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

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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 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 caused by 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.

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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 approaches to modeling this relationship. The first approach assumes that a one-time, permanent change in temperature affects the long-run level of output per capita, but not the long-run growth rate of output per capita. 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 per capita. 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). The damage functions in these models imply that a 3°C increase in global average temperature will decrease economic output by approximately two 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 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 instead of 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 under 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).

In this paper, we revisit the level versus growth effect debate while paying special attention to the distinction between permanent and temporary changes in economic

[1]The two 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.

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 future 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 assume temperature affects TFP and examine the consequences of a one-time, permanent change in temperature. We extract two lessons from the simple model. First, we can infer the long-run impact of temperature on GDP per capita from the short-run impact of temperature on TFP. In all neoclassical growth models, the steady-state growth rate of output per capita depends only on the growth rate of TFP. If a change in temperature decreases the growth rate of TFP, then it also decreases the steady-state (i.e., permanent) growth rate of output per capita. This is the case of a *growth effect*. If instead a change in temperature only decreases the level of TFP, then it decreases the long-run level of GDP per capita, but it has no impact on the long-run growth rate of GDP per capita. This is the case of a *level effect*.

The second lesson from the simple model is that it is difficult to infer the long-run impact of temperature on GDP per capita from the short-run impact of temperature on GDP per capita. Even if temperature only affects the level of TFP (and so has no long-run effect on GDP growth), it still reduces the short-run growth rate of GDP per capita as the economy transitions to a new steady state with a lower (de-trended) capital stock. Thus, observing a short-run impact of temperature on GDP per capita growth does not necessarily imply a long-run impact (i.e., a *growth effect*).

Building on the insights from the simple model, we empirically investigate whether temperature affects the level or the 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 the dependent variable, instead of GDP per capita. Second, we incorporate nonlinear impacts of temperature following Burke et al. (2015). Overall, the evidence suggests that temperature affects the level of TFP, but not the long-run 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] In other words, a change in temperature has a short run, but not a long run, impact on growth in output per capita.

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 from similar analyses 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.

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 nonlinear impact of temperature on TFP, 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.

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 of 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 (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 discussions. 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.

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), Burke et al. (2015, 2018), and 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).[6] 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 are sensitive to changes in specification. They focus on GDP, rather than TFP. Using cross-country GDP data, 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 the response of capital to the temperature shock. Kalkuhl and Wenz (2020) also stress that it is difficult to distinguish between temporary and permanent impacts of temperature on economic

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

growth in panel models with GDP per capita as the dependent variable. Instead, they use cross-sectional and long difference regressions and do not find evidence for growth effects. We show that using TFP as the dependent variable makes it possible to distinguish between level and growth effects in panel data. 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.[7]

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. 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

[7] In ongoing work, Klenow et al. (2023) also stress the importance of distinguishing between temporary and permanent impacts of temperature on economic growth. See also the presentation by Klenow (2020) to the Federal Reserve Bank of San Francisco and the Climate Impact Lab.

of future increases in temperature from climate change. Section 5 concludes.

2 Background and Motivation

We discuss a simple model to provide a framework for understanding the effects of temperature on the level and growth rate of output per capita.[8] We use the model to derive theoretically consistent equations that can separate 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 a temporary or permanent effect 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 per capita. 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 per capita.[9] In either case, the change in temperature permanently changes the long-run level of output per capita.

[8] 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. Our simple model has a fixed savings rate and no forward looking behavior. Consequently, climate has no impact on the economic dynamics conditional on weather.

[9] 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 per capita in both cases. A temporary change in temperature will have a temporary impact on the growth rate of output per capita, 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.

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.*

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.[10]

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. 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 TFP from period

[10] The defining feature of the Solow model is a constant savings rate. The theoretical distinctions between level and growth effects are the same in a more general neoclassical growth model with an endogenous savings rate. Regardless of whether the savings rate is endogenous, the long-run growth rate of income per capita is determined entirely by the growth rate of TFP. A change in the level of TFP only affects the growth rate of GDP per capita along the transition path.

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 $D_l = 1 \ \forall T$.[11]

The dotted light 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 per capita incorporates the changes in both TFP and capital. Output drops in period t^* due to the fall in TFP, and then grows more slowly than the baseline case while capital transitions to the new BGP. Once capital reaches the new BGP, output per capita growth returns to its original rate. The bottom right panel summarizes these dynamics and shows that the increase in temperature leads to a temporary decrease in economic growth (over the transition), but not a permanent decrease in economic growth (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.

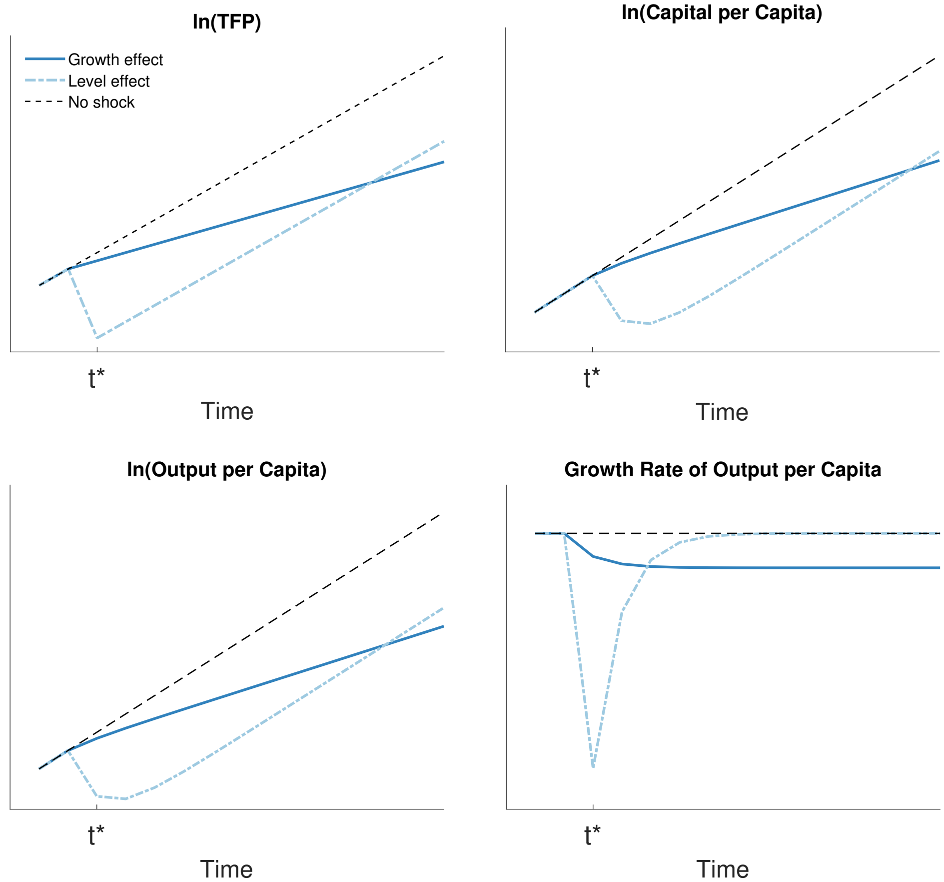
The solid dark blue line in Figure 1 sketches the dynamics following a one-time

[11] In the empirical analysis, we allow for the possibility that both effects exist simultaneously. In the case where both exist, the long-run impact of temperature on the growth rate of GDP per capita still depends only on the growth effect.

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 values. 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 the endogenous response of capital 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.

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



Note: The figure shows the consequences of 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).

2.2 Empirical Strategy

We discuss empirical methods for distinguishing between level and growth effects of temperature on TFP in the context of the simple model. 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

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

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

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

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

$$\Delta \tilde{a}_{it} \approx g + \gamma T_{it}. \tag{4}$$

Putting these together yields,

$$\Delta y_{it} \approx g_i + \beta \Delta T_{it} + \gamma T_{it} + \alpha \Delta y_{it-1}. \tag{5}$$

Equation (5) 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 (5).

The goal of estimating (5) would be to learn about the behavior of TFP from data on GDP per capita. This inference requires including both the level and the change in temperature as well as a lagged dependent variable in the regression. In specifications that omit the lagged dependent variable or include only the level of temperature, it is not clear whether changes in the growth rate of GDP per capita are driven by TFP or by capital.

A more direct 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. To derive the analog of (5) for TFP, we take logs and first differences of (3) to get

$$\Delta a_{it} = \beta \Delta T_{it} + \Delta \tilde{a}_{it}.$$

Substituting in (4) gives

$$\Delta a_{it} \approx g_i + \beta \Delta T_{it} + \gamma T_{it}. \tag{6}$$

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 (6) in our empirical analysis, but allow for nonlinearites 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 affects 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 per capita, but not the long-run growth rate of GDP per capita. 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.[12]

[12] 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).

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

$$\Delta y_{it} = \gamma_1 T_{it} + \gamma_2 T_{it}^2 + \text{controls} + \epsilon_{it}. \tag{7}$$

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:

$$\Delta y_{it} = 1 + g_i^Y + \gamma_1 T_{it} + \gamma_2 T_{it}^2, \tag{8}$$

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 (7) regardless of whether temperature affects output through the level-effects or the growth-effects damage function. Thus, the estimation results from (7) do not, in isolation, imply that projections of future climate damage should be based entirely on growth effects, as (8) 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 results or in prominent policy outlets like the IPCC reports (Masson-Delmotte et al., 2018). These robustness analyses do not account for the endogenous response of capital to the temperature shock, 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.[13] 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.

3.2 Empirical Specification

We model the dynamics of TFP as

$$A_{it} = \exp\left(\beta_1 T_{it} + \beta_2 T_{it}^2 + \xi_1 P_{it} + \xi_2 P_{it}^2 + \eta_t + \epsilon_{it}\right) A_{it-1}^{\rho} \tilde{A}_{it} \tag{9}$$

$$\tilde{A}_{it+1} = (1 + g_i + \gamma_1 T_{it+1} + \gamma_2 T_{it+1}^2 + \kappa_t + \nu_{it})\tilde{A}_{it}, \tag{10}$$

where P_{it} is precipitation. The TFP process includes four generalizations relative to the specification in the simple model, given in (3). First, both damage functions have quadratic components: $D_g = \gamma_1 T_{it} + \gamma_2 T_{it}^2$ and $D_l = \exp(\beta_1 T_{it} + \beta_2 T_{it}^2)$. Burke et al. (2015) show that these nonlinearities are important for capturing the different marginal effects of a change in temperature 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 implies that a one-time, permanent change in temperature can affect the level of TFP for several periods, without having a permanent affect.

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

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

and first differences of (9) yields

$$\Delta a_{it} = \beta_1 \Delta T_{it} + \beta_2 \Delta T_{it}^2 + \xi_1 \Delta P_{it} + \xi_2 \Delta P_{it}^2 + \rho \Delta a_{it-1} + \Delta \tilde{a}_{it} + \Delta \eta_t + \Delta \epsilon_{it}. \quad (11)$$

Taking logs and first differences of (10), evaluating at time t and applying the small value approximation $\ln(1+x) \approx x$ for growth rates yields

$$\Delta \tilde{a}_{it} = g_i + \gamma_1 T_{it} + \gamma_2 T_{it}^2 + \kappa_t + \nu_{it}. \quad (12)$$

Substituting (12) into (11) yields our main estimating equation:

$$\Delta a_{it} = \gamma_1 T_{it} + \gamma_2 T_{it}^2 + \beta_1 \Delta T_{it} + \beta_2 \Delta T_{it}^2 + \xi_1 \Delta P_{it} + \xi_2 \Delta P_{it}^2 + \rho \Delta a_{it-1} + g_i + b_t + u_{it}, \quad (13)$$

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 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 (13) 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 (13) 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 (13) 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, differences in average temperature growth rates across countries are also not a source of identifying variation. Consistent with the existing literature, we interpret the results as the causal impact of changes in temperature on TFP. The key assumption for causality is that annual shocks to temperature are uncorrelated with annual shocks to other variables that affect TFP.

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. Standard errors corrected for heteroskedasticity and autocorrelation of order two are in parentheses.[14,15] 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 quadratic term. The optimal temperature is approximately 11°C, which is slightly lower than findings in the existing literature.[16] 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

[14] Across all specifications Arellano-Bond tests reject the null of no autocorrelation of order one, but fail to reject the null of no autocorrelation of order two. To be conservative and consistent with Bond et al. (2010), we correct for autocorrelation of order two.

[15] Appendix Table B1 reports results with standard errors clustered by country. In this case, we continue to reject the null of no level effects. We still cannot reject the null hypothesis of no growth effects, but the p-value is lower than in our main results (p=0.12). As shown in Appendix Figure C1 and Figure 8, these growth effects would imply a substantial economic benefit from future temperature change for most countries.

[16] The optimal temperature for column 1 equals $-\gamma_1/(2\gamma_2)$. Based on our structural equations for TFP growth, (9) and (10), this is the value of temperature that maximizes the growth rate of TFP in the absence of level effects ($\beta_1 = \beta_2 = 0$). Similarly, the optimal temperature in column 2 equals $-\beta_1/(2\beta_2)$. This is the level of temperature that maximizes the level of TFP, in the absence of growth effects ($\gamma_1 = \gamma_2 = 0$). We do not report an optimal temperature for column 3, because this object is not well defined when there are both growth and level effects. Due to rounding, our results differ from those calculated directly from the estimates reported in the table.

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.

Table 1: Main Results

Dep. Variable: $\Delta LnTFP$	(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)
$\Delta LnTFP_{t-1} : \rho_1$	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. Heteroskedasticity-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. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

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, the data can support the assumption that the level of temperature affects the level of TFP.

In column 3, we estimate (13), 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.

Of course, there is considerable uncertainty in the regressions, and it is important 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 for temperatures below 26.7°C. Thus, for most countries in the world, the (statistically insignificant) growth effects would imply a positive impact of temperature on TFP 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 three approaches to address this issue. First, Appendix Table B2 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 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. Second, 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 B3 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.

Third, we use dynamic panel instruments (see, e.g., Anderson and Hsiao, 1982; Arellano and Bond, 1991). In columns 1, 3, and 5 of Appendix Table B4, we re-estimate the specifications from Table 1 using the second lag of the dependent variable to instrument for the first lag. The first stage F-statistic exceeds 20 in all three regressions. The instrument has almost no effect on the coefficient on the lagged dependent variable in the second stage regression, suggesting that the bias caused by the inclusion of the lagged dependent variable in the OLS regressions is not substantial. We continue to see evidence of level effects but not of growth effects. In columns 2, 4, and 6 of Appendix Table B4, we re-estimate the specifications from Table 1 using the second and third lags of the dependent variable to instrument for the first lag. Including two instruments weakens the power of the instruments, but allows us to test for overidentification. The test fails to reject the null hypothesis that the instruments can be excluded from the second stage in all three regressions.

We focus on the OLS results instead of the IV results in the main text because the IV results suggest that any bias caused by the inclusion of the lagged dependent variable is minimal and because the results from the overidentification tests are sensitive to the choice of the instrument. For example, using the second and third lagged levels of log TFP to instrument for the lagged dependent variable violates the exclusion restriction and increases the coefficient on the lagged dependent variable to several times its value in the OLS regressions.[17] The similarity of the main results

[17]The violation of the exclusion restriction could imply that we should include more lags of the dependent variable in our baseline specification. Appendix Table B6 presents the OLS results with

when we drop the lagged dependent variable, use TFP innovations, or use dynamic panel instruments suggest that our main conclusions from Table 1 are not driven by biases introduced by the lagged dependent variable.[18]

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.[19]

Appendix Table B8 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 B8 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 B10 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.This specification supports the existence of both level and growth effects in column 3. However, the

four lags of the dependent variable. Only the first lag is significant and the results are again similar to our baseline results in Table 1.

[18]Following the existing literature, our main results assume that the temperature coefficients are homogeneous across countries. In Appendix Table B7, we follow Bond et al. (2010) and implement a version of the Pesaran and Smith (1995) mean group estimator. To do so, we estimate separate time series regressions for each country and report the median of the country-level coefficients and a robust estimate of the mean. To account for time fixed effects, all variables in the country-level regressions are measured relative to the average across countries within a given year. The coefficients in these regressions are similar to our baseline results, but the confidence intervals are much larger and all of the temperature variables are insignificant.

[19]Allowing for country-specific trends implies that the impacts of temperature on TFP are no longer identified from country-specific trends in the growth rate of temperature (e.g. as a result of climate change).

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 B11 follows Kiley (2021) and interacts country fixed effects with a post-1990 dummy. Here, there are strong growth effects in column 3, suggesting that increases in temperature reduce the growth rate of TFP whenever $T > 9.4°C$. 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, the coefficients should add to zero. In Appendix Table B12, 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 evidence for level effects but not growth effects.[20]

We also explore the sensitivity of our results with respect to our measure of TFP. In our main analysis, we use the Solow residual to calculate TFP, assuming that labor share is constant across countries and over time (Gollin, 2002). Appendix Table B13 re-estimates the specifications from Table 1 using TFP measured at constant national prices from the Penn World Tables (rtfpna) as the dependent variable. The PWT measure allows the labor share of income to vary over time and across countries. The results are similar to those in our main specification.

As an alternate method to determine whether a change in temperature has a temporary or permanent effect on TFP growth, we estimate the impulse response of TFP growth to a temperature shock using local projections.(Jordà, 2005).[21] To do so, we re-estimate (13) with $\Delta a_{it+h} - \Delta a_{it-1}$ as the dependent variable, where

[20] 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.

[21] Studies by Acevedo et al. (2017, 2020) and ongoing work by Klenow et al. (2023) also use local projections to study the long-run impacts of temperature change.

$h = 1, 2, \ldots 20$ denotes the horizon in years. Panel (a) of Appendix Figure C6 plots the response for a country with an annual average temperature of 8 degrees Celsius, which is five degrees below the optimum from column 2 of Table 1. Panel (b) plots the response for a country with an annual average temperature of 13 degrees Celsius, which is near the optimum. Panel (c) plots the response for a country with an annual average temperature of 18 degrees Celsius, which is five degrees above the optimum. In all three panels, the shaded gray region shows the 95 percent interval, calculated using robust standard errors corrected for autocorrelation of order two. In the initial period, the temperature shock increases TFP growth in the cold country, decreases TFP growth in the hot country, and does not have a statistically significant impact on TFP growth in the country with the optimal temperature. In almost all the periods after the initial period, the temperature shock does not have a statistically significant effect on TFP growth. These results are consistent with our earlier finding that a change in temperature has a temporary, but not a permanent effect on TFP growth.

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 B14, we re-estimate the specifications from Table 1 but interact 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. Appendix Table B15 presents a closely related analysis 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. Our finding that there is no significant heterogeneity in the coefficients between different countries is consistent with the findings of Burke et al. (2015), who show similar results with GDP per capita as the dependent variable.[22]

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

We examine the direct 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. Using GDP per capita as the dependent variable also allows us to compare our results to Burke et al. (2015) and Dell et al. (2012).

Table 2 re-estimates the specifications from Tables 1 and B2 with GDP per capita, instead of TFP, as the dependent variable. Column 1 estimates a specification that includes the level of temperature, but does not include the change in temperature or a lagged dependent variable. This is similar to the main specification in Burke et al. (2015).[23] As in their results, the data suggest a nonlinear relationship between the level of temperature and the growth-rate of GDP per capita. However, this short-run relationship does not tell us whether the change in economic growth in response to the temperature shock is permanent or temporary.[24]

Column 5 includes both the level and the change in temperature. This is similar to the main specification in Dell et al. (2012), except that we include nonlinear impacts of temperature and they instead include linear specifications with temperature coefficients that differ by level of development. The joint significance test rejects the null that temperature has no impact on the level of GDP per capita (p=0.02) and almost rejects the null that temperature has no impact on the growth rate of

[22]Our main results account for heterogeneous marginal impacts of temperature with a quadratic term. In Appendix Table B16, we allow for additional heterogeneity by interacting annual temperature with average temperature over the sample period, along the lines of Carleton et al. (2022). We find no evidence for heterogeneity beyond the quadratic term. In Appendix Table B17, 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.

[23]Burke et al. (2015) also include country-specific quadratic time trends. Appendix Table B18 recreates Table 2 and includes quadratic time trends to be directly comparable to Burke et al. (2015). For completeness, columns 2 and 4 add lagged dependent variables to the specifications in columns 1 and 3.

[24]Column 3 assumes a different data generating process and finds a nonlinear relationship between the level of temperature and the level of GDP per capita. If this was the true data generating process, it would imply that there are no transition dynamics following a temperature shock. Note that this case is different than the case of a level effect. In the level effect case, a shock to temperature induces transition dynamics in capital and slows economic growth in the short run.

GDP per capita (p=0.11). Dell et al. (2012) find that temperature affects both the level and the growth rate of GDP per capita. We view our findings as being broadly consistent with theirs and implying that a change in temperature likely affects the growth rate of GDP per capita in the short run. This interpretation is consistent with the simple model, which predicts that a change in temperature should affect the short-run growth rate of GDP per capita regardless of whether there is a growth effect or a level effect.

The results in column 5 do not tell us whether the effect of the temperature shock on GDP per capita growth will be temporary or permanent (i.e., whether there is a level effect or a growth effect). Using TFP as the dependent variable allows us to distinguish between these two cases. Alternatively, one could use a regression with GDP per capita as the dependent variable to try to learn how TFP responds to a temperature shock. One imperfect way to accomplish this goal is to add a lagged dependent variable to the GDP per capita regression, which partially controls for the response of capital to the temperature shock. Column 6 reports the results from this specification. Including the lagged dependent variable increases the magnitude of the coefficient on the change in temperature relative to column 5 and decreases the magnitude of the coefficient on the level of temperature. Moreover, the joint significance test rejects the null that temperature has no impact on the level of GDP per capita ($p < 0.01$) but fails to reject the null that temperature has no impact on the growth rate of GDP per capita ($p = 0.30$). These results suggest a temperature shock has a short run but not a long run effect on econmic growth. However, the results with TFP in Table 1 provide stronger evidence that the effects on economic growth are temporary. The key advantage of using TFP as the dependent variable is that we can directly test the theoretical conditions required to distinguish between level and growth effects in panel data.[25]

[25]In the appendix to their paper, Dell et al. (2012) find growth effects in specifications similar to column 6 of Table 2. They model heterogeneous marginal effects of temperature by considering linear specifications with temperature coefficients that differ by level of development. Following Burke et al. (2015), our nonlinear specification captures these heterogeneous marginal effects. Since poorer countries tend to have temperatures above the optimum, the marginal impact of an increase in temperature will be larger, on average, in a poorer country. results in Appendix Tables B14 and B15, as well as Appendix Section C.3 in Burke et al. (2015), suggest that modeling heterogeneous impacts through nonlinearities in temperature is a better match for data. Even after accounting for the nonlinear impacts of temperature, our results in columns 5 and 6 of Table 2 demonstrate that accounting for capital dynamics is important for distinguishing between growth and level effects.

Table 2: GDP per Capita Results

Dep. Variable: $\Delta LnGDPPC$	(1)	(2)	(3)	(4)	(5)	(6)
$Temp.:\gamma_1$	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. Heteroskedasticity-robust standard errors, corrected for autocorrelation of order two, are in parentheses. ***$p<0.01$, **$p<0.05$, *$p<0.10$.

Appendix Table B19 directly examines the impact of temperature on capital per capita. Consistent with the simple model predictions and the findings in Tables 1 and 2, we find evidence that the level of temperature does not affect the contemporaneous level of capital, but it does affect the short-run growth rate of capital.[26]

Our theoretical framework assumes that temperature has no effect on the quantity of labor. Appendix Table B20 recreates Appendix Table B19 with employment as the dependent variable. Consistent with our assumption, we do not find evidence of level or growth effects of temperature on employment.

3.3.4 Summary of Historical Evidence

The above evidence generally supports the existence of level effects, but not growth effects. The impact of a change in temperature on economic growth will be permanent if and only if a change in temperature permanently changes the growth rate of TFP. In all other cases, the short-run response of economic growth is driven by the response of capital along the transition to the new balanced growth path. In Table 1, we use methods from Bond et al. (2010), and find evidence that the level of temperature affects the level of TFP, but not the growth rate of TFP. In Section 3.3.2, we show this result is robust to numerous modifications to our baseline approach. In Section 3.3.3, we show that data on GDP per capita, capital per capita, and labor are also consistent with the finding of level effects in Table 1.

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.[27] 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

[26] 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.

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

post-1990 dummies. Furthermore, 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 existing literature, which is subject to the same caveats.

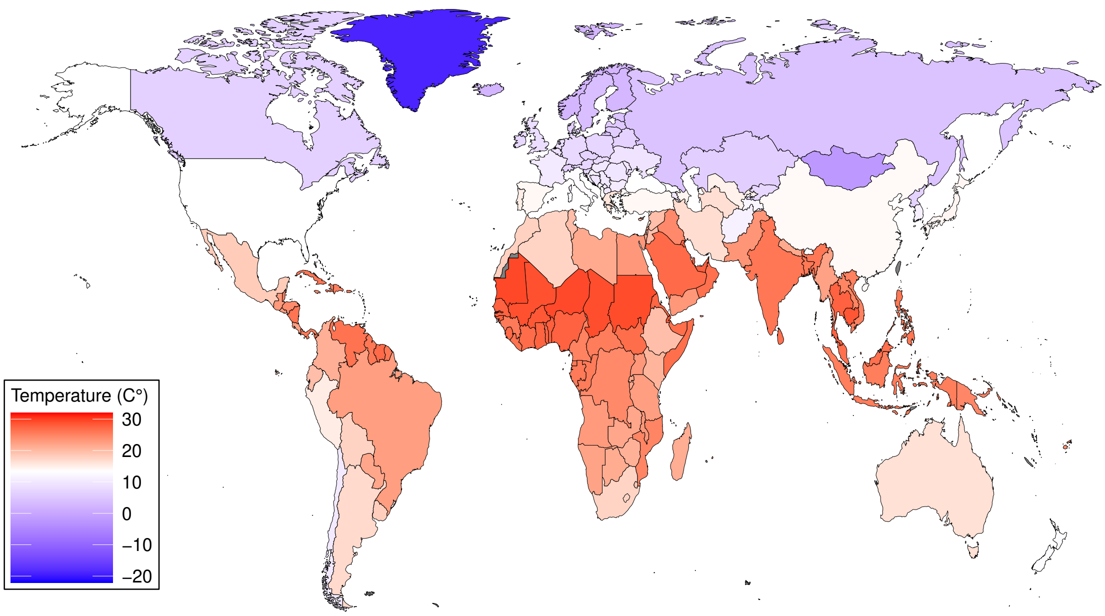
4.1 Data

The nonlinear relationship between temperature and TFP implies that the impact of higher temperatures from climate change will depend on both a country's initial temperature and on its projected change in temperature. Figure 2 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 13°C identified in Table 1, countries in red are hotter than the optimum, and countries in blue are colder than the optimum. Overall, the relatively wealthy countries 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.

We use country-specific projections of the change in temperature in each year from 2010 to 2100 that are consistent with the RCP 8.5 emissions scenario.[28] RCP 8.5 was

[28]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 2: Average Annual Temperature in 2010

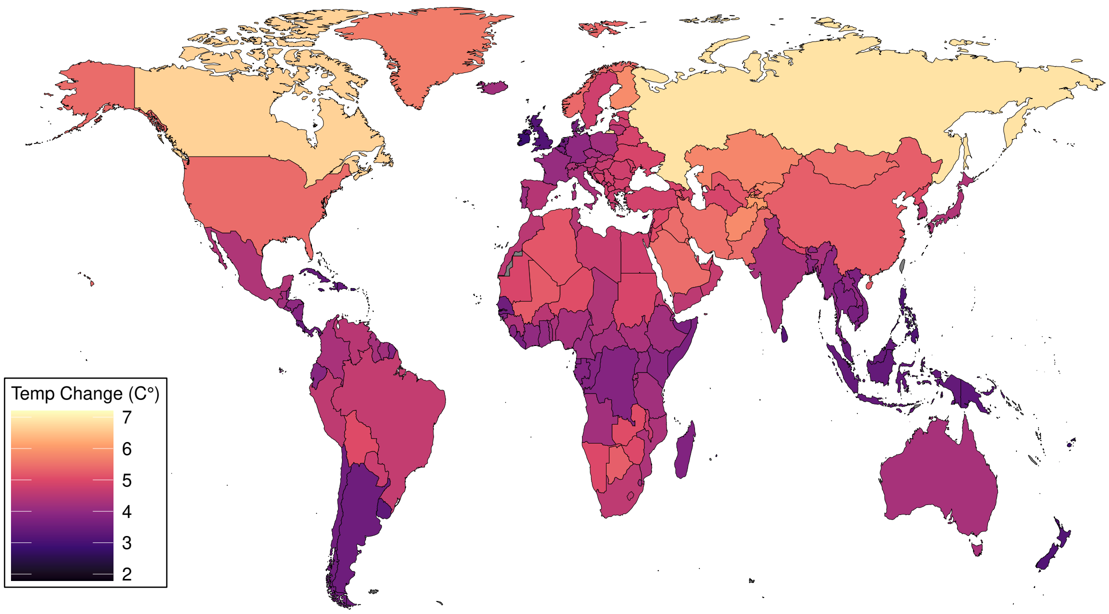


Note: The lightest color corresponds to the optimal temperature from column 2 of Table 1.

originally developed to project global emissions in the absence of wide-spread climate policy. Figure 3 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 (country-specific) 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, which is equal to the average population growth rate from the Penn World Tables (Feenstra et al., 2015).

Figure 3: 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.

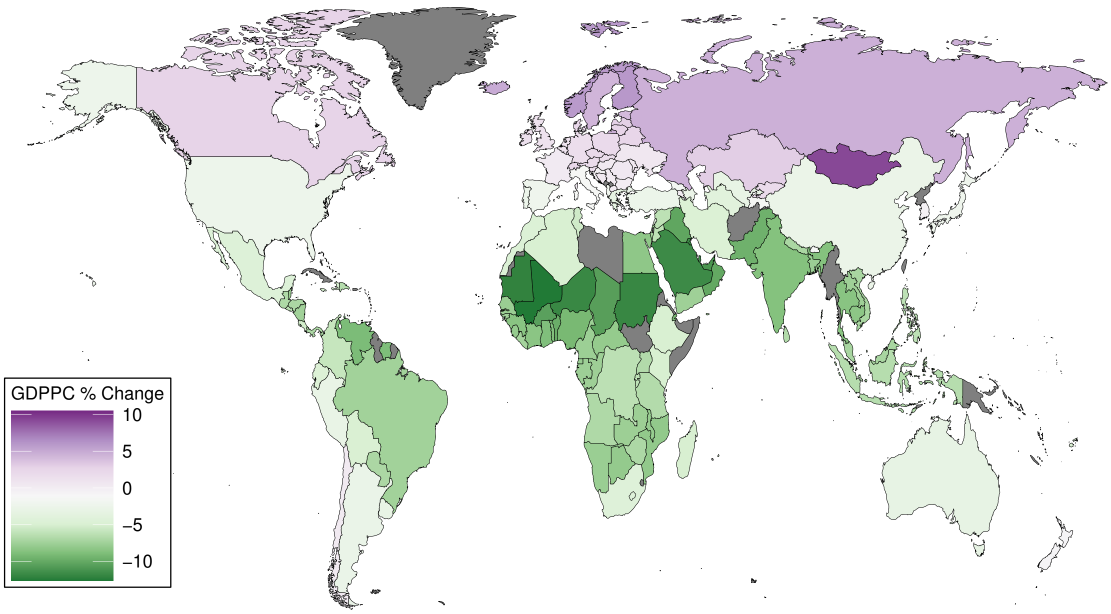
4.2 Method

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 following equation forward,

$$\Delta a_{it} = \hat{\beta}_1 \Delta T_{it} + \hat{\beta}_2 \Delta T_{it}^2 + \hat{\xi}_1 \overline{\Delta P}_i + \hat{\xi}_2 \overline{\Delta P}_i^2 + \hat{\rho} \Delta a_{it-1} + \hat{g}_i + \hat{\bar{u}}, \tag{14}$$

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 to 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 (14). 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 specification from (9) and (10). In

Figure 4: 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.

the climate-change simulation, we feed in the projected time path of TFP from (14), using the temperature projections consistent with RCP 8.5. In the no-climate change simulation, we feed in the projected time path of TFP from (14) 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.[29]

4.3 Results

Figure 4 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 of temperature affects the level of TFP. They find that 2100 GDP per capita in low-income economies like Brazil and India would be approximately 8 percent lower 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.[30] 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 United States and increases output per capita by 0.4 percent in France.

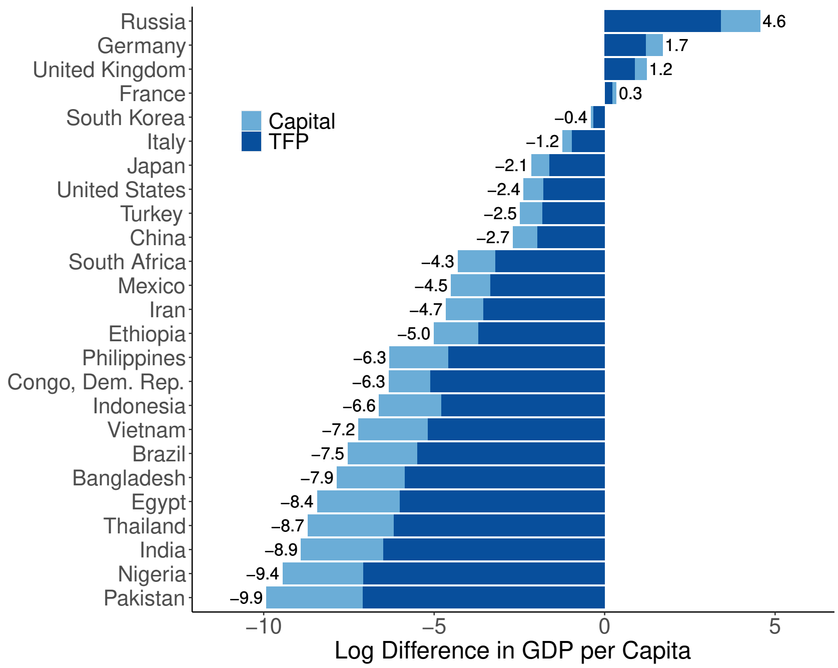
Figure 5 decomposes the simulated impact of climate change on GDP per capita into the impact on capital per capita and TFP for the 25 most populous countries. We use $\Delta \ln(Y_{it}/N_{it}) = \Delta \ln A_{it} + \alpha \Delta \ln(K_{it}/N_{it})$ to calculate the decomposition. Changes in TFP account 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 6 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

[29] A key contribution of our approach is to project the future impacts of climate change in a Solow-style model that maintains the distinction between transition (temporary) and steady state (permanent) growth in income per capita. One drawback of using a Solow model is that our projections abstract from the impact of changes in productivity on the savings rate.

[30] 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 5: Decomposition of Climate Impacts



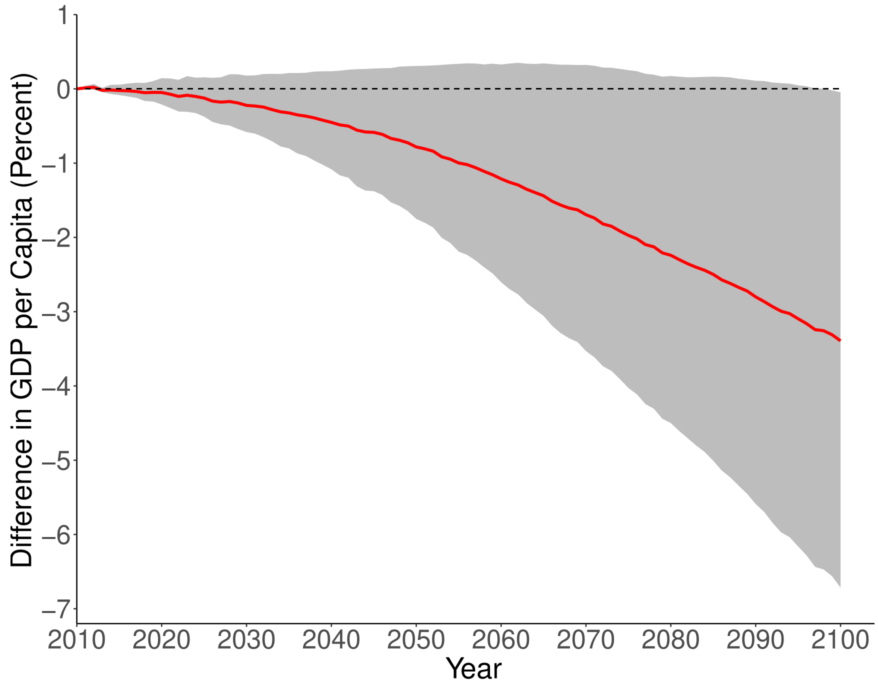
Note: This figure decomposes the simulated impact of climate change on GDP per capita into the impact on capital per capita and TFP for the 25 most populous countries. The projection is calculated using the level-effects specification in column 2 of Table 1.

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 6 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 per capita.

Figure 7 decomposes the effects of temperature on world GDP per capita into impacts on capital per capita 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 contribution of capital to the loss in GDP per capita increases over time from near zero in 2010 to 23 percent in 2100.

The projected effects we have presented so far 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 8 compares the projections using the

Figure 6: Impact of Climate Change on World GDP per Capita



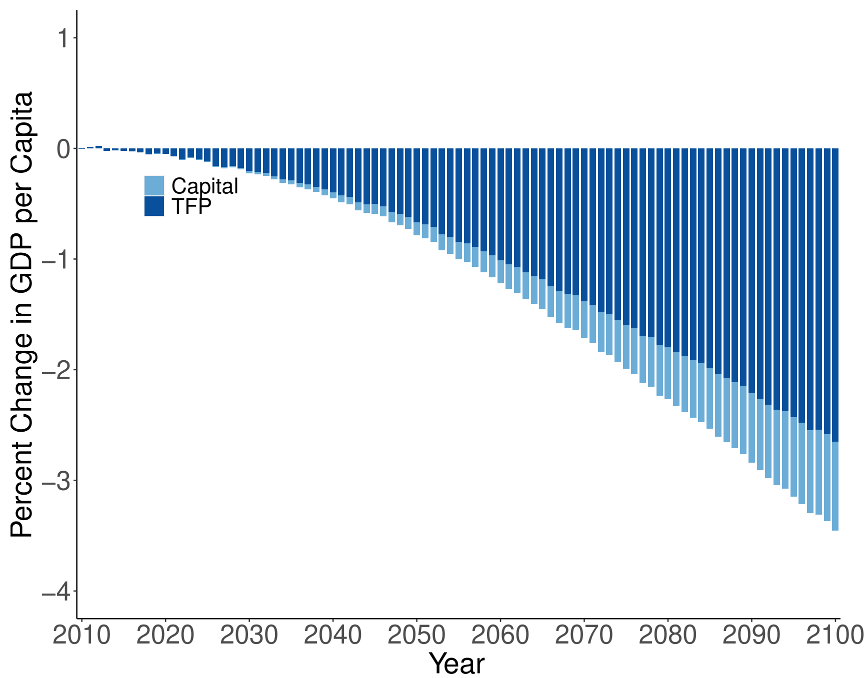
Note: The solid red line plots the impact of the temperature increase caused by climate change on global GDP per capita in each year from 2010-2100. The projection is calculated using the level-effects specification from column 2 of Table 1. The shaded gray region marks the boot-strapped 95 percent confidence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

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 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

Figure 7: Decomposition of Climate Impacts



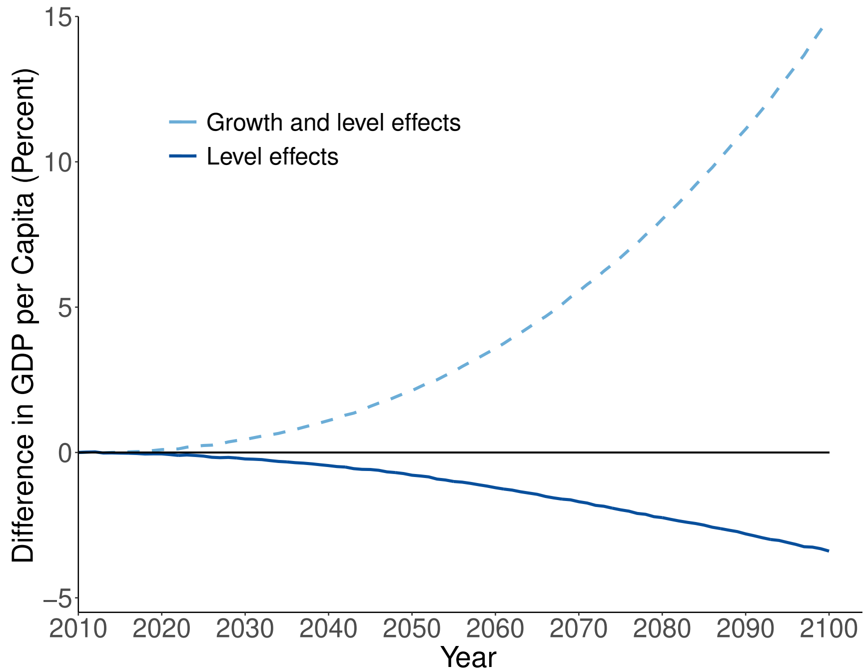
Note: This figure decomposes the simulated impact of climate change on GDP per capita into the impact on capital per capita and TFP for the world in each year from 2010 to 2100. The projection is calculated using the level-effects specification in column 2 of Table 1.

results, they find much larger output losses from future changes in temperature. 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 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 per capita as the dependent variable. The projection equation is

$$\Delta y_{it} = \hat{\gamma}_1 T_{it} + \hat{\gamma}_2 T_{it}^2 + \xi_1 \overline{\Delta P}_i + \xi_2 \overline{\Delta P}_i^2 + \hat{\rho} \Delta y_{it-1} + \hat{\hat{u}} + \hat{g}_i. \quad (15)$$

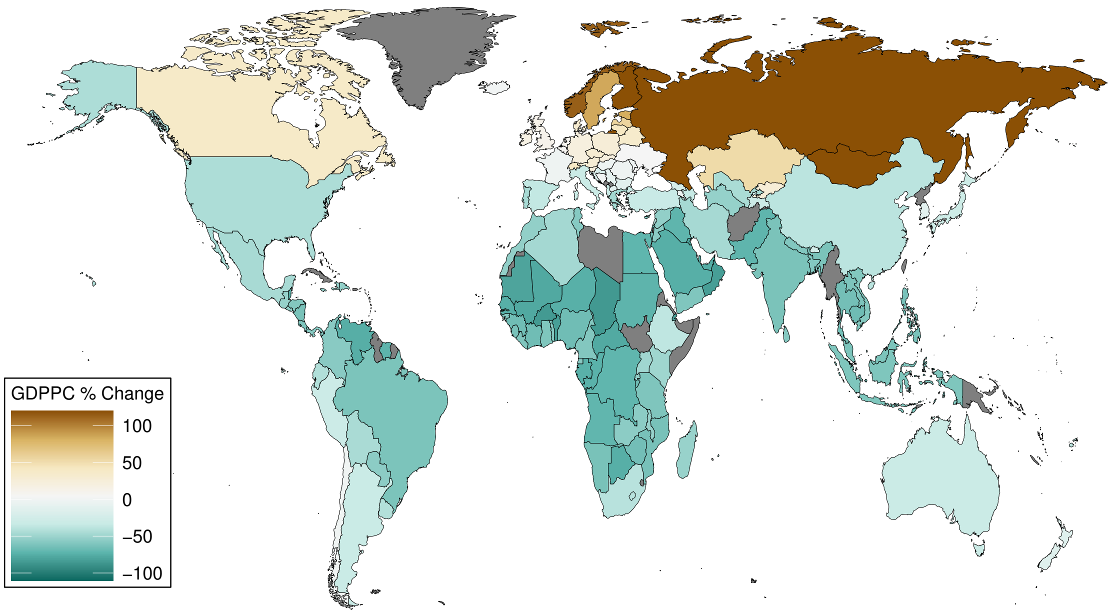
Figure 8: Comparison of the Impact of Climate Change on World GDP per Capita



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.

The results, presented in Figure 9, reveal much larger climate change impacts than the baseline results in Figure 4. For example, United States 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.

Figure 9: 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.

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 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 rising temperatures from climate change are smaller, but still substantial, when the impacts on growth are temporary, rather than permanent.

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Online Appendix
"Projecting the impact of rising temperatures: The role of macroeconomic dynamics"

By: Gregory Casey, Stephie Fried, and Ethan Goode

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: Main Results With Clustered Standard Errors

Dep. Variable: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp. : \gamma_1$	0.0036**		0.0015
	(0.0013)		(0.0014)
$Temp.^2 : \gamma_2$	-0.0002*		-0.0000
	(0.0001)		(0.0001)
$\Delta Temp. : \beta_1$		0.0104**	0.0095**
		(0.0033)	(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
	(0.0093)	(0.0091)	(0.0090)
$\Delta Precip.^2 : \xi_2$	-0.0008	-0.0004	-0.0004
	(0.0023)	(0.0022)	(0.0022)
$\Delta LnTFP_{t-1} : \rho$	0.1882***	0.1904***	0.1898***
	(0.0387)	(0.0388)	(0.0387)
N	6,654	6,654	6,654
Adj. R-squared	0.12	0.12	0.12
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.0166		0.1169
$\beta_1 = \beta_2 = 0$ (p-value)		0.0008	0.0031
Optimal Temperature	11.06	13.09	

Note: The table reports the main results with heteroskedasticity-robust standard errors clustered at the country level. All specifications include country and year fixed effects. 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 Without the Lagged Dependent Variable

	(1)	(2)	(3)
Dep. Variable: $\Delta LnTFP$	Growth	Level	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. Heteroskedasticity-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 TFP Innovations

Dep. Variable: $\Delta LnTFP$ 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. Heteroskedasticity-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: Dynamic Panel Results

Dep. Variable: $\Delta LnTFP$	(1)	(2)	(3)	(4)	(5)	(6)
$Temp. : \gamma_1$	0.0031	0.0027			0.0011	0.0007
	(0.0017)	(0.0017)			(0.0019)	(0.0018)
$Temp.^2 : \gamma_2$	-0.0001	-0.0001			0.0000	0.0000
	(0.0001)	(0.0001)			(0.0001)	(0.0001)
$\Delta Temp. : \beta_1$			0.0077***	0.0061*	0.0071**	0.0057*
			(0.0023)	(0.0025)	(0.0026)	(0.0029)
$\Delta Temp.^2 : \beta_2$			-0.0003***	-0.0003**	-0.0003**	-0.0003**
			(0.0001)	(0.0001)	(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	0.0131	0.0132	0.0097	0.0096	0.0094	0.0092
	(0.0077)	(0.0077)	(0.0077)	(0.0077)	(0.0077)	(0.0076)
$\Delta Precip.^2 : \xi_2$	-0.0017	-0.0019	-0.0012	-0.0013	-0.0012	-0.0013
	(0.0019)	(0.0019)	(0.0019)	(0.0019)	(0.0019)	(0.0019)
$\Delta LnTFP_{t-1} : \rho_1$	0.1909	0.1474	0.1934	0.1503	0.1902	0.1458
	(0.1735)	(0.1931)	(0.1735)	(0.1928)	(0.1742)	(0.1939)
N	6,571	6,488	6,571	6,488	6,571	6,488
Kleibergen-Papp F-Stat	20.73	9.24	21.14	9.41	20.98	9.31
Hansen J-test		0.3463		0.3794		0.3841
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.1738	0.2661			0.4642	0.4195
$\beta_1 = \beta_2 = 0$ (p-value)			0.00	0.01	0.01	0.01

Note: The table reports the results from the dynamic panel IV in which we instrument for $\Delta \ln TFP_{t-1}$. In columns 1, 3, and 5 $\Delta \ln TFP_{t-2}$ is the only instrument. Columns 2, 4, 6 add $\Delta \ln TFP_{t-3}$ as a second instrument. All specifications include country and year fixed effects. Heteroskedasticity-robust standard errors, corrected for autocorrelation of order two, are in parentheses. Columns 1 and 2 are the specifications with only growth effects, columns 3 and 4 are the specifications with only level effects and columns 5 and 6 are the specifications with both growth and level effects. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table B5: Dynamic Panel First Stage Results

Dep. Variable: $\Delta LnTFP_{t-1}$	(1)	(2)	(3)	(4)	(5)	(6)
$\Delta LnTFP_{t-2} : \rho_2$	0.1823***	0.1656***	0.1832***	0.1662***	0.1824***	0.1654***
	(0.0400)	(0.0385)	(0.0399)	(0.0383)	(0.0398)	(0.0383)
$\Delta LnTFP_{t-3} : \rho_3$		0.0036		0.0051		0.0049
		(0.0315)		(0.0314)		(0.0313)
$Temp. : \gamma_1$	0.0010	-0.0002			0.0029	0.0017
	(0.0017)	(0.0018)			(0.0018)	(0.0018)
$Temp.^2 : \gamma_2$	0.0001	0.0001			-0.0000	0.0000
	(0.0001)	(0.0001)			(0.0001)	(0.0001)
$\Delta Temp. : \beta_1$			-0.0040	-0.0070**	-0.0056*	-0.0080**
			(0.0027)	(0.0026)	(0.0028)	(0.0027)
$\Delta Temp.^2 : \beta_2$			0.0003*	0.0003**	0.0003*	0.0003**
			(0.0001)	(0.0001)	(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	-0.0070	-0.0089	-0.0030	-0.0054	-0.0034	-0.0058
	(0.0077)	(0.0074)	(0.0080)	(0.0077)	(0.0080)	(0.0077)
$\Delta Precip.^2 : \xi_2$	0.0019	0.0021	0.0013	0.0016	0.0014	0.0017
	(0.0020)	(0.0019)	(0.0020)	(0.0019)	(0.0020)	(0.0019)
N	6,571	6,488	6,571	6,488	6,571	6,488

Note: The table reports the the first stage regression of the dynamic panel IV in which we instrument for $\Delta \ln TFP_{t-1}$. In columns 1, 3, and 5 $\Delta \ln TFP_{t-2}$ is the only instrument. Columns 2, 4, 6 add $\Delta \ln TFP_{t-3}$ as a second instrument. All specifications include country and year fixed effects. Heteroskedasticity-robust standard errors, corrected for autocorrelation of order two, are in parentheses. Columns 1 and 2 are the specifications with only growth effects, columns 3 and 4 are the specifications with only level effects and columns 5 and 6 are the specifications with both growth and level effects. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table B6: Results With Additional Dependent Variable Lags

Dep. Variable: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp. : \gamma_1$	0.0024		0.0003
	(0.0017)		(0.0018)
$Temp.^2 : \gamma_2$	-0.0001		0.0000
	(0.0001)		(0.0001)
$\Delta Temp. : \beta_1$		0.0078***	0.0076**
		(0.0021)	(0.0024)
$\Delta Temp.^2 : \beta_2$		-0.0003***	-0.0004***
		(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	0.0110	0.0077	0.0073
	(0.0076)	(0.0076)	(0.0075)
$\Delta Precip.^2 : \xi_2$	-0.0013	-0.0008	-0.0008
	(0.0019)	(0.0019)	(0.0018)
$\Delta LnTFP_{t-1} : \rho_1$	0.1549***	0.1570***	0.1565***
	(0.0397)	(0.0396)	(0.0396)
$\Delta LnTFP_{t-2} : \rho_2$	-0.0254	-0.0254	-0.0259
	(0.0339)	(0.0341)	(0.0341)
$\Delta LnTFP_{t-3} : \rho_3$	0.0277	0.0262	0.0261
	(0.0217)	(0.0216)	(0.0217)
$\Delta LnTFP_{t-4} : \rho_4$	-0.0305	-0.0301	-0.0304
	(0.0254)	(0.0255)	(0.0256)
N	6,405	6,405	6,405
Adj. R-squared	0.13	0.13	0.13
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.3536		0.5037
$\beta_1 = \beta_2 = 0$ (p-value)		0.0002	0.0005
Optimal Temperature	11.76	11.59	

Note: The table reports the main results with additional lags of the dependent variable. All specifications include country and year fixed effects. Heteroskedasticity-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: Mean Group Estimator Results

Dep. Variable: $\Delta LnTFP$	(1) Growth Mean	(2) Growth Median	(3) Level Mean	(4) Level Median	(5) Both Mean	(6) Both Median
$Temp. : \gamma_1$	-0.0029	-0.0015			-0.0060	-0.0056
	(1.1688)				(0.5103)	
$Temp.^2 : \gamma_2$	-0.0001	-0.0000			0.0001	0.0001
	(0.3116)				(0.0994)	
$\Delta Temp. : \beta_1$			0.0116	0.0130	0.0115	0.0106
			(1.2013)		(1.2390)	
$\Delta Temp.^2 : \beta_2$			-0.0004	-0.0004	-0.0004	-0.0005
			(0.2053)		(0.2261)	
$\Delta Precip. : \xi_1$	0.0514*	0.0459	0.0438	0.0448	0.4554	0.0416
	(1.3072)		(1.5329)		(1.4515)	
$\Delta Precip.^2 : \xi_2$	-0.0175	-0.0176	-0.0175	-0.0132	-0.0168	-0.0126
	(0.9652)		(0.9698)		(0.9946)	
$\Delta LnTFP_{t-1} : \rho$	0.2608***	0.2676	0.3482***	0.3517	0.2696***	0.2763
	(0.1002)		(0.0744)		(0.0982)	
N	6,654	6,654	6,654	6,654	6,654	6,654

Note: The table reports the results using the Bond et al. (2010) generalization of the Pesaran and Smith (1995) mean group estimator. In this approach, separate time series regressions are run for each country. Columns 1, 3, and 5 report robust estimates of the mean of the temperature coefficients across each of the regressions. Columns 2, 4, 6 report the median of the coefficients. Columns 1 and 2 correspond to the specification with only growth effects, columns 3 and 4 correspond to the specification with only level effects, and columns 5 and 6 correspond to the specification with both growth and level effects. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table B8: Results With Linear Time Trends

Dep. Variable: $\Delta LnTFP$	(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)
$\Delta LnTFP_{t-1} : \rho_1$	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. Heteroskedasticity-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: Results With Quadratic Time Trends

Dep. Variable: $\Delta LnTFP$	(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)
$\Delta LnTFP_{t-1}: \rho_1$	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. Heteroskedasticity-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: Results With Region-by-Year Fixed Effects

Dep. Variable: $\Delta LnTFP$	(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)
$\Delta LnTFP_{t-1} : \rho_1$	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. Heteroskedasticity-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 Post-1990 Dummies

Dep. Variable: $\Delta LnTFP$	(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)
$\Delta LnTFP_{t-1}: \rho_1$	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 when 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. Heteroskedasticity-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 B12: Results With More Lags of Temperature

Dep. Variable: $\Delta LnTFP$	(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 lags of temperature in columns 1-4, respectively. All specifications include country and year fixed effects. Heteroskedasticity-robust standard errors, corrected for autocorrelation of order two, are in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table B13: Results With Penn World Tables Measure of TFP

	(1)	(2)	(3)
Dep. Variable: $\Delta LnTFP$	Growth	Level	Both
$Temp. : \gamma_1$	0.0015		-0.0033
	(0.0026)		(0.0028)
$Temp.^2 : \gamma_2$	-0.0000		0.0002
	(0.0001)		(0.0001)
$\Delta Temp. : \beta_1$		0.0057**	0.0074**
		(0.0022)	(0.0025)
$\Delta Temp.^2 : \beta_2$		-0.0003**	-0.0004***
		(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	-0.0055	-0.0100	-0.0106
	(0.0082)	(0.0082)	(0.0082)
$\Delta Precip.^2 : \xi_2$	0.0027	0.0033	0.0033
	(0.0019)	(0.0019)	(0.0019)
$\Delta LnTFP_{t-1} : \rho$	0.1125*	0.1154*	0.1140*
	(0.0486)	(0.0483)	(0.0481)
N	4,509	4,509	4,509
Adj. R-squared	0.09	0.10	0.10
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.6642		0.2159
$\beta_1 = \beta_2 = 0$ (p-value)		0.0055	0.0006
Optimal Temperature	17.00	9.09	

Note: The table reports the results with the Penn World Tables measure of TFP (rtfpna) as the dependent variable. All specifications include country and year fixed effects. Heteroskedasticity-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 B14: Heterogeneity by Level of Development

Dep. Variable: $\Delta LnTFP$	(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)
$\Delta LnTFP_{t-1} : \rho_1$	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. Heteroskedasticity-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 B15: Heterogeneity by Economic Structure

	(1)	(2)	(3)
Dep. Variable: $\Delta LnTFP$	Growth	Level	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)
$\Delta LnTFP_{t-1} : \rho_1$	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 agricultural and non-agricultural economies. We define an economy as agricultural if the share of value added from agriculture is above the median in 2010, and non-agricultural otherwise. All specifications include country and year fixed effects. Heteroskedasticity-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 B16: Heterogeneity by Temperature

Dep. Variable: $\Delta LnTFP$	(1) Growth	(2) Level	(3) Both
$Temp_t$	0.0049		-0.0021
	(0.0042)		(0.0050)
$Temp_t^2$	0.0001		0.0004
	(0.0004)		(0.0004)
$\Delta Temp. : \beta_1$		0.0123^{***}	0.0131^{**}
		(0.0036)	(0.0045)
$\Delta Temp.^2 : \beta_2$		0.0004	0.0001
		(0.0015)	(0.0016)
$Temp. \times \bar{T} : \gamma_1^{\bar{T}}$	-0.0004		0.0001
	(0.0004)		(0.0004)
$Temp.^2 \times \bar{T} : \gamma_2^{\bar{T}}$	-0.0000		-0.0000
	(0.0000)		(0.0000)
$\Delta Temp. \times \bar{T} : \beta_1^{\bar{T}}$		-0.0018	-0.0016
		(0.0032)	(0.0033)
$\Delta Temp.^2 \times \bar{T} : \beta_2^{\bar{T}}$		0.0000	0.0000
		(0.0000)	(0.0000)
$\Delta Precip.$	0.0086		0.0049
	(0.0080)		(0.0079)
$\Delta Precip.^2$	-0.0009		-0.0003
	(0.0019)		(0.0019)
$\Delta LnTFP_{t-1}$	0.1879^{***}	0.1904^{***}	0.1895^{***}
	(0.0386)	(0.0385)	(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)	0.2863		0.6994
$\beta_1 = \beta_2 = 0$ (p-value)		0.0024	0.0134
$\gamma_1^{\bar{T}} = \gamma_2^{\bar{T}} = 0$ (p-value)	0.3462		0.8776
$\beta_1^{\bar{T}} = \beta_2^{\bar{T}} = 0$ (p-value)		0.8396	0.6503

Note: The table reports the results when we interact annual temperature with average temperature over the period ($\bar{T}$), along the lines of Carleton et al. (2022). All specifications include country and year fixed effects. Heteroskedasticity-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 B17: Results With Temperature Interactions

Dep. Variable: $\Delta LnTFP$	(1)
$Temp_{t-1}$	-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. Heteroskedasticity-robust standard errors, corrected for autocorrelation of order two, are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

Table B18: GDP per Capita Results With Quadratic Time Trends

Dep. Variable: $\Delta LnGDPPC$	(1)	(2)	(3)	(4)	(5)	(6)
$Temp. : \gamma_1$	0.0076*	0.0075*			0.0025	0.0015
	(0.0032)	(0.0032)			(0.0045)	(0.0044)
$Temp.^2 : \gamma_2$	-0.0004**	-0.0004**			-0.0002	-0.0002
	(0.0001)	(0.0001)			(0.0002)	(0.0002)
$\Delta Temp. : \beta_1$			0.0075**	0.0081**	0.0061	0.0072*
			(0.0025)	(0.0026)	(0.0035)	(0.0036)
$\Delta Temp.^2 : \beta_2$			-0.0003***	-0.0003***	-0.0002	-0.0002
			(0.0001)	(0.0001)	(0.0001)	(0.0001)
$\Delta Precip. : \xi_1$	0.0064	0.0069	0.0047	0.0049	0.0054	0.0056
	(0.0079)	(0.0078)	(0.0077)	(0.0078)	(0.0076)	(0.0077)
$\Delta Precip.^2 : \xi_2$	-0.0005	-0.0006	-0.0002	-0.0003	-0.0004	-0.0004
	(0.0019)	(0.0019)	(0.0019)	(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	6,654	6,654	6,654
Adj. R-squared	0.24	0.24	0.24	0.24	0.24	0.24
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.0096	0.0073			0.2040	0.2190
$\beta_1 = \beta_2 = 0$ (p-value)			0.0022	0.0006	0.2170	0.1168
Optimal Temperature	9.76	9.57	12.03	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. Heteroskedasticity-robust standard errors, corrected for autocorrelation of order two, are in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table B19: Results With Capital as the Dependent Variable

Dep. Variable: $\Delta LnKPC$	(1)	(2)	(3)
$Temp. : \gamma_1$	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. Heteroskedasticity-robust standard errors, corrected for autocorrelation of order two, are in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

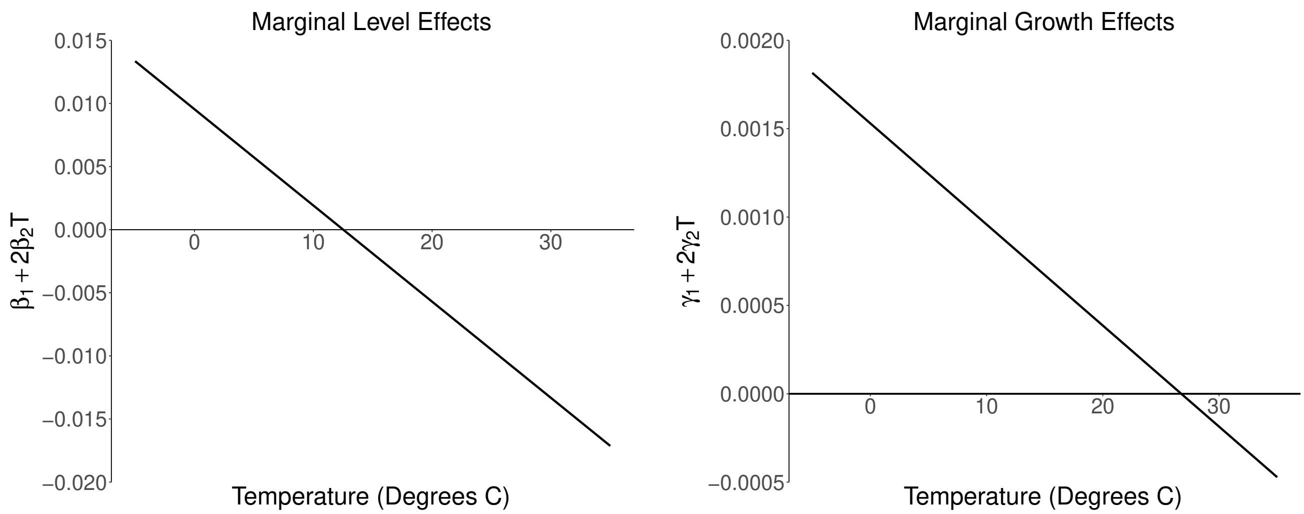
Table B20: Results With Labor as the Dependent Variable

Dep. Variable: ΔLnL	(1)	(2)	(3)
$Temp. : \gamma_1$	-0.0004		-0.0004
	(0.0009)		(0.0010)
$Temp.^2 : \gamma_2$	0.0000		0.0000
	(0.0000)		(0.0000)
$\Delta Temp. : \beta_1$		0.0004	0.0007
		(0.0018)	(0.0020)
$\Delta Temp.^2 : \beta_2$		-0.0000	-0.0000
		(0.0000)	(0.0001)
$\Delta Precip. : \xi_1$	0.0000	0.0000	0.0000
	(0.0036)	(0.0036)	(0.0036)
$\Delta Precip.^2 : \xi_2$	-0.0003	-0.0003	-0.0003
	(0.0008)	(0.0008)	(0.0008)
N	6,232	6,232	6,232
Adj. R-squared	0.44	0.44	0.44
$\gamma_1 = \gamma_2 = 0$ (p-value)	0.9232		0.9165
$\beta_1 = \beta_2 = 0$ (p-value)		0.9665	0.9437
Optimal Temperature	12.36	27.76	

Note: The table reports the results with the log of employment per capita as the dependent variable. All specifications include country and year fixed effects. Heteroskedasticity-robust standard errors, corrected for autocorrelation of order two, are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

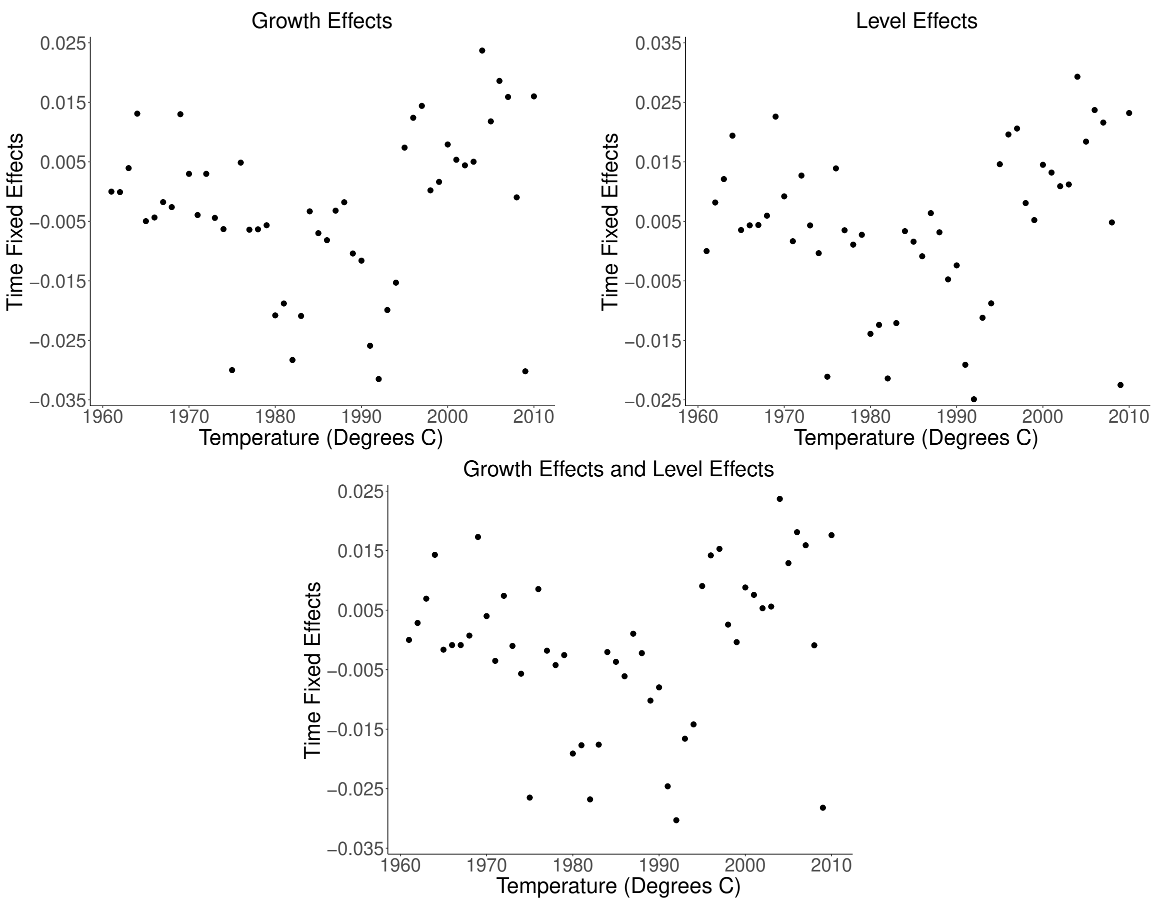
C Additional Figures

Figure C1: Marginal Effects



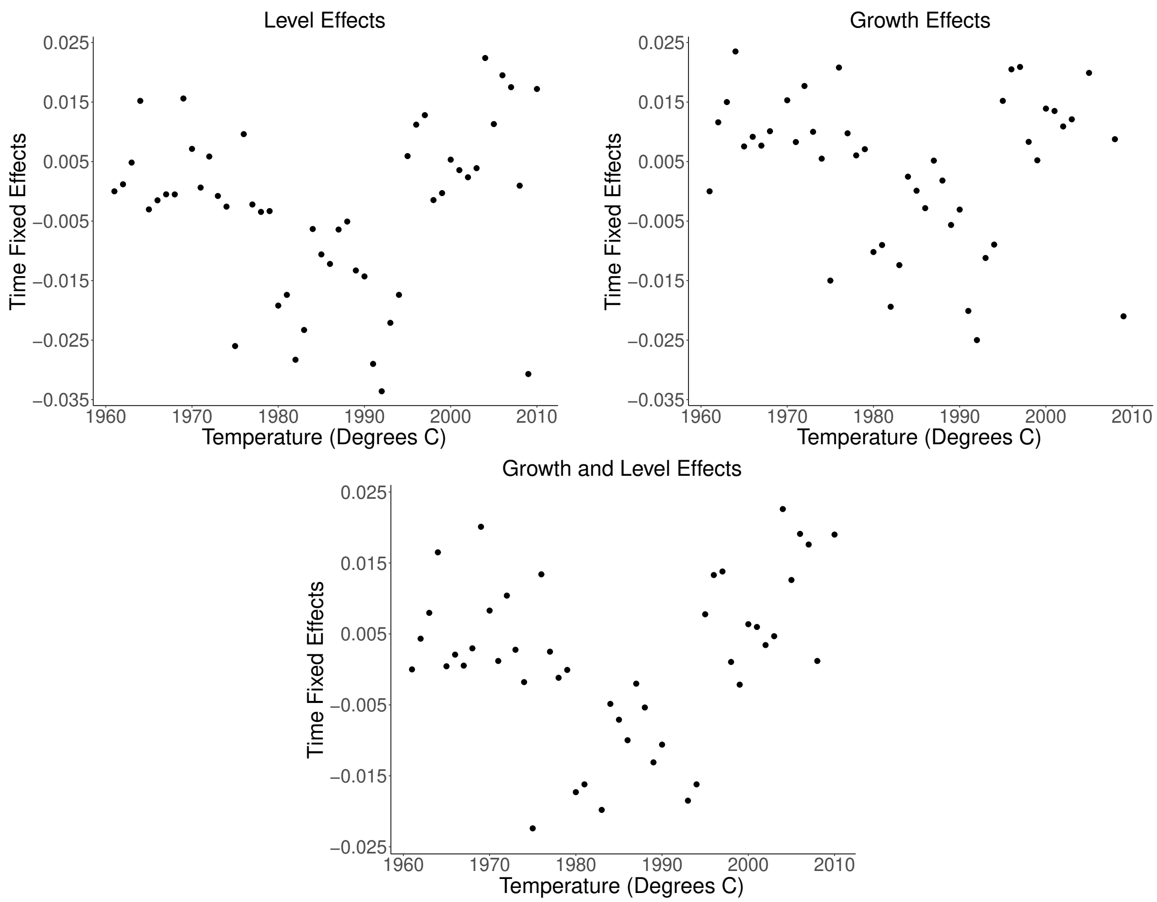
Note: The figure plots the marginal level effects (left column) and the marginal growth effects (right column) from the specification with both level and growth effects in the main results (column 3 of Table 1).

Figure C2: Main Results: Time Fixed Effects



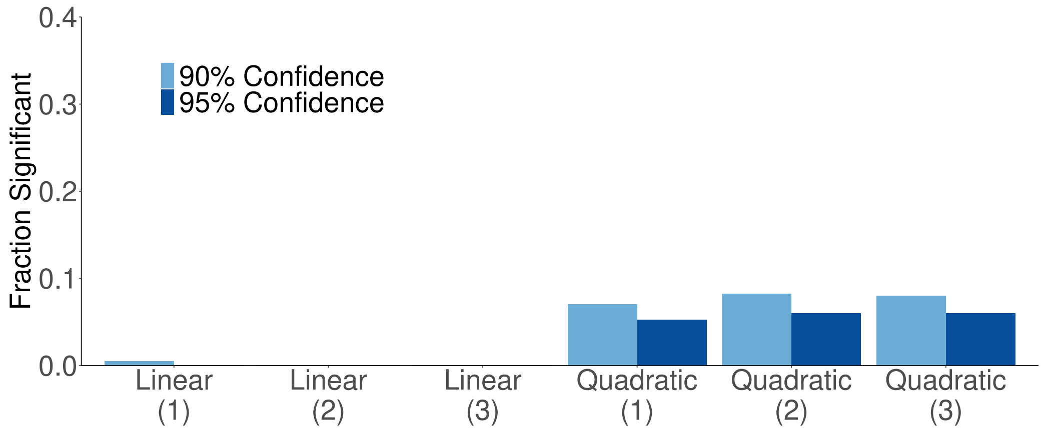
Note: The figure plots the time fixed effects for the regression estimates reported in Table 1. The top left panel corresponds to column 1, the top right panel corresponds to column 2, and the bottom panel corresponds to column 3.

Figure C3: GDP per Capita Results: Time Fixed Effects



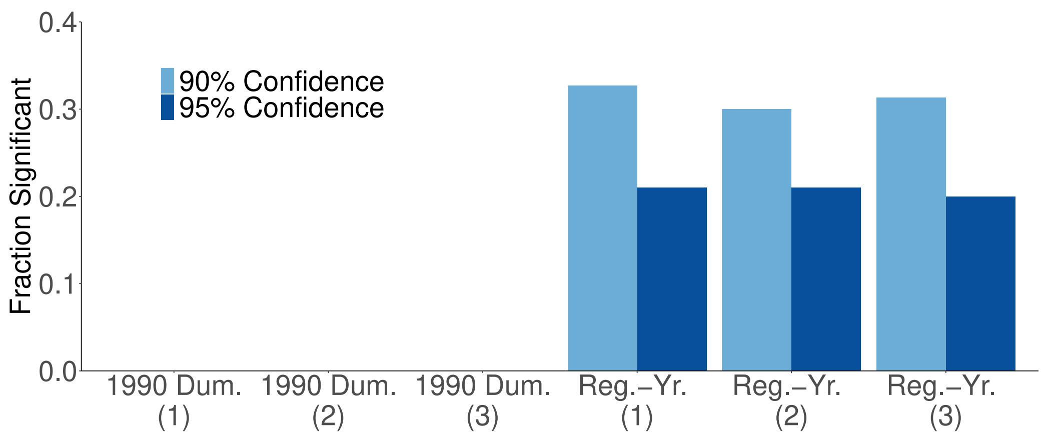
Note: The figure plots the time fixed effects for the regression estimates reported in Table 2 for the specifications that include the lagged dependent variable. The top left panel corresponds to column 1, the top right panel corresponds to column 2, and the bottom panel corresponds to column 3.

Figure C4: Fraction of Statistically Significant Trends



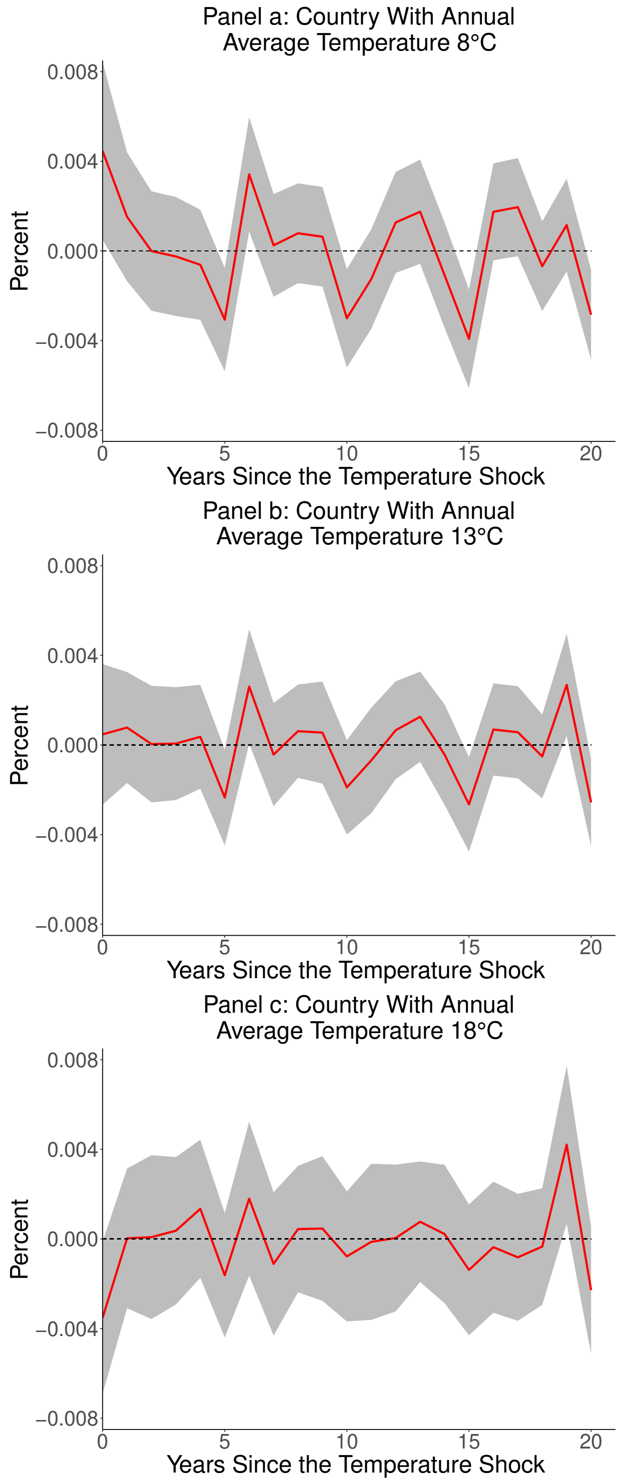
Note: The first three bar-groups show the fraction of country-specific linear trends that are statistically significant at the five (dark blue) and ten (light blue) percent levels for the estimates in Table B8. The second three bar-groups show the fraction of country-specific trends (linear or quadratic) that are statistically significant at the five (dark blue) and ten (light blue) percent levels for the estimates in Table B9. 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 B11. 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 B10. The numbers in parentheses indicate the column from the corresponding table.

Figure C6: The Response of TFP Growth to a Temperature Shock



Note: Panels a, b, and c plot the impulse response of TFP growth to a temperature shock in period zero, in countries with an annual average temperature equal to 8°C, 13°C, and 18°C, respectively. We use local projections to estimate the impulse response (Jordà, 2005). The shaded grey region denotes the 95 percent confidence interval calculated using robust standard errors corrected for autocorrelation of order two.