specification with both growth and level effects. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table B3: Results With Linear Time Trends

Dep. Var.: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp.: \gamma_1$	0.0085*		0.0025
	(0.0035)		(0.0042)
$Temp.^2: \gamma_2$	-0.0004**		-0.0002
	(0.0001)		(0.0002)
$\Delta Temp.: \beta_1$		0.0094***	0.0080*
		(0.0028)	(0.0034)
$\Delta Temp.^2: \beta_2$		-0.0004***	-0.0003*
		(0.0001)	(0.0001)
$\Delta Precip.: \xi_1$	0.0065	0.0040	0.0045
	(0.0079)	(0.0079)	(0.0078)
$\Delta Precip.^2: \xi_2$	-0.0004	-0.0000	-0.0001
	(0.0019)	(0.0019)	(0.0019)
$\Delta LnTFP_{t-1}: \rho$	0.1284***	0.1299***	0.1297***
	(0.0374)	(0.0374)	(0.0374)
N	6,654	6,654	6,654
Adj. R-squared	0.14	0.14	0.14
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.0120		0.4677
$\beta_1 = \beta_2 = 0$ (p-value)		0.0003	0.0399
Optimal Temperature	11.35	12.57	

Note: The table reports the results when we include country-specific linear time trends. All specifications include country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects and column 3 is the specification with both growth and level effects. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table B4: Results With Quadratic Time Trends

Dep. Var.: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp. : \gamma_1$	0.0068*		0.0013
	(0.0031)		(0.0043)
$Temp.^2 : \gamma_2$	-0.0004**		-0.0002
	(0.0001)		(0.0002)
$\Delta Temp. : \beta_1$		0.0075**	0.0068
		(0.0025)	(0.0035)
$\Delta Temp.^2 : \beta_2$		-0.0003***	-0.0002*
		(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	0.0075	0.0054	0.0059
	(0.0077)	(0.0077)	(0.0076)
$\Delta Precip.^2 : \xi_2$	-0.0008	-0.0005	-0.0006
	(0.0019)	(0.0018)	(0.0018)
$\Delta LnTFP_{t-1} : \rho$	0.0644	0.0660	0.0656
	(0.0366)	(0.0366)	(0.0366)
N	6,654	6,654	6,654
Adj. R-squared	0.18	0.18	0.18
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.0110		0.3070
$\beta_1 = \beta_2 = 0$ (p-value)		0.0008	0.1215
Optimal Temperature	9.43	11.49	

Note: The table reports the results when we include country-specific quadratic time trends, following Burke et al. (2015). All specifications include country- and year-fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects and column 3 is the specification with both growth and level effects. $***p < 0.01$, $**p < 0.05$, $*p < 0.10$.

Table B5: Results With Region-by-Year Fixed Effects

Dep. Var.: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp. : \gamma_1$	0.0119***		0.0093**
	(0.0031)		(0.0032)
$Temp.^2 : \gamma_2$	-0.0003**		-0.0002
	(0.0001)		(0.0001)
$\Delta Temp. : \beta_1$		0.0099**	0.0050
		(0.0031)	(0.0033)
$\Delta Temp.^2 : \beta_2$		-0.0004***	-0.0003*
		(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	0.0082	0.0057	0.0056
	(0.0078)	(0.0078)	(0.0077)
$\Delta Precip.^2 : \xi_2$	-0.0010	-0.0006	-0.0006
	(0.0019)	(0.0019)	(0.0019)
$\Delta LnTFP_{t-1} : \rho$	0.1511***	0.1524***	0.1520***
	(0.0364)	(0.0363)	(0.0362)
N	6,654	6,654	6,654
Adj. R-squared	0.17	0.17	0.17
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.0006		0.0042
$\beta_1 = \beta_2 = 0$ (p-value)		0.0014	0.0480
Optimal Temperature	18.78	13.55	

Note: The table reports the results when we include region-by-year fixed effects. We split the countries into 6 regions, using the division specified in Dell et al. (2012). All specifications include country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects and column 3 is the specification with both growth and level effects. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table B6: Results With Post-1990 Dummies

Dep. Var.: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp. : \gamma_1$	0.0073***		0.0054**
	(0.0019)		(0.0021)
$Temp.^2 : \gamma_2$	-0.0004***		-0.0003*
	(0.0001)		(0.0001)
$\Delta Temp. : \beta_1$		0.0104**	0.0074*
		(0.0032)	(0.0032)
$\Delta Temp.^2 : \beta_2$		-0.0004***	-0.0003*
		(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	0.0068	0.0043	0.0051
	(0.0079)	(0.0079)	(0.0078)
$\Delta Precip.^2 : \xi_2$	-0.0006	-0.0003	-0.0004
	(0.0019)	(0.0019)	(0.0019)
$\Delta LnTFP_{t-1} : \rho$	0.1662***	0.1690***	0.1675***
	(0.0388)	(0.0389)	(0.0388)
N	6,654	6,654	6,654
Adj. R-squared	0.12	0.12	0.12
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.0005		0.0234
$\beta_1 = \beta_2 = 0$ (p-value)		0.0001	0.0533
Optimal Temperature	9.74	12.72	

Note: The table reports the results we include country-specific dummy variables that equal one if the year is greater than 1990, and zero otherwise. All specifications include country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects and column 3 is the specification with both growth and level effects. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table B7: Results With More Lags of Temperature

Dep. Var.: $\Delta LnTFP$	(1) 2 lags	(2) 3 lags	(3) 4 lags	(4) 5 lags
$Temp. : \gamma_1$	0.0100**	0.0102**	0.0103**	0.0091**
	(0.0032)	(0.0033)	(0.0032)	(0.0033)
$Temp.^2 : \gamma_2$	-0.0004***	-0.0004***	-0.0004***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
$Temp_{t-1} : \eta_1$	-0.0054	-0.0052	-0.0051	-0.0054
	(0.0032)	(0.0033)	(0.0034)	(0.0034)
$Temp^2_{t-1} : \nu_1$	0.0003**	0.0003**	0.0003*	0.0003*
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
$Temp_{t-2} : \eta_2$	-0.0045	-0.0040	-0.0039	-0.0043
	(0.0029)	(0.0031)	(0.0032)	(0.0032)
$Temp^2_{t-2} : \nu_2$	0.0001	0.0001	0.0001	0.0001
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
$Temp_{t-3} : \eta_3$		-0.0013	-0.0010	-0.0019
		(0.0031)	(0.0033)	(0.0035)
$Temp^2_{t-3} : \nu_3$		0.0001	0.0001	0.0001
		(0.0001)	(0.0001)	(0.0001)
$Temp_{t-4} : \eta_4$			-0.0012	-0.0036
			(0.0032)	(0.0031)
$Temp^2_{t-4} : \nu_4$			0.0001	0.0002
			(0.0001)	(0.0001)
$Temp_{t-5} : \eta_5$				0.0053
				(0.0038)
$Temp^2_{t-5} : \nu_5$				-0.0001
				(0.0001)
$\Delta Precip. : \xi_1$	0.0124	0.0123	0.0123	0.0122
	(0.0080)	(0.0081)	(0.0081)	(0.0081)
$\Delta Precip.^2 : \xi_2$	-0.0020	-0.0020	-0.0020	-0.0020
	(0.0019)	(0.0020)	(0.0020)	(0.0020)
$\Delta LnTFP_{t-1} : \rho$	0.1720***	0.1719***	0.1716***	0.1716***
	(0.0416)	(0.0417)	(0.0417)	(0.0417)
N	6,103	6,103	6,103	6,103
Adj. R-squared	0.12	0.12	0.12	0.12
$\sum_i \eta_i = 0$ (p-value)	0.9353	0.8818	0.6534	0.7299
$\sum_i \nu_i = 0$ (p-value)	0.6034	0.3805	0.1882	0.2181

Note: The table reports the results when we include 2,3,4,5 lages of temperature in columns 2-5, respectively. All specifications include country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table B8: Heterogenity by Level of Development

Dep. Var.: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp. \times Rich : \gamma_1^R$	0.0056		0.0010
	(0.0035)		(0.0044)
$Temp.^2 \times Rich : \gamma_2^R$	-0.0003		-0.0001
	(0.0002)		(0.0002)
$Temp. \times Poor : \gamma_1^P$	0.0029		0.0010
	(0.0018)		(0.0018)
$Temp.^2 \times Poor : \gamma_2^P$	-0.0001		0.0000
	(0.0001)		(0.0001)
$\Delta Temp. \times Rich : \beta_1^R$		0.0100***	0.0092**
		(0.0029)	(0.0035)
$\Delta Temp.^2 \times Rich : \beta_2^R$		-0.0004**	-0.0003*
		(0.0001)	(0.0002)
$\Delta Temp. \times Poor : \beta_1^P$		0.0136	0.0129
		(0.0142)	(0.0142)
$\Delta Temp.^2 \times Poor : \beta_2^P$		-0.0005	-0.0005
		(0.0003)	(0.0003)
$\Delta Precip. : \xi_1$	0.0080	0.0055	0.0048
	(0.0081)	(0.0079)	(0.0078)
$\Delta Precip.^2 : \xi_2$	-0.0008	-0.0005	-0.0003
	(0.0019)	(0.0019)	(0.0019)
$\Delta LnTFP_{t-1} : \rho$	0.1879***	0.1904***	0.1894***
	(0.0387)	(0.0386)	(0.0385)
N	6,654	6,654	6,654
Adj. R-squared	0.12	0.12	0.12
$\gamma_1^R = \gamma_2^R = 0$ (p-value)	0.2175		0.6980
$\gamma_1^P = \gamma_2^P = 0$ (p-value)	0.2536		0.3553
$\beta_1^R = \beta_2^R = 0$ (p-value)		0.0017	0.0304
$\beta_1^P = \beta_2^P = 0$ (p-value)		0.0069	0.0073
$\gamma_1^P = \gamma_1^R$ (p-value)	0.50		0.99
$\gamma_2^P = \gamma_2^R$ (p-value)	0.31		0.44
$\beta_1^R = \beta_1^P$ (p-value)		0.80	0.80
$\beta_2^R = \beta_2^P$ (p-value)		0.84	0.66

Note: The table reports the results when we allow the coefficient estimates to differ for rich and poor countries. We define a country as rich it has above median GDP per capita in 2010 and poor otherwise. All specifications include country- and year-fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects and column 3 is the specification with both growth and level effects. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table B9: Heterogenity By Economic Structure

Dep. Var.: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp. \times Ag. : \gamma_1^A$	0.0035*		0.0010
	(0.0018)		(0.0018)
$Temp.^2 \times Ag. : \gamma_2^A$	-0.0001		0.0000
	(0.0001)		(0.0001)
$Temp. \times NonAg. : \gamma_1^N$	0.0022		-0.0021
	(0.0034)		(0.0044)
$Temp.^2 \times NonAg. : \gamma_2^N$	-0.0002		-0.0001
	(0.0002)		(0.0002)
$\Delta Temp. \times Ag. : \beta_1^A$		0.0151	0.0144
		(0.0121)	(0.0121)
$\Delta Temp.^2 \times Ag. : \beta_2^A$		-0.0006*	-0.0006*
		(0.0003)	(0.0003)
$\Delta Temp. \times NonAg. : \beta_1^N$		0.0071*	0.0079*
		(0.0028)	(0.0036)
$\Delta Temp.^2 \times NonAg. : \beta_2^N$		-0.0002	-0.0002
		(0.0001)	(0.0002)
$\Delta Precip. : \xi_1$	0.0080	0.0051	0.0044
	(0.0081)	(0.0079)	(0.0079)
$\Delta Precip.^2 : \xi_2$	-0.0008	-0.0004	-0.0002
	(0.0019)	(0.0019)	(0.0019)
$\Delta LnTFP_{t-1} : \rho$	0.1881***	0.1902***	0.1893***
	(0.0386)	(0.0386)	(0.0385)
N	6,654	6,654	6,654
Adj. R-squared	0.12	0.12	0.12
$\gamma_1^A = \gamma_2^A = 0$ (p-value)	0.1393		0.2149
$\gamma_1^N = \gamma_2^N = 0$ (p-value)	0.4617		0.3725
$\beta_1^A = \beta_2^A = 0$ (p-value)		0.0001	0.0000
$\beta_1^N = \beta_2^N = 0$ (p-value)		0.0160	0.0310
$\gamma_1^N = \gamma_1^A$ (p-value)	0.73		0.51
$\gamma_2^N = \gamma_2^A$ (p-value)	0.84		0.51
$\beta_1^A = \beta_1^N$ (p-value)		0.51	0.60
$\beta_2^A = \beta_2^N$ (p-value)		0.24	0.17

Note: The table reports the results when we allow the coefficient estimates to differ for agriculture and non-agriculture economies. We define an economy as agriculture if the share of value added from agriculture is above the median in 2010, and non-agriculture otherwise. All specifications include country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects and column 3 is the specification with both growth and level effects. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table B10: GDP per capita Results With Quadratic Time Trends

	(1)	(2)	(3)
Dep. Var.: $\Delta LnGDPPC$	Growth	Level	Both
$Temp. : \gamma_1$	0.0075*		0.0015
	(0.0032)		(0.0044)
$Temp.^2 : \gamma_2$	-0.0004**		-0.0002
	(0.0001)		(0.0002)
$\Delta Temp. : \beta_1$		0.0081**	0.0072*
		(0.0026)	(0.0036)
$\Delta Temp.^2 : \beta_2$		-0.0003***	-0.0002
		(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	0.0069	0.0049	0.0056
	(0.0078)	(0.0078)	(0.0077)
$\Delta Precip.^2 : \xi_2$	-0.0006	-0.0003	-0.0004
	(0.0019)	(0.0019)	(0.0019)
$\Delta LnGDPPC_{t-1} : \rho$	0.0808*	0.0825*	0.0820*
	(0.0363)	(0.0363)	(0.0363)
N	6,654	6,654	6,654
Adj. R-squared	0.24	0.24	0.24
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.0073		0.2190
$\beta_1 = \beta_2 = 0$ (p-value)		0.0006	0.1168
Optimal Temperature	9.57	11.90	

Note: The table reports the results with GDP per capita as the dependent variable when we include country-specific quadratic time trends, following Burke et al. (2015). All specifications include country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects and column 3 is the specification with both growth and level effects. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table B11: Results With Temperature Interactions

	(1)
Dep. Var.: $\Delta LnTFP$	OLS
$Temp_{t-1}$	-0.0105**
	(0.0037)
$Temp^2_{t-1}$	-0.0022
	(0.0020)
$Temp_t$	0.0089**
	(0.0033)
$Temp^2_t$	-0.0029
	(0.0020)
$Temp_t$ x $Temp_{t-1}$	0.0054
	(0.0040)
$Temp.^2_t$ x $Temp.^2_{t-1}$	-0.0000
	(0.0000)
$\Delta Precip.$	0.0049
	(0.0080)
$\Delta Precip.^2$	-0.0003
	(0.0019)
$\Delta LnTFP_{t-1}$	0.1894***
	(0.0385)
N	6,654
Adj. R-squared	0.12

Note: The specification includes country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

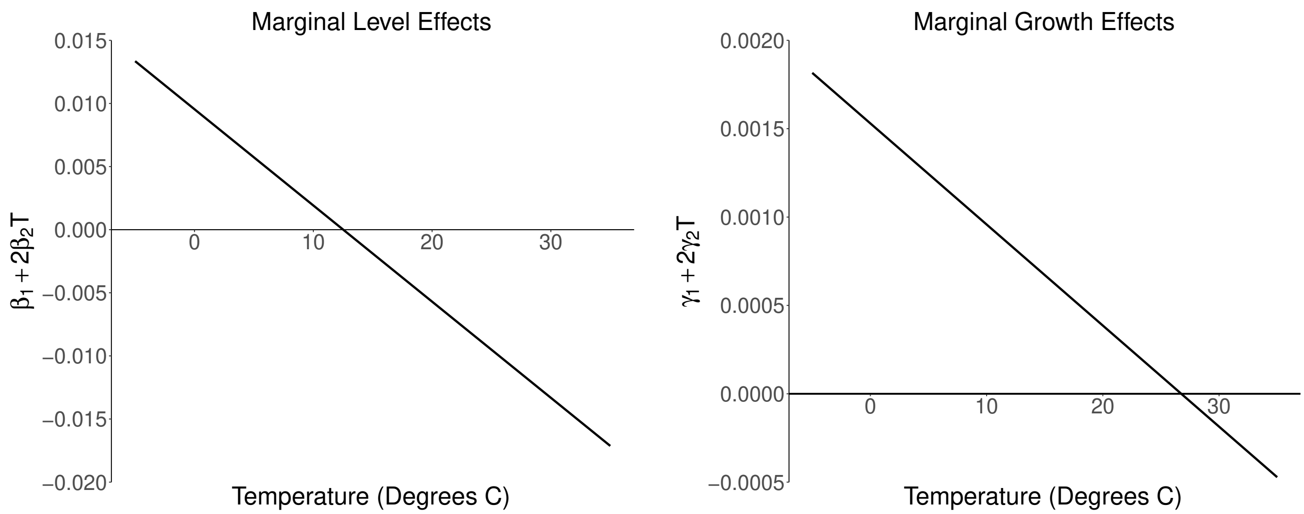
Table B12: Results With Capital as the Dependent Variable

Dep. Var.: $\Delta LnKPC$	(1) Growth	(2) Level	(3) Both
$Temp. : \gamma_1$	0.0030***		0.0031***
	(0.0007)		(0.0008)
$Temp.^2 : \gamma_2$	-0.0001*		-0.0001*
	(0.0000)		(0.0000)
$\Delta Temp. : \beta_1$		0.0024**	0.0005
		(0.0008)	(0.0009)
$\Delta Temp.^2 : \beta_2$		-0.0000	0.0000
		(0.0000)	(0.0000)
$\Delta Precip. : \xi_1$	-0.0020	-0.0014	-0.0014
	(0.0027)	(0.0027)	(0.0027)
$\Delta Precip.^2 : \xi_2$	0.0004	0.0003	0.0003
	(0.0007)	(0.0007)	(0.0007)
N	6,654	6,654	6,654
Adj. R-squared	0.53	0.53	0.53
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.0000		0.0000
$\beta_1 = \beta_2 = 0$ (p-value)		0.0019	0.2730
Optimal Temperature	18.68	27.34	

Note: The table reports the results with the log of capital per capita as the dependent variable. All specifications include country- and year- fixed effects. Robust standard errors, corrected for autocorrelation of order two, are in parentheses. Column 1 is the specification with only growth effects, column 2 is the specification with only level effects and column 3 is the specification with both growth and level effects. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

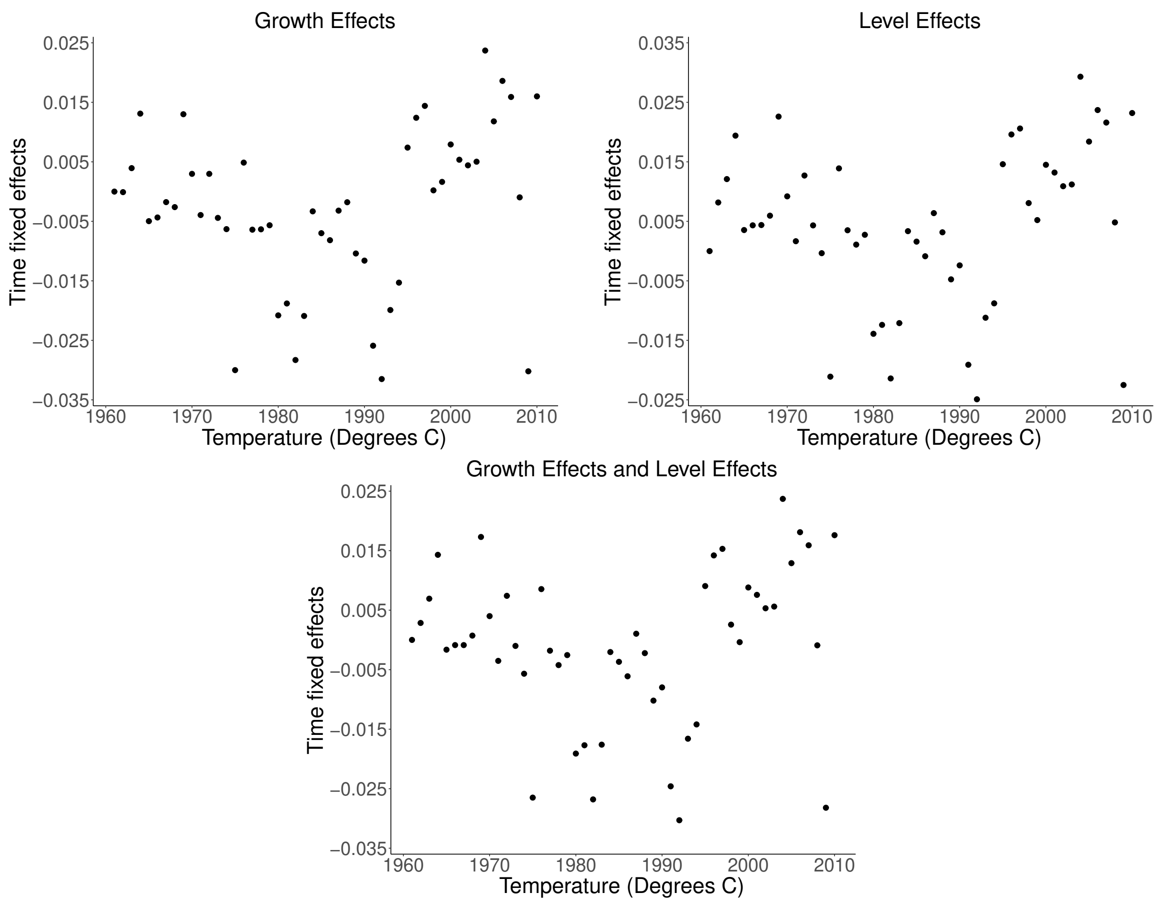
C Additional Figures

Figure C1: Marginal Effects



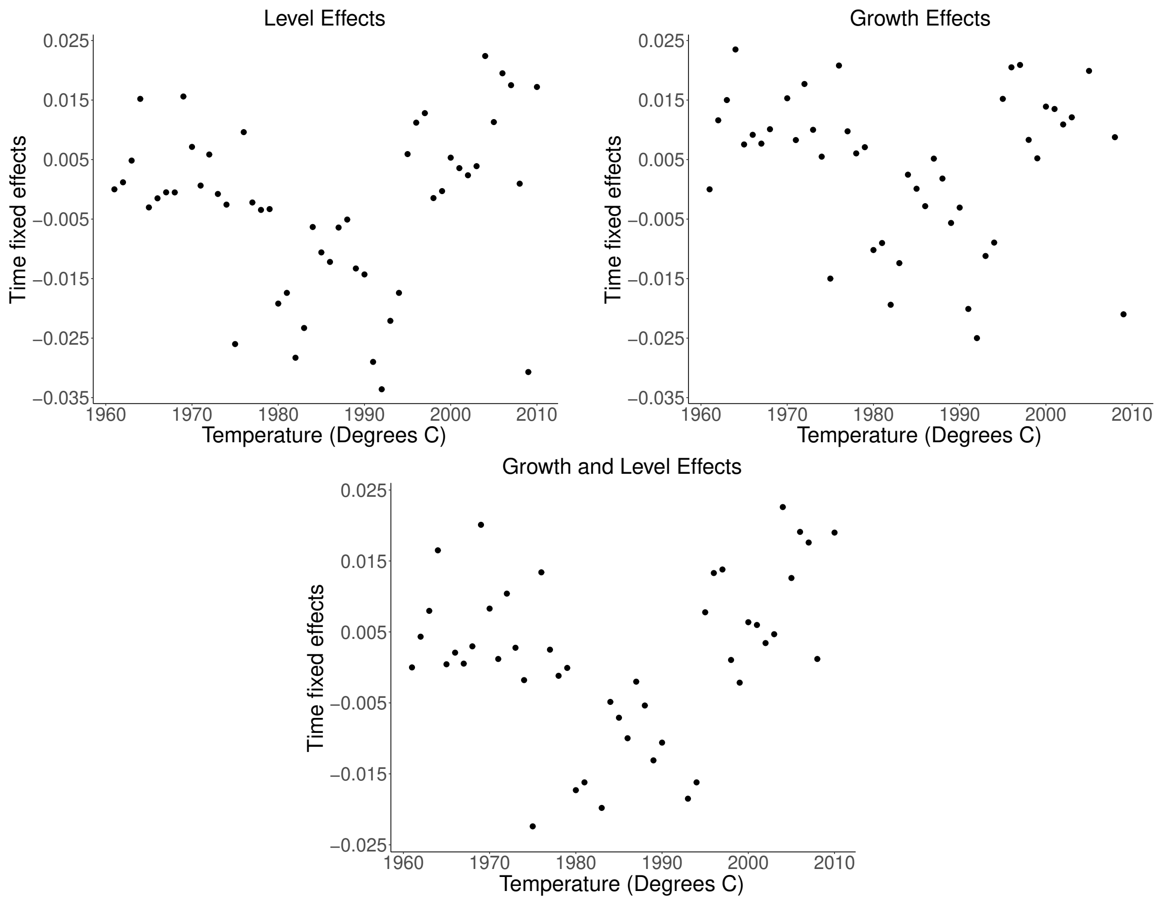
Note: The figure plots the marginal level effects (left column) and the marginal growth effects (right column) from the specification with both level and growth effects in the main results (column 3 of Table 1).

Figure C2: Main Results: Time Fixed Effects



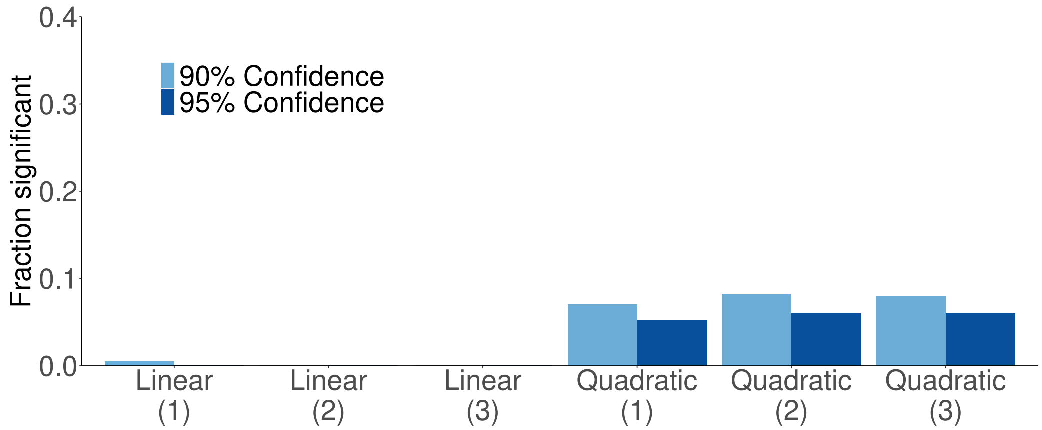
Note: The figure plots the time fixed effects for regression estimates reported in Table 1. The top left panel corresponds to column 1, the top right panel corresponds to column 2, and the bottom panel corresponds to column 3.

Figure C3: GDP per Capita Results: Time Fixed Effects



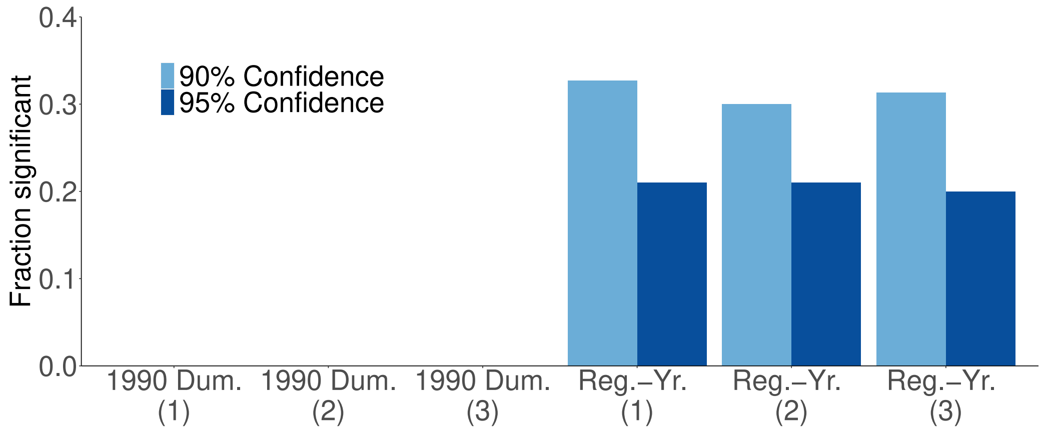
Note: The figure plots the time fixed effects for regression estimates reported in Table 2 for the specifications that include the lagged dependent variable. The top left panel corresponds to column 1, the top right panel corresponds to column 2, and the bottom panel corresponds to column 3.

Figure C4: Fraction of Statistically Significant Trends



Note: The first three bar-groups show the fraction of country-specific linear trends that are statistically significant at the five (dark blue) and ten (light blue) percent levels for the estimates in Table B3. The second three bar-groups show the fraction of country-specific trends (linear or quadratic) that are statistically significant at the five (dark blue) and ten (light blue) percent levels for the estimates in Table B4. The numbers in parentheses indicate the column from the corresponding table.

Figure C5: Fraction of Statistically Significant Dummies and Fixed Effects



Note: The first three bar-groups show the fraction of country-specific 1990 dummy variables that are statistically significant at the five (dark blue) and ten (light blue) percent levels for the estimates in Table B6. The second three bar-groups show the fraction of region-by-year fixed effects that are statistically significant at the five (dark blue) and ten (light blue) percent levels for the estimates in Table B5. The numbers in parentheses indicate the column from the corresponding table.