Projecting the impacts of temperature change: The role of macroeconomic dynamics

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

[a]Williams College

[b]Federal Reserve Bank of San Francisco

June 2022

Abstract

We use theory and empirics to distinguish between the impact of temperature on transition (temporary) and steady state (permanent) growth in output per capita. Using insights from growth theory, we show that the short-run impact of a change in temperature on economic growth is not informative about the long-run impact because of endogenous capital dynamics. Based on this insight, we examine the short-run impact of temperature on total factor productivity (TFP). This approach accounts for capital dynamics and is informative about the long-run impact of temperature on economic growth. While there is uncertainty, our estimates suggest that a change in temperature will have a temporary, but not a permanent, impact on growth in output per capita. We use our empirical estimates and theoretical framework to project the impacts of future temperature changes due to climate change. We find substantial output losses from climate change, but these losses are smaller than the projected losses in the existing empirical literature, which assumes that a change in temperature permanently affects economic growth.

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

1 Introduction

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

Macroeconomic climate-economy models almost always assume that temperature has a level effect (e.g., Nordhaus and Boyer, 2003; Golosov et al., 2014; Barrage, 2020; Hassler et al., 2019). For example, the damage functions in these models imply that a 3°C increase in global average temperature will decrease economic output by approximately 2 percent (Nordhaus and Moffat, 2017).[1] In contrast, a smaller empirical literature, beginning with Dell et al. (2012), argues that temperature has a growth effect. In an influential study, Burke et al. (2015) project the reduced-form estimates of the growth effect forward and find future climate damages that are an order of magnitude larger than what most macroeconomic climate-economy models suggest.[2]

The difference in outcomes between these two approaches has important policy implications. If temperature has a growth effect, then optimal carbon taxes are likely to be much higher than if temperature only has a level effect (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. (2018) on growth effects to argue that policy should be aimed at keeping global average temperature change below 1.5°C, instead of the more commonly cited 2°C target (Masson-Delmotte et al., 2018). Understanding the impacts of climate change is also essential for designing

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

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

government policies that assist adaptation (Fankhauser, 2017).

In this paper, we revisit the level versus growth effects debate while paying special attention to the distinction between permanent and temporary changes in economic growth following a productivity shock. As in the existing empirical literature, we focus on temperature shocks only and abstract from other climate impacts. Our analysis has four steps. First, we present a simple model which we use to study the different dynamic implications of growth and level effects. A key implication of the model is that the short-run behavior of total factor productivity (TFP) is informative about the long-run behavior of output per capita. Second, drawing on intuition from the model, we empirically investigate the impact of temperature on TFP. Third, we combine our empirical results with an extended version of the model to project the impacts of future changes in temperature. Fourth, we compare our findings to the influential empirical literature that projects the impacts of future changes in temperature from reduced-form estimates.

The simple model integrates level and growth effects of temperature into an otherwise standard Solow (1956) model. We use the model to demonstrate that, even though level and growth effects have very different predictions for the long-run impact of temperature on output per capita, they have similar short-run predictions. The similar short-run predictions make it hard to distinguish between level and growth from annual panel data on GDP and temperature as the previous literature has done. In particular, even if temperature has a level effect on GDP per capita, it will still affect the growth rate of GDP per capita in the short run, as capital adjusts to the new productivity level (Fankhauser and Tol, 2005; Moore and Diaz, 2015; Letta and Tol, 2019). Unlike GDP per capita, the short-run behavior of TFP is informative about the long-run relationship between temperature and GDP per capita, because it avoids complications caused by capital dynamics.

Based on this insight, we empirically investigate whether the level of temperature affects the level or the growth rate of TFP. As in the existing literature that uses GDP per capita as the dependent variable, we focus on annual variation in average temperature in a country-year panel. We draw on Bond et al. (2010) to distinguish between the changes in the level and growth rate of TFP. Thus, our analysis is similar to the important work of Dell et al. (2012), who also use the Bond et al.

(2010) methodology to study growth and level effects of temperature. We build on their work in two ways. First, drawing on the insights from the simple model, we use TFP as our dependent variable, instead of GDP per capita. Second, we incorporate non-linear impacts of temperature following Burke et al. (2015). Overall, the evidence suggests that temperature affects the level of TFP, but not the growth rate of TFP. Thus, the historical data suggest that temperature has a level effect on GDP per capita, but not a growth effect.[3]

To understand the quantitative implications of these results, we use our estimates and model to project the impact of future temperature changes on GDP per capita around the world. We combine projections of future temperature from climate models with our regression estimates to construct reduced-form projections for TFP in scenarios with and without climate change. To capture capital dynamics, we simulate the extended Solow (1956) model under our projected climate-change and no-climate-change time paths of TFP. We measure the impact of climate change on GDP per capita as the difference between the model simulations with and without climate change. Our results suggest that, under Representative Concentration Pathway (RCP) 8.5 (Meinshausen et al., 2011), future changes in temperature will reduce global GDP by 3.4 percent with a 95 percent confidence interval of (-6.71, -0.05).[4] This aggregate number masks considerable heterogeneity. Given the non-linear impact of temperature on TFP growth, hotter countries are more negatively impacted by climate change. For example, GDP per capita falls by 8.5 percent in India, a relatively hot country, but only by 2.3 percent in the US, a comparatively colder country.

While our projected impacts of future changes in temperature on GDP per capita are substantial, they are significantly smaller than those from the existing empirical literature. For example, Burke et al. (2015) find that changes in temperature consistent with RCP 8.5 would decrease world GDP by approximately 20 percent.

[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 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).

The key force behind this difference is the distinction between transition and steady state growth (i.e., between level and growth effects). The numbers cited in influential policy reports come from specifications that implicitly assume all short-run variation in GDP per capita following a change in temperature is due to growth effects.[5] Our analysis of historical data suggests that the short-run impact of temperature on GDP per capita growth is instead due to level effects. In other words, we find that the effects of temperature on growth in income per capita are temporary, while the numbers cited in policy reports assume the effects are permanent (Masson-Delmotte et al., 2018).

It is important to highlight the scope of our analysis. We follow the existing literature and focus only on changes in annual average temperature at the country level. As a result, our projections do not include (i) other climate impacts that are orthogonal to temperature like sea level rise and natural disasters (e.g., Hsiang and Jina, 2014; Bakkensen and Barrage, 2018; Bernstein et al., 2019), (ii) the impacts of more finely grained temperature variation like daily or seasonal fluctuations (e.g., Schlenker and Roberts, 2009; Colacito et al., 2019), or (iii) the distributional impacts of temperature. Moreover, by estimating the historical impacts of temperature in an annual panel and using the estimates to project forward, we assume that the relationship between temperature and TFP is stable over time. Thus, we abstract from the possibility of future improvements in adaptation technology, which weaken the link between temperature and TFP (Pindyck, 2013). We also do not consider interactions between current and past temperatures. After several years of above-trend temperature, an additional hot year might have a smaller effect because individuals and firms have learned how to adapt, or a larger effect because of depleted adaptation capital (Lemoine, 2020). Our goal in this paper is to draw connections between macroeconomic theory and the existing empirical literature on temperature and output, which is already influential in policy circles. Extending the climate projections to incorporate some of these broader issues is an important topic for future research.

Related Literature. Our paper is related to several important strands of the existing literature. Our econometric methodology builds closely off of Bond et al. (2010),

[5] Importantly, the underlying papers also include specifications that allow for both growth and level effects in robustness analyses.

Dell et al. (2012), and Burke et al. (2015, 2018). 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). Our paper is closely related to a subset of this literature focusing on growth versus level effects. Newell et al. (2021) conduct sensitivity analyses based on the regression specification from Burke et al. (2015) and show that the estimates of the growth effects are imprecise. They focus on GDP, rather than TFP. Bastien-Olvera and Moore (2021) estimate level versus growth effects with low frequency temperature variation and find evidence for level effects.[6] A key focus of our paper is estimating the impacts of temperature in a manner that accounts for capital dynamics. Kahn et al. (2021) account for capital dynamics in a setting that assumes that temperature has a level effect on TFP. 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. Letta and Tol (2019) project the impacts of temperature on TFP assuming only level effects. The 2017 World Economic Outlook report from the IMF (Acevedo et al., 2017) projects the impact of temperature change on GDP per capita, assuming that temperature affects the level of TFP. More generally, our approach is related to integrated assessment models that use growth models to 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

[6]Due to differences in terminology between the environmental science and macroeconomics literatures, they refer to a permanent change in the level of GDP as a growth effects and use level effect to refer to a case where a permanent change in temperature has no impact on the long-run level of GDP and instead only affects the level of GDP temporarily.

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

climate change (e.g., Moore and Diaz, 2015; Dietz and Stern, 2015).

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 total factor productivity in a country-year panel. In Section 4, we project the impacts of future changes in temperature. In Section 5, we compare our findings to the earlier literature. Section 6 concludes.

2 Background and Motivation

We discuss a simple model to highlight the importance of macroeconomic dynamics for understanding the effects of temperature shocks on the level and growth rate of output per capita. We use the model to derive theoretically consistent equations that can separate these growth and level effects in the historical data. Finally, we discuss the connections between our approach and the existing influential 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

Permanent changes in temperature could have temporary or permanent effects on the growth rate of output per capita. We use the term *level effect* to reference the case in which a permanent change in temperature has a temporary effect on the growth rate of output, and the term *growth effect* to reference the case in which a permanent change in temperature has a permanent effect on the growth rate of output.[8]

[8]Since we are focused on long-run increases in temperature from climate change, our definitions of growth and level effects focus on permanent changes in temperature. However, we can also consider how a temporary change in temperature would affect the level and growth rate of GDP in both cases. In particular, a temporary change in temperature will have a temporary impact on the growth rate of output, regardless of whether there are level or growth effects. A temporary change in

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 (temporary) and steady state (permanent) economic growth.

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

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

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

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

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

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

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

temperature will have a permanent effect on the level of GDP per capita if there are growth effects and no impact on the long-run level of GDP per capita if there are level effects. While we focus on the long-run trends, the short-run volatility of temperature could be important for designing stabilization policy (Kiley, 2021).

of TFP from period t to period $t+1$. We refer to D_g as the growth-effect damage function. Function $D_l : \mathbb{R}_+ \to [0,1]$ describes the relationship between climate in period t and the level of TFP in period t, conditional on $\tilde{A}_t$. We refer to D_l as the level-effect damage function.

To compare the implications of the level- and growth-effect damage functions, we use the simple model to analyze a one-time, permanent increase in temperature. We study the two extreme cases: (1) climate change only affects the level of TFP, implying that $D_g = 0\ \forall T$, and (2) climate change only affects the growth rate of TFP, implying that $D_l = 1\ \forall T$.

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

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

In sum, endogenous capital dynamics imply that the level- and growth-effect damage functions yield similar short-run predictions for output per capita following a temperature shock, even though the long-run predictions are different. The similarity makes it difficult to distinguish between level and growth effects from the short-run response of GDP per capita to temperature. In contrast, the short-run response of TFP to a temperature shock is indicative of the long-run behavior of GDP per capita. These observations suggest that estimating the effects of temperature on TFP, instead of on GDP per capita, can circumvent the issues posed by endogenous capital dynamics and better distinguish between level and growth effects.

2.2 Empirical Strategy

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

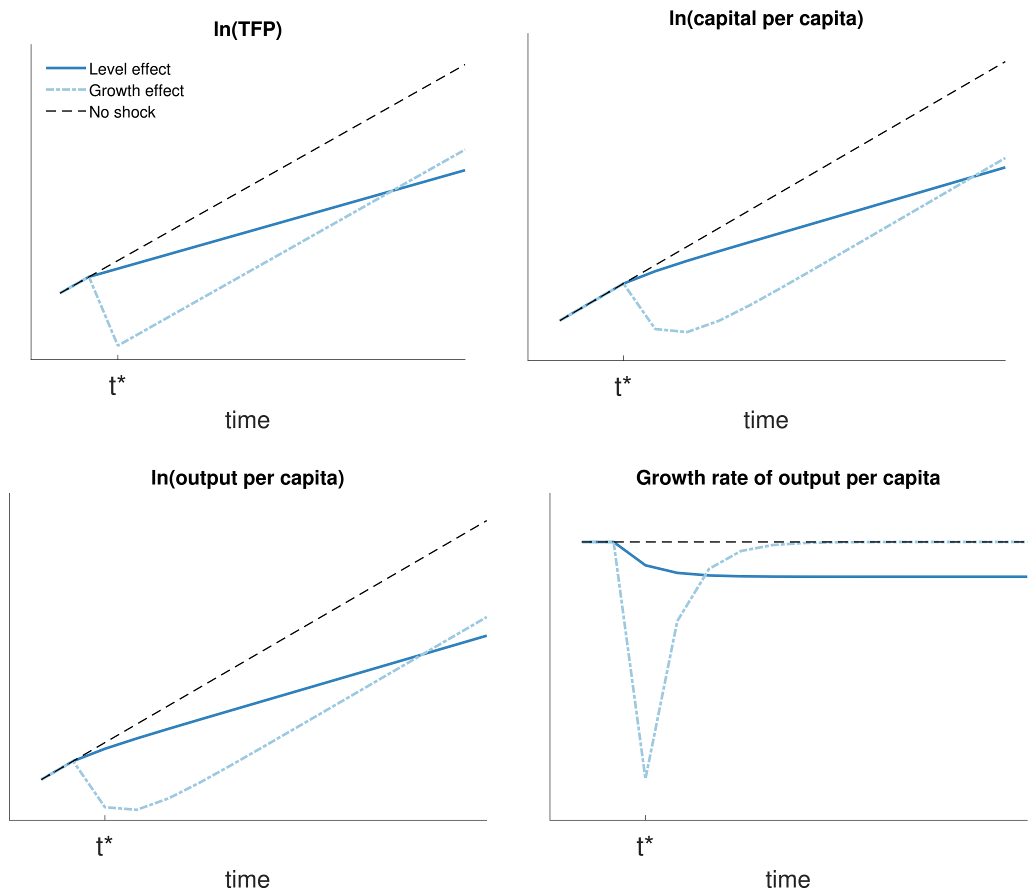
In this setting, $Y_{it} = e^{\beta T_{it}} \tilde{A}_{it} \left(s_i Y_{it-1}\right)^{\alpha} N_i^{1-\alpha}$. Taking logs yields

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

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

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

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



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

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

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

Putting these together yields,

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

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

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

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

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

2.3 Projected Impacts in the Existing Literature

The standard approach in macroeconomic climate models, beginning with DICE, is to assume that temperature effects the level of TFP, but not the growth rate of TFP (e.g., Nordhaus, 1992; Golosov et al., 2014; Barrage, 2020; Hassler et al., 2019). Consequently, these models assume that changes in climate will affect the long-run level of GDP, but not not the long-run growth rate of GDP. This assumption has been called into question by an empirical literature which shows that temperature affects the growth rate of GDP per capita over short periods of time (Dell et al., 2012; Burke et al., 2015, 2018). This empirical work is not as directly at odds with the modelling literature as it initially appears. As the analysis of the simple model highlights, even a *level effect* of climate on TFP will generate short-run changes in economic growth, as found in the empirical literature.[9]

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

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

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

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

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

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

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

Importantly, the existing literature often does include specifications that distinguish between level and growth effects in robustness analyses and appendices (Burke et al., 2015, 2018). However, these results are generally not emphasized in the main text or in prominent policy outlets like the IPCC reports (Masson-Delmotte et al., 2018). The simple model highlights the importance and the challenges with separating level and growth effects, implying that the robustness analyses in the earlier work are perhaps better suited for projecting climate change impacts than the main results. Even so, these robustness analyses do not account for capital dynamics, one of the main contributions of our paper.

3 Analysis of Historical Data

3.1 Data

Our data are a country-year panel. We use data on annual average temperature (measured in degrees Celsius) and precipitation (measured in millimeters) in each country from 1960-2010 compiled by Burke et al. (2015). The underlying data are from Matsuura and Willmott (2018). We use data on capital (K_{it}), output (Y_{it}), and population (N_{it}) from the Penn World Tables 10.0 (Feenstra et al., 2015) to calculate TFP in each country over this same time period.[10] 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.

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

3.2 Empirical Specification

We model the dynamics of TFP as

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

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

where P_{it} is precipitation. The TFP process includes four important generalizations relative to the simple model (equation 3). First, we assume that both damage functions have quadratic components: $D_g = \gamma_1 T_{it} + \gamma_2 T_{it}^2$ and $D_l = \exp\left(\beta_1 T_{it} + \beta_2 T_{it}^2\right)$. Burke et al. (2015) highlight the importance of this non-linear specification. A marginal increase in temperature is beneficial for cold countries with annual average temperatures below the optimum and harmful for hot countries with annual average temperature above the optimum. Second, in both equations, 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, we allow precipitation to affect the level of TFP. Precipitation is a common control variable in existing empirical research. Fourth, we include the term A_{it-1}^{ρ}, which accounts for the fact that shocks to the level of TFP – including those induced by temperature – might not die out immediately. In other words, it allows for a one-time, permanent change in temperature to affect the level of TFP for several periods without permanently affecting the growth rate of TFP.[11] Without the inclusion of the lagged dependent variable, we risk conflating a level shock to TFP that lasts for several periods with a permanent change in the growth rate of TFP.

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

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

Taking logs and first differences of (9), evaluating at time t and applying the small

[11] The inclusion of $\rho > 0$ also allows temporary deviations in temperature from long-run trends to impact TFP for multiple periods.

value approximation $\ln(1+x) \approx x$ for growth rates yields

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

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

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

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

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

It is useful to discuss the sources of variation in regression equation (12). Since the regression includes time fixed effects, global trends in temperature are not a source of identifying variation.[12] Similarly, since the regression includes country fixed effects, mean changes in temperature within a country are also not a source of identifying variation. Instead, the relevant variation comes from country-specific deviations of temperature from its mean growth rate. This includes short-run shocks to tempera-

[12] By excluding this variation and then using the results for our projection analysis, we implicitly assume that all changes in temperature – both deviations from global trends and the global trends themselves – have the same impact on country-level outcomes. In this way, we abstract from general equilibrium interactions between changes in temperature and international trade that might play different roles in response to global and country-specific changes in temperature (Desmet and Rossi-Hansberg, 2015; Costinot et al., 2016).

ture and country-specific trends in the growth rate of temperature.

3.3 Results

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

3.3.1 Main Specification

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

In column 2, we estimate the specification that assumes instead 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 at just over 13°C. The joint significance test strongly rejects the null that there is no effect of temperature on TFP ($p < 0.01$), and the coefficient on the lagged dependent variable is virtually unchanged from the first column. Thus, when ignoring growth effects, we find that the data can support the assumption that the level of temperature affects the level of TFP.

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

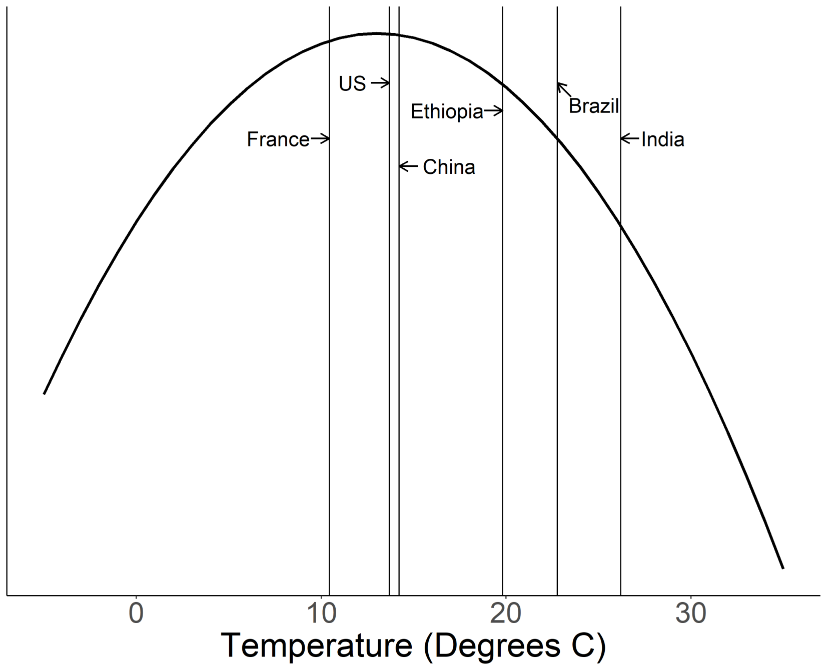
Table 1: Main Results

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

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

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. To show how increases in temperature differ across countries, Figure 2 plots the relationship between temperature and TFP from column 2 along with the 2010 temperatures for a select group of countries. The relatively wealthy countries tend to be near the optimum, while countries in poorer parts of world, including South Asia, South

Figure 2: Optimal Temperature



Note: The figure plots $\hat{\beta}_1 T + \hat{\beta}_2 T^2$ where $\hat{\beta}_1$ and $\hat{\beta}_2$ are the coefficient estimates from column 2 in Table 1. The vertical lines denote the average annual temperature for selected countries in 2010.

America and Africa, tend to be to the right of the optimum.

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 growth. The estimated growth effects could be insignificant, for example, because of imprecise measurement of TFP. To aid in the interpretation of the results, Appendix Figure C1 takes the results from column 3 and plots the marginal level effects ($\partial a_{it}/\partial T_{it} = \beta_1 + 2\beta_2 T_{it}$) and marginal growth effects ($\partial \Delta a_{it}/\partial T_{it} = \gamma_1 + 2\gamma_2 T_{it}$) for different temperatures. Strikingly, the marginal growth effects are positive until 26.7°C. Thus, for most countries in the world, the (statistically insignificant) growth effects would imply a positive impact of temperature on GDP growth.

3.3.2 Robustness

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

Second, Appendix Table B2 re-estimates 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 TFP on its first lagged value. Once again, this alternative specification has no impact on the qualitative takeaways. Quantitatively, using TFP innovations increases the magnitude of the level effect coefficients and shrinks the magnitude of the growth effect coefficients. Together, the robustness results from Appendix Tables B1 and B2 suggest that our main results in Table 1 are not driven by biases introduced by the lagged dependent variable.

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

Appendix Table B3 adds country-specific linear trends to the main specification.

[13] When allowing for country-specific trends, we are no longer using country-specific trends in the growth rate of temperature (e.g. as a result of climate change) to identify the impacts of temperature on TFP.

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

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 B7, we re-estimate the specifications from Table 1 when interacting all of the temperature variables with dummies that capture whether a country has above-median GDP/capita in 2010 ('$Rich_i$') or below-median GDP/capita in 2010 ('$Poor_i$'). We find that the data continue to support the existence of level effects after allowing for heterogeneity in the temperature coefficients. In particular, column 3 rejects the null hypothesis of no level effects for both rich and poor countries, but fails to reject the null of no growth effects for either group. For all coefficients, the null hypothesis of no difference between rich and poor countries cannot be rejected.[14]

[14] In Appendix Table B9, 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.

3.3.3 Summary of Historical Evidence

The above evidence generally supports the existence of level effects, but not growth effects. This finding suggests that previous studies using panel data likely identified growth effects because of capital accumulation or persistent TFP shocks, both of which cause changes in temperature to temporarily affect the growth of GDP. It is important to acknowledge, however, that there is uncertainty surrounding this implication, even within the subset of possible specifications that we investigate.[15] In particular, 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. However, the growth effects have opposite implications in each specification. In the specification with region-by-year fixed effects, increases in temperature increase GDP growth for most countries. In the specification with post-1990 dummies, increases in temperature decrease GDP growth in most countries and all of the 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

We combine our empirical estimates with the simple model to project the impact of future changes in temperature from climate change on GDP per capita around the world.

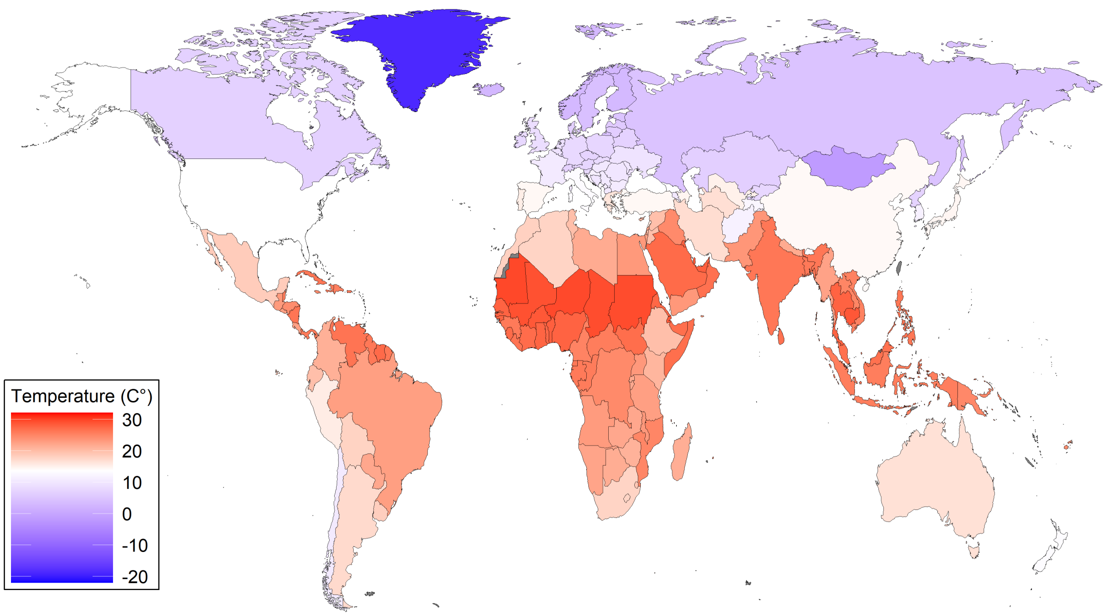
4.1 Data

We use country-specific projections of the change in temperature in each year from 2010 to 2100 consistent with the RCP 8.5 emissions scenario.[16] RCP 8.5 was originally developed to project global emissions in the absence of wide-spread climate policy.

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

[16] 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. We do not have the yearly projections. For these countries, we linearly interpolate the temperature change in each year based on the projected temperature change from 2010 to 2100.

Figure 3: Average Annual Temperature in 2010

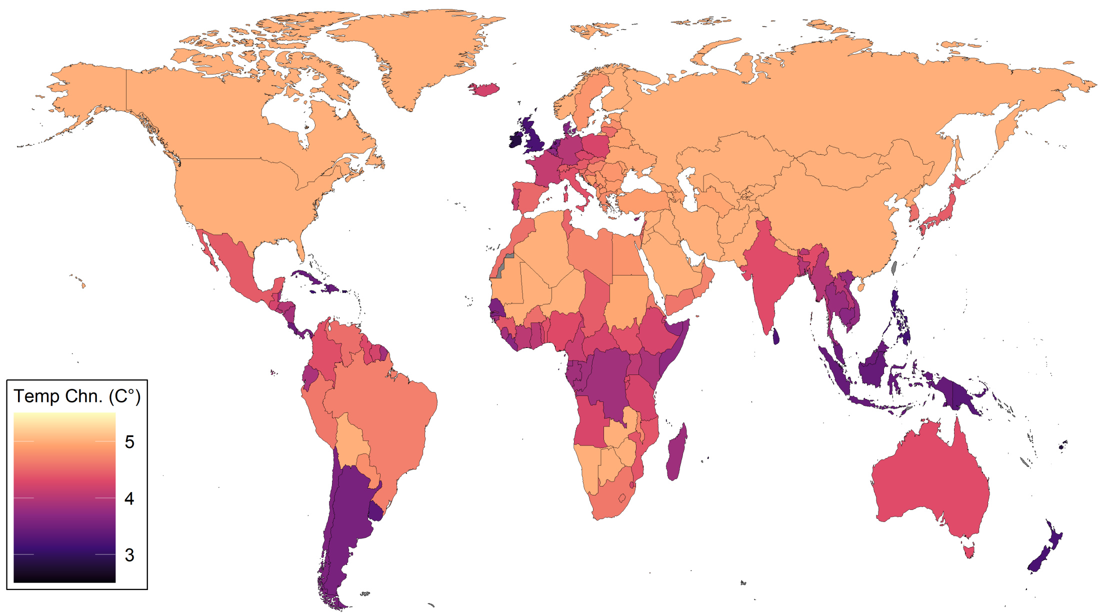


Note: The map shows the annual average temperature in each country in 2010. The lightest color corresponds to the optimal temperature from column 2 of Table 1.

Figure 3 shows the temperature in each country around the world in 2010, the starting point of our projection period. Countries in white, like the United States, have temperature near the optimum temperature of 11°C identified in Figure 2, implying that initial changes in temperature will have approximately no impact on TFP. Countries in red are hotter than the optimum, implying that initial increases in temperature decrease the level of TFP, and countries in blue are colder than the optimum, implying that initial increases in temperature increase the level of TFP. Unsurprisingly, the map demonstrates that poorer countries tend to be more vulnerable to increases in temperature. Figure 4 shows the change in temperature in each country between the two end points of our analysis, 2010 and 2100.

We calibrate the parameters of the simple model directly from the available data. We set the savings rate, s_i, and the depreciation rate, δ_i, equal to their average values from the Penn World Tables (Feenstra et al., 2015) in each country. We set $\alpha = 0.33$ in all countries, consistent with the cross-country evidence on capital's share of income

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



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

(Gollin, 2002). Additionally, we assume that the population in each country grows at a constant country-specific rate, equal to the average population growth rate from the Penn World Tables (Feenstra et al., 2015).

4.2 Method

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

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

where 'hat' denotes the point estimates from column 2 of Table 1. There is no trend in the estimated time fixed effects, and we set the time fixed effect in the projection equal the average of the estimated time fixed effects, $\hat{\bar{u}}$.[17] We set the change in precipitation in each country equal to its historical mean, denoted by the bars in equation (13). To determine 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 extended Solow model in each country. In the climate-change simulation, we feed in the projected time path of TFP from equation (13), using the temperature projections consistent with RCP 8.5. In the no-climate change simulation, we feed in the projected time path of TFP from equation (13) when we set the ΔT_{it} and ΔT_{it}^2 equal to zero, which implies that future temperatures in each country are constant at their values in 2010. We measure the impact of climate change as the percent difference in output between the no-climate-change and climate-change simulations.

4.3 Results

Figure 5 shows the impact of climate change on 2100 GDP per capita in each country. Countries close to the equator with high initial temperatures suffer the largest losses. For example, 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 climate change and assume that the level temperature affects the level of TFP. They find that in low-income economies 2100 GDP per capita would be approximately 8 percent lower under RCP 8.5, compared to a future without any additional climate change.

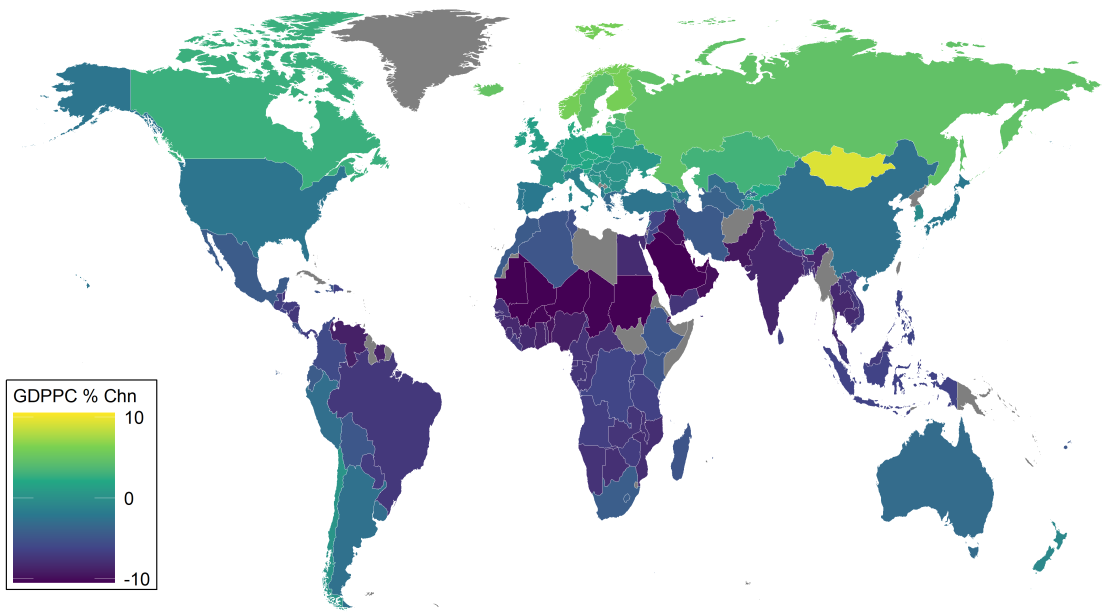
Countries at higher absolute latitudes with low initial temperatures experience benefits from climate change.[18] For example, climate change increases output per person in Canada by 2.8 percent and in Russia by 4.7 percent. Countries in the mid-latitudes with 2010 temperatures close to the optimum experience the smallest effects. For example, climate change reduces output per capita by 2.3 percent in the US and increases output per capita by 0.3 percent in France and Belgium.

Figure 6 decomposes the impact of climate change on GDP per capita into the

[17] Appendix figure C2 plots the time fixed effects.

[18] 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 from climate change.

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

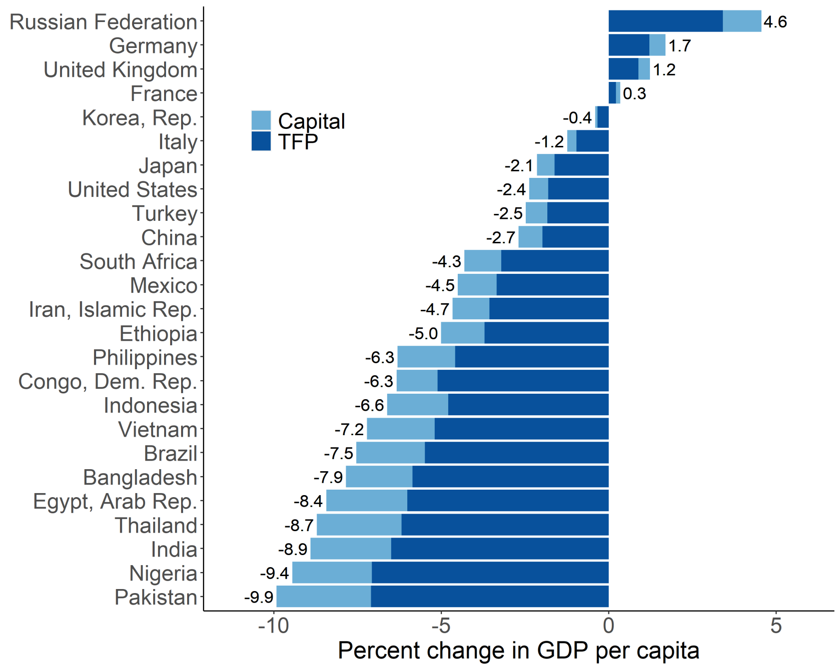


Note: The map shows the impact of the increase in temperature from climate change on GDP per capita in 2100. The projection is calculated using the level-effects specification in column 2 of Table 1.

impact on capital per capita and TFP for the 25 most populous countries. We use the identity that $\Delta \ln(Y_{it}/N_{it}) = \Delta \ln A_{it} + \alpha \Delta \ln(K_{it}/N_{it})$ to calculate the decomposition. In all the countries, changes in both capital and TFP account for substantial portions of the impact of climate change on GDP per capita. However, changes in TFP account for more of the climate change impacts than changes in capital. This difference is at least partially due to the fact that the capital stock does not have time to fully react to the temperature increases near year 2100.

Figure 7 plots the aggregate effects of temperature change on world GDP per capita from 2010-2100. The projections imply that temperature change reduces GDP per capita by approximately 0.75 percent in 2050 and by over 3 percent in 2100. To provide a sense of the uncertainty surrounding these projections, we follow Burke et al. (2015) and bootstrap the regression estimates 1000 times, sampling countries with replacement.

Figure 6: Decomposition of Climate Impacts

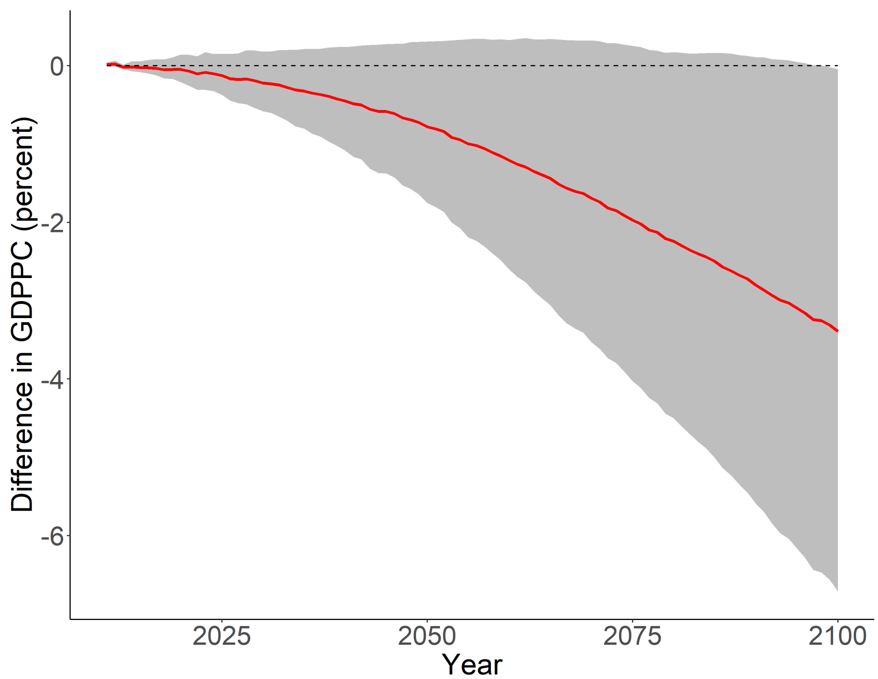


Note: This figure decomposes the impact of climate change between TFP and capital per person for the 25 most populous countries. The projection is calculated using the level-effects specification in column 2 of Table 1.

We simulate the model for each bootstrap, using the same procedure as we did for the main specification. The grey area in Figure 7 plots the resulting 95 percent confidence interval. The confidence interval in 2100 spans a range from virtually no impact to a 6.5 percent decrease in global GDP.

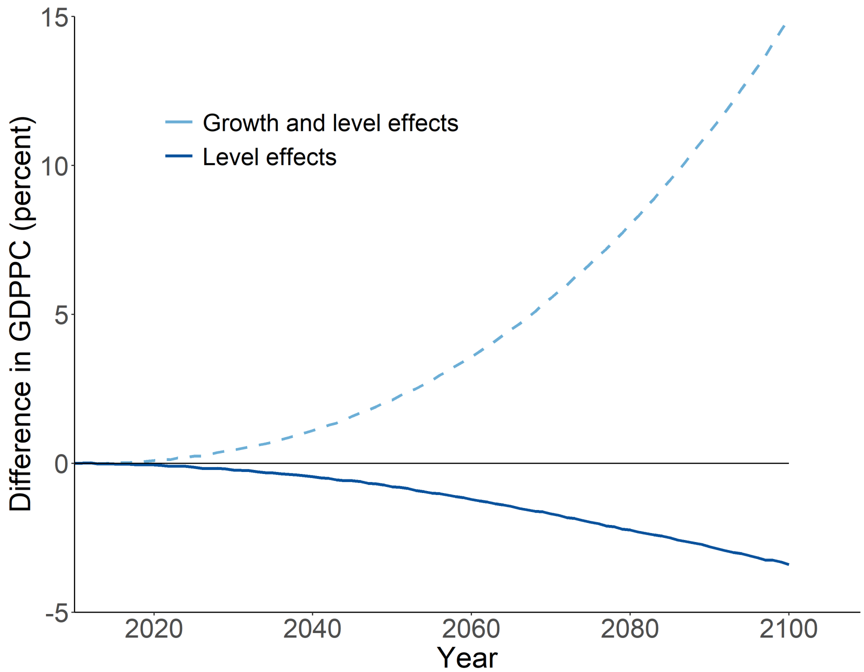
So far, the results we have presented assume that there are only level effects. While the bulk of the empirical evidence points in this direction, we cannot rule out the existence of growth effects. Figure 8 compares the projections using the estimates from columns 2 of Table 1 (only level effects) with the projections using the estimates from column 3 in Table 1 (both growth and level effects). Somewhat 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.

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



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

Figure 8: 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.

5 Additional Analyses

We estimate the effects of temperature on GDP per capita and compare the results from Section 4 to earlier work.

5.1 Estimated effects of temperature on GDP per capita

Table 2 re-estimates specifications from Tables 1 and B1 with GDP per capita, instead of TFP, as the dependent variable. As discussed in Section 2.2, controlling for lags of the dependent variable can capture capital dynamics in panel regressions when GDP per capita is the dependent variable. Here, we focus on the case of a single lag, which would perfectly control for capital only in the special case of full depreciation.

Column 1 of Table 2 recreates the standard regression from the existing literature. It includes only growth effects ($\beta_1 = \beta_2 = 0$) and no lagged dependent variable. As expected, the growth effects are statistically significant in this specification. Column 2 shows that they are still significant after controlling for the lagged dependent variables. Columns 3 and 4 use similar specifications assuming only level effects ($\gamma_1 = \gamma_2 = 0$). The level effects in both of these specifications are also statistically significant.

Columns 5 and 6 present the key results. Column 5 allows for both growth and level effects and does not include a lagged dependent variable. The joint significance test rejects the null hypothesis of no level effects ($p < 0.05$) and only barely rejects the null of no growth effects at standard level ($p = 0.11$). Column 6 allows for both growth and level effects while (at least partially) controlling for capital dynamics with the lagged dependent variable.

Table 2: GDP per capita Results

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

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

As expected, accounting for capital dynamics increases the magnitude of the level effect coefficients, which are statistically significant ($p < 0.01$), and shrinks the magnitude of the growth effect coefficients, which are statistically insignificant ($p = 0.30$). This result suggests that the estimated growth effects in column 5 were actually picking up short-run changes in growth induced by level effects. We can interpret the results in Table 2 in the context of the theory presented in Section 2.1 and our main results presented in Table 1. A one-time, permanent change in temperature will affect the growth of GDP per capita for several periods, even when temperature only has a *level effect*. This medium-run impact is captured by the lagged dependent variable, and it will eventually die out because $\rho < 1$. Appendix Table B8 shows that these results are generally robust to including country-specific quadratic trends, though the precision of the estimates declines and the level effects are insignificant at conventional levels ($p = 0.12$).

5.2 Reduced-form Growth Effects

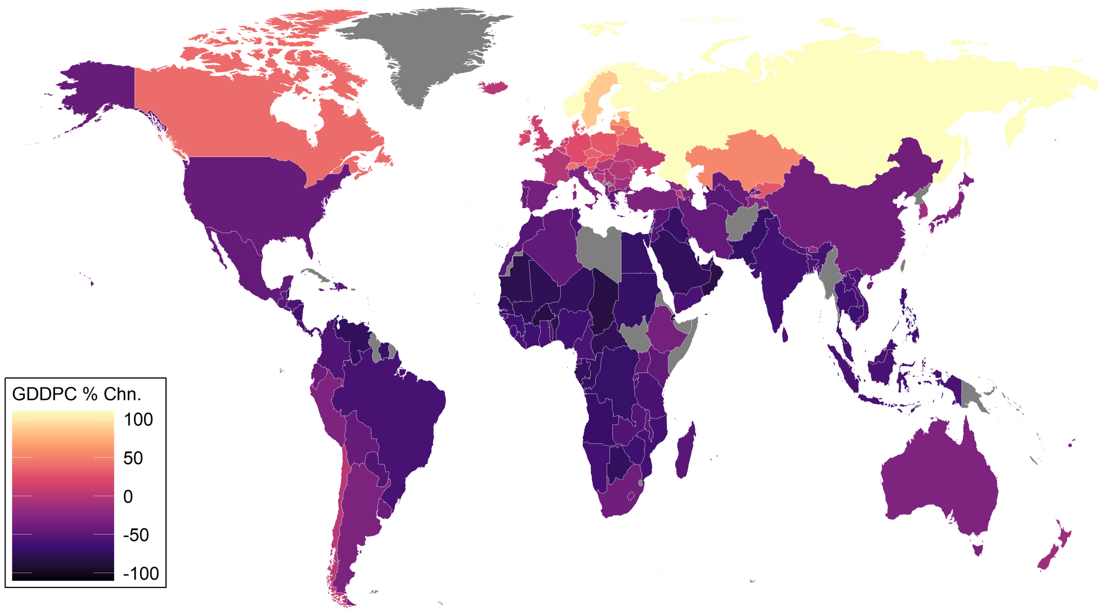
Burke et al. (2015) project the impacts of temperature increases under RCP 8.5 assuming that there are only growth effects of temperature and no level effects. Relative to our results, they find much larger output losses from future changes in climate. However, their analysis differs from ours in other dimensions. In particular, 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) and (iii) cap the impacts of climate change at 30°C.

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, while minimizing some of the other differences with our approach. The projection equation is

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

The results are presented in Figure 9. The impacts of climate change are much bigger than the baseline results in Figure 5. For example, US GDP per capita drops

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.

by 35 percent, compared to just over 2 percent in our model-based results. Similarly, GDP per capita in India drops by over 70 percent compared to approximately 8.5 percent in the model-based results. These results confirm that our findings differ from those of Burke et al. (2015) largely because of the distinction between level and growth effects.

6 Conclusion

Our paper combines theory with empirics to study the impacts of climate change.[19] Standard economic theory suggests that investigating the impact of temperature on TFP provides important insights into the ongoing debate about whether temperature

[19]See Bakkensen and Barrage (2018) for a discussion of how theory can be used to inform analyses of the impacts of natural disasters.

has permanent or temporary effects on economic growth. Motivated by theory, we explore whether the level of temperature affects the level of TFP, the growth rate of TFP, or both. While uncertainty remains, the evidence generally supports the notion that temperature only affects the level of TFP, implying that it affects the growth rate of output per capita in the short run, but not in the long run.

To get a sense of the magnitude of this effect, we combine the estimated impact of temperature on TFP in historical data with projections of future temperature changes from climate change to generate projections of future TFP. We then embed the TFP projections in a simple growth model, which generates predictions for how future changes in temperature will affect capital accumulation and output per capita around the world. While the effects are substantial, they are smaller than the predictions from an existing literature, which assumes that a one time change in temperature permanently alters the growth rate of output per capita. These results suggest that projections of climate impacts should not assume that all impacts of temperature on economic growth are permanent.

Our results suggest that further investigation into the relationship between temperature and TFP is likely to provide important insights into the ongoing debate about whether temperature has permanent or temporary effects on economic growth. As highlighted by Newell et al. (2021), there are always many options for generalizing a regression specification, which may impact whether or not the regressions provide evidence for the existence of growth effects. In particular, our results suggest that understanding how to account for country-specific trends in TFP growth is essential for resolving the debate. Using standard methods to control for such trends from the temperature-growth literature, the evidence supports the notion that there are only level effects, but we did identify alternate specifications that supported the existence of growth effects, suggesting that this is a crucial area for further investigation.

References

Acevedo, S., Mrkaic, M., Novta, N., Poplawski-Ribeiro, M., Pugacheva, E., and Topalova, P. (2017). The effects of weather shocks on economic activity: How can low-income countries cope. *IMF World Economic Outlook Chpt. 3.*

Bakkensen, L. and Barrage, L. (2018). Climate shocks, cyclones, and economic growth: bridging the micro-macro gap. *NBER Working Paper*.

Barrage, L. (2020). Optimal dynamic carbon taxes in a climate–economy model with distortionary fiscal policy. *Review of Economic Studies*, 87(1):1–39.

Bastien-Olvera, B. and Moore, F. (2021). Persistent effect of temperature on gdp identified from lower frequency temperature variability.

Bernstein, A., Gustafson, M. T., and Lewis, R. (2019). Disaster on the horizon: The price effect of sea level rise. *Journal of financial economics*, 134(2):253–272.

Bond, S., Leblebicioğlu, A., and Schiantarelli, F. (2010). Capital accumulation and growth: a new look at the empirical evidence. *Journal of Applied Econometrics*, 25(7):1073–1099.

Burke, M., Davis, W. M., and Diffenbaugh, N. S. (2018). Large potential reduction in economic damages under un mitigation targets. *Nature*, 557(7706):549–553.

Burke, M., Hsiang, S. M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature*, 527(7577):235–239.

Colacito, R., Hoffmann, B., and Phan, T. (2019). Temperature and growth: A panel analysis of the united states. *Journal of Money, Credit and Banking*, 51(2-3):313–368.

Costinot, A., Donaldson, D., and Smith, C. (2016). Evolving comparative advantage and the impact of climate change in agricultural markets: Evidence from 1.7 million fields around the world. *Journal of Political Economy*, 124(1):205–248.

Dell, M., Jones, B. F., and Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, 4(3):66–95.

Deryugina, T. and Hsiang, S. (2017). The marginal product of climate. Technical report, National Bureau of Economic Research.

Desmet, K. and Rossi-Hansberg, E. (2015). On the spatial economic impact of global warming. *Journal of Urban Economics*, 88:16–37.

Dietz, S. and Stern, N. (2015). Endogenous growth, convexity of damage and climate risk: how nordhaus' framework supports deep cuts in carbon emissions. *The Economic Journal*, 125(583):574–620.

Fankhauser, S. (2017). Adaptation to climate change. *Annual Review of Resource Economics*, 9:209–230.

Fankhauser, S. and Tol, R. S. (2005). On climate change and economic growth. *Resource and Energy Economics*, 27(1):1–17.

Feenstra, R. C., Inklaar, R., and Timmer, M. P. (2015). The next generation of the penn world table. *American Economic Review*, 105(10):3150–82.

Gollin, D. (2002). Getting income shares right. *Journal of political Economy*, 110(2):458–474.

Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. *Econometrica*, 82(1):41–88.

Hassler, J., Krusell, P., Olovsson, C., and Reiter, M. (2019). Integrated assessment in a multi-region world with multiple energy sources and endogenous technical change preliminary.

Henseler, M. and Schumacher, I. (2019). The impact of weather on economic growth and its production factors. *Climatic Change*, 154(3):417–433.

Hsiang, S. M. and Jina, A. S. (2014). The causal effect of environmental catastrophe on long-run economic growth: Evidence from 6,700 cyclones. *NBER Working Paper*.

Kahn, M. E., Mohaddes, K., Ng, R. N., Pesaran, M. H., Raissi, M., and Yang, J.-C. (2021). Long-term macroeconomic effects of climate change: A cross-country analysis. *Energy Economics*, 104:105624.

Kiley, M. T. (2021). Growth at risk from climate change.

Klenow, P. (2020). Climate change and long run economic growth. Conference on Economic Risks of Climate Change. https://impactlab.org/news-insights/economic-risks-of-climate-change-implications-for-financial-regulators/.

Lemoine, D. (2020). Estimating the consequences of climate change from variation in weather. *NBER Working Paper*.

Letta, M. and Tol, R. S. (2019). Weather, climate and total factor productivity. *Environmental and Resource Economics*, 73(1):283–305.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., et al. (2018). Global warming of 1.5°C. *IPCC*, 1:1–9.

Matsuura, K. and Willmott, C. J. (2018). Terrestrial air temperature: 1900–2017 gridded monthly time series. *University of Delaware, Newark, DE Retreived from http://climate.geog.udel.edu/~climate/html_pages/Global2017/README.GlobalTsT2017.html*.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L., Lamarque, J.-F., Matsumoto, K., Montzka, S. A., Raper, S. C., Riahi, K., et al. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic change*, 109(1):213–241.

Moore, F. C. and Diaz, D. B. (2015). Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change*.

Newell, R. G., Prest, B. C., and Sexton, S. E. (2021). The GDP-temperature relationship: implications for climate change damages. *Journal of Environmental Economics and Management*, 108:102445.

Nickell, S. (1981). Biases in dynamic models with fixed effects. *Econometrica: Journal of the econometric society*, pages 1417–1426.

Nordhaus, W. D. (1992). An optimal transition path for controlling greenhouse gases. *Science*, 258(5086):1315–1319.

Nordhaus, W. D. and Boyer, J. (2003). *Warming the World: Economic Models of Global Warming*. MIT press.

Nordhaus, W. D. and Moffat, A. (2017). A survey of global impacts of climate change: replication, survey methods, and a statistical analysis. *NBER Working Paper No. 23646*.

Pesaran, M. H. and Smith, R. (1995). Estimating long-run relationships from dynamic heterogeneous panels. *Journal of econometrics*, 68(1):79–113.

Pindyck, R. S. (2013). Climate change policy: what do the models tell us? *Journal of Economic Literature*, 51(3):860–72.

Schlenker, W. and Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of Sciences*, 106(37):15594–15598.

Solow, R. M. (1956). A contribution to the theory of economic growth. *Quarterly Journal of Economics*, 70(1):65–94.

Appendices

A Data

Table A1: Summary

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

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

B Sensitivity

Table B1: Results Without Lagged Dependent Variable

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

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

Table B2: Results With TFP Innovations

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

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

Table B3: Results With Linear Time Trends

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

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

Table B4: Results With Quadratic Time Trends

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

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

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

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

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

Table B6: Results With Post-1990 Dummy

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

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

Table B7: Heterogenity Results

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

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

Table B8: GDP per capita Results With Quadratic Time Trends

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

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

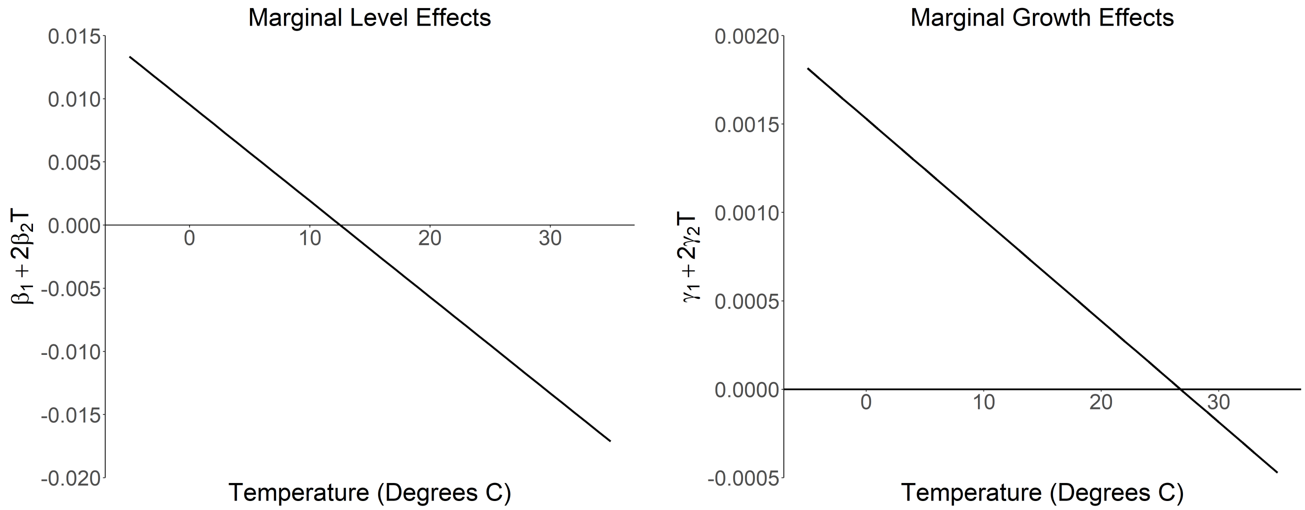
Table B9: Results With Temperature Interactions

	(1)
Dep. Var.: $\Delta LnTFP$	ols1
$Temp_{t-1}$	-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)
$Temp_t \times Temp_{t-1}$	0.0054
	(0.0040)
$Temp^2_t \times Temp^2_{t-1}$	-0.0000
	(0.0000)
$\Delta Precip_t$	0.0036
	(0.0028)
$\Delta Precip^2_t$	0.0000
	(.)
$\Delta \log TFP_{t-1}$	0.1894***
	(0.0385)
N	6,654
Adj. R-squared	0.12

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

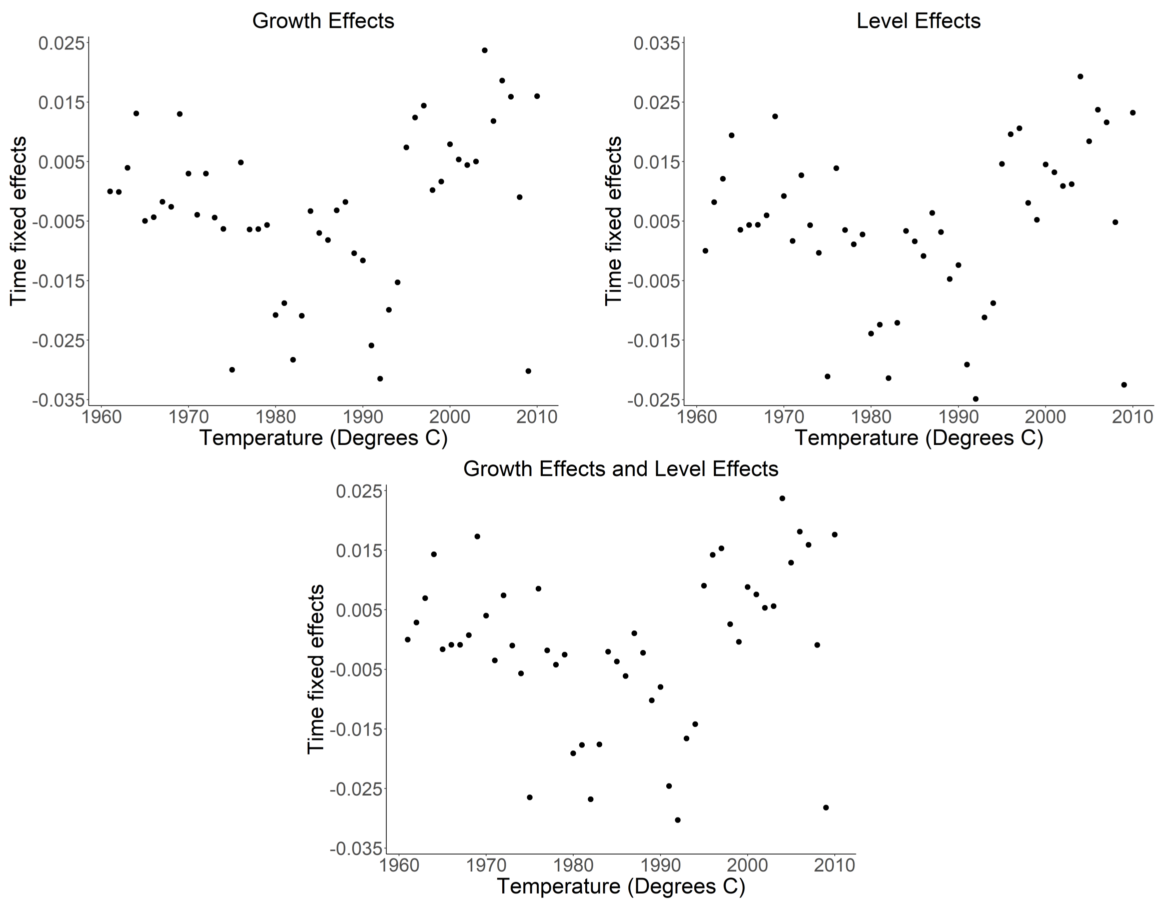
C Additional Figures

Figure C1: Marginal Effects



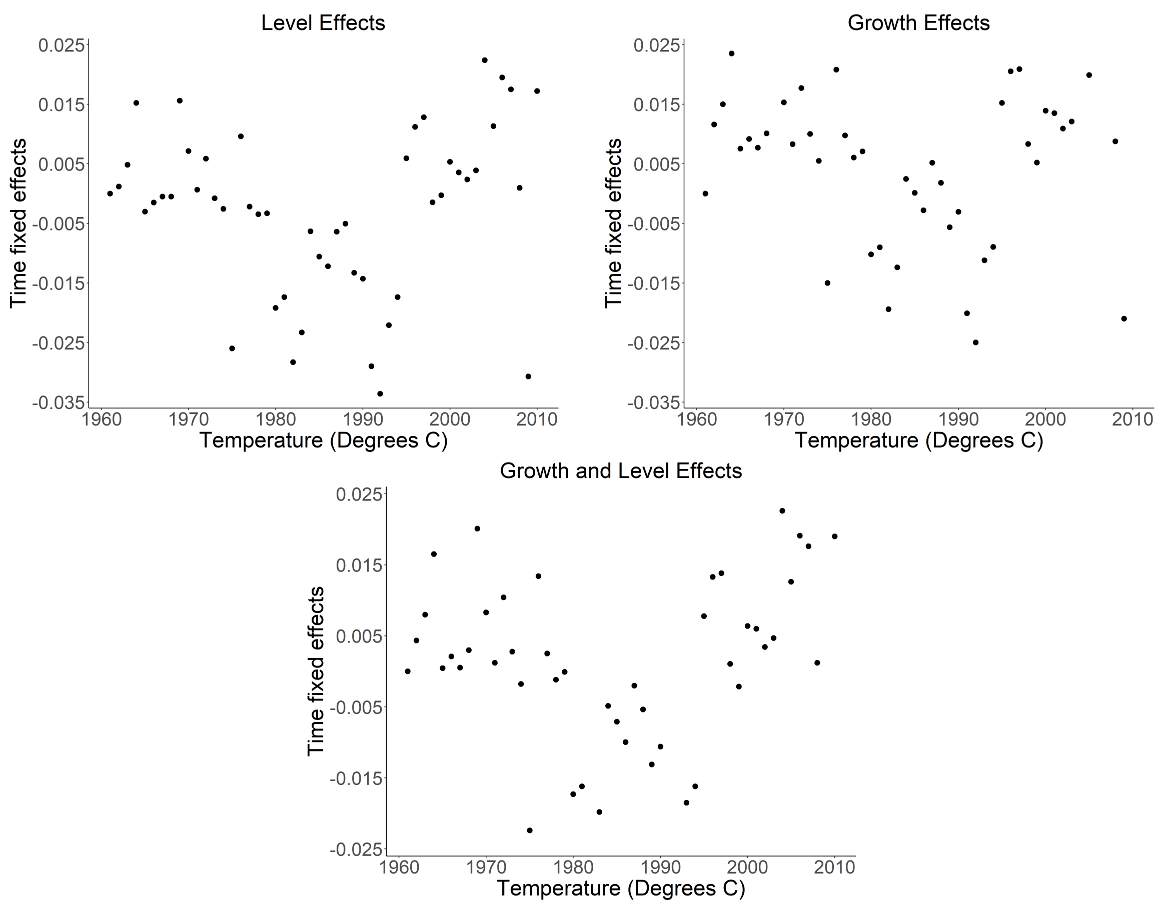
Note: The figure plots the time fixed effects for regression estimates reported in Table 1, which includes both level and growth effects. The left panel shows the impact of the level of temperature on the level of ln(TFP), holding growth effects fixed. The right panel shows the impact of the level of temperature on the growth rate of ln(TFP), holding level effects fixed.

Figure C2: Main Results: Time Fixed Effects



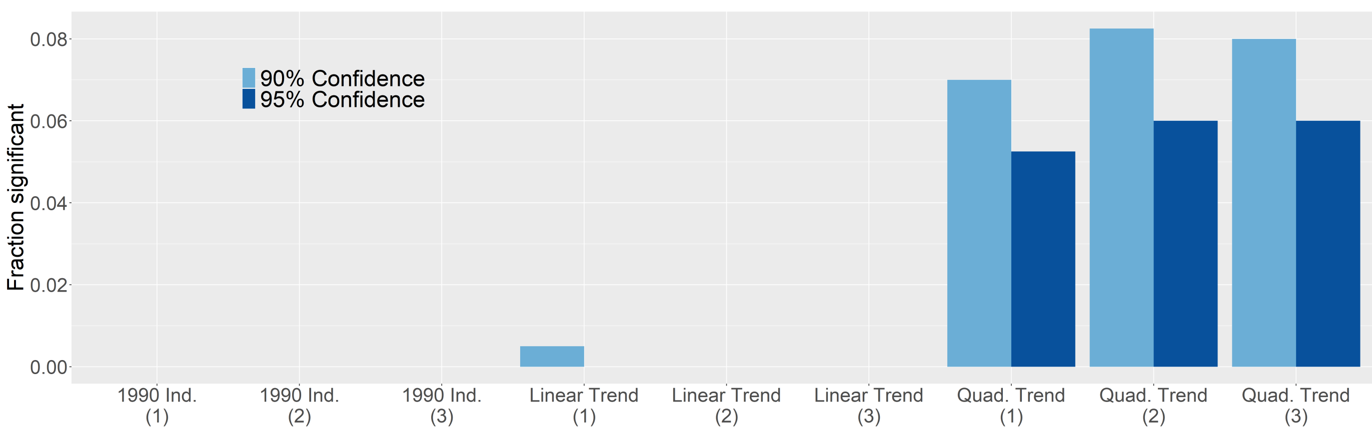
Note: The figure plots the time fixed effects for regression estimates reported in Table 1. The top left panel corresponds to column 1, the top right panel corresponds to column 2, and the bottom panel corresponds to column 3.

Figure C3: GDPPC Results: Time Fixed Effects



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

Figure C4: Fraction of Statistically Significant Trends



Note: The first three bar-groups show the fraction of country-specific 1990 dummy variables that are statistically significant at the five (dark blue) and ten (light blue) percent levels for the estimates in Table B6. The second three bar-groups show the fraction of country-specific linear trends that are statistically significant at the five (dark blue) and ten (light blue) levels for the estimates in Table B3. The final 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) levels for the estimates in Table B4. The numbers in parentheses indicate the column from the corresponding table.