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Abstract

Projections of climate change damages based on climate-econometric estimates suggest that, without mitigation, global warming could reduce average global incomes by over 20% towards the end of the century (Burke et al., 2015). This figure significantly surpasses climate damages in Integrated Assessment Models (IAMs). For example, global climate damages obtained with the seminal DICE model are just a 7% reduction in output (Nordhaus, 2018). Here, we show that the discrepancy between the projections can be resolved by accounting for growth convergence in a climate-econometric approach that is consistent with the macroeconomic models underlying most IAMs. By re-estimating the global non-linear relationship between temperature and country-level economic growth, our convergence-consistent projections reveal that under an unmitigated warming scenario, global climate damages amount to 6%.

JEL-Codes: O400, O440, Q540, Q550, Q560.

Keywords: climate change, economics growth, convergence, integrated assessment models.

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1 Introduction

Estimating the future economic consequences of climate change is crucial for developing efficient climate policies. Integrated Assessment Models (IAMs) serve as a standard tool for formulating efficient climate policy pathways by weighing the costs of climate policies against the costs of climate damages. For instance, the United States Interagency Working Group on the Social Cost of Greenhouse Gases (IWG, 2021) employs three peer-reviewed IAMs to calculate the social cost of three greenhouse gases (GHGs). These estimates are then applied in regulatory impact analyses to inform optimal emissions abatement strategies (Aldy et al., 2021).

IAMs typically incorporate neo-classical growth models, utilizing the best available data from physical and economic sciences to establish relationships between economic production, climate change, climate policy costs, and climate change's impacts on economic activity. These models employ a neoclassical production function characterized by exogenous technical change and diminishing returns of capital. The rate of technical change pins down the long-run growth rate of income, which is independent of productivity levels or investment rates. As climate change reduces aggregate productivity, the (average and marginal) productivity of capital subsequently declines. This leads to lower investment and a lower future capital stock. Because of diminishing returns to capital, the endogenous reduction in the future capital stock causes the average productivity of capital to converge back to old levels. As a result, output levels are permanently lower compared to a scenario without climate change, but the growth rate is only temporarily lower, converging back to the old level in the long run. Only steady productivity growth through ongoing technical progress can drive long-run capital and output growth.[1]

IAMs have been developed since the late 1980s. In the meantime, climate change has continued to progress in the real world, with observable impacts on economies worldwide. Recent climate-econometric approaches leverage this data to empirically estimate climate change damage functions and project future climate change damages (e.g., Burke et al., 2015, 2018). However, these approaches do not directly apply the neoclassical growth model of IAMs to the data and, specifically, they do not account for the convergence effects inherent in neoclassical growth models. With the muted convergence effects in these projections, climate change has persistent differential effects on income across counties and leads to a strong divergence in economic incomes across countries, resulting in pronounced winners and losers.

This paper presents a climate-econometric approach that enhances the empirical estimation and projections of climate change's macroeconomic impacts, aligning them more closely with the theoretical models underpinning IAMs and the methods employed in the broader empirical growth literature (Barro and Sala-i Martin, 1992; Temple, 1999; Johnson and Papageorgiou, 2020). By adopting the foundational

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[1] Some recent IAMs consider that climate change could have a lasting effect on economic growth, such as through alterations in innovation rates (e.g., Gerlagh, 2023). In this paper, our primary focus is on generating empirical estimates of climate impacts that align with the underlying economic theory of the most prevalent IAMs. In the conclusion, we discuss the possibility of future work to explore estimates consistent with more recent IAM model frameworks.

Solow-Swan macroeconomic growth model, we derive a convergence-consistent equation for estimating the impacts of climate indicators–temperature and precipitation–on economic growth rates, using country-level data. Subsequently, we apply our empirical estimates to project economic damages from climate change throughout the 21st century under the widely-used high-emissions scenario RCP8.5.

We confirm previous evidence for a non-linear effect of temperature on economic output levels. However, unlike previous studies, we do not find evidence of enduring impacts on economic growth. When projecting economic damages from climate changes, we rather observe that incorporating convergence effects considerably diminishes climate damages. Whereas prior estimates indicate that climate change will reduce global average incomes by approximately 20%, our central specification indicates a reduction in global average incomes close to 6%. This reconciles the discrepancies in climate damages between the climate-econometric approach and the IAM literature. Moreover, accounting for convergence considerably narrows the range of country-level economic growth rates projected for the end of the century, indicating that climate change has less of an impact on inter-country income inequality than previously found.

This paper adds to the growing body of literature on empirically-based estimates of climate's impact on economic growth using climate-econometric methods (Dell et al., 2014). Specifically, it addresses a crucial open question concerning whether climate change affects income levels or rather income growth rates (Burke et al., 2015; Kalkuhl and Wenz, 2020; Newell et al., 2021). Most closely related to this paper is (Dell et al., 2012), who estimate the effect of temperature and precipitation on economic growth and find that rising temperatures reduce economic growth in poorer countries. Our study builds on this paper by considering non-linear effects of temperature and precipitation on economic growth and applying the resulting estimates to projections of climate damages. Including non-linear effects of climate variables, we cannot confirm the previous evidence for a persistent growth effect. Additionally, we emphasize the importance of accounting for convergence effects when applying estimates in projections.

In Section 2, we build on a concise neo-classical growth model and derive an empirical model, factoring in convergence, to estimate the macroeconomic climate damages. In Section 3, we detail the data utilized in the empirical estimation process. In Section 4, we present our findings. Finally, in Section 5, we draw our conclusions.

2 Estimating growth effects with convergence

2.1 Neoclassical macroeconomic growth and convergence

The Solow-Swan model relates aggregate output to labor and capital inputs through a constant-returns-to-scale Cobb-Douglas technology. In the long-run, the model finds that the economy under consideration reaches a steady-state where per-capita output is described by[2]

$$y(t) := \ln \frac{Y(t)}{L(t)} = \ln A(0) + g\,t + \frac{\alpha}{1-\alpha}\ln s - \frac{\alpha}{1-\alpha}\ln(n+g+\delta) + \epsilon \tag{1}$$

where $y(t)$ is the natural logarithm of per-capita output in year t, $\frac{Y(t)}{L(t)}$ is the per-capita output, s is the savings rate, n is population growth, g is labor-productivity growth, α is the production elasticity of capital, and δ is the capital depreciation rate. The term $A(0)$ represents all exogenous, non-economic, sources of productivity. Already Mankiw et al. (1992, p. 5) emphasizes that "the $A(0)$ term reflects not just technology but resource endowments, climate, institutions."

This standard equation predicts that long-run income levels vary across countries with $A(0)$, g, α, s, n, and δ. However, the prediction for long-run income growth is simply g, independent of all the other determinants. This means that shocks to the economies have no permanent growth effects unless they permanently affect the trend productivity growth rate.

If a permanent increase in temperature lowers productivity levels permanently, pre-shock capital stocks can no longer be sustained and investment falls. In the long-run, lower capital stock levels restore pre-shock returns to investment. After this adjustment process, the output levels are permanently lower, but the growth rate is back to the old level. Whenever there is more capital than justified by the productivity levels, the returns to investment are low, and growth is slowed down until the capital stock has adjusted to productivity levels. Only steady productivity growth through ongoing technical progress can drive long-run capital and output growth.

In DICE and most other IAMs, it is by assumption that climate impacts productivity levels, but not the long-run trend of technological change. Consequently, the long-run growth rate is not affected by climate. However, the absence of long-run growth effects predicted by neoclassical growth theory can and needs to be empirically tested. This requires a more dynamic approach than Equation (1). The workhorse dynamic equation to estimate the determinants of growth and long-run level of per capita income in country i from time $t-1$ to t is the 'convergence equation' (Acemoglu, 2009, Section 3.2):

$$\Delta y_{i,t} = g_i - \lambda(y_{i,t-1} - y^*_{i,t-1}) \tag{2}$$

where $y_{i,t}$ is the natural logarithm of per capita income so that the left-hand side represents per capita income growth, $y^*_{i,t} = y^*_{i,0} + g_i t$ is the long-run exponential growth path to which actual income y_{it} is converging, and $\lambda > 0$ measures the 'speed of convergence' (Temple, 1999), which is proportional to $1-\alpha$, i.e. the production elasticity of inputs other than capital in the production function.[3] Decreasing returns to man-made capital imply $1-\alpha > 0$. Here g_t, λ, and $y^*_{i,0}$ need to be estimated from observable

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[2] The (discrete-time Cobb-Douglas) Solow model can be presented by production function $Y = K^\alpha (AL)^{1-\alpha}$ and capital accumulation function $\Delta K = sY - \delta K$. In Appendix C.1 we show how (1) and (2) can be derived from these two equations.

[3] Defining $z_{it} = y_{it} - y^*_{it}$ as the deviation of actual income from trend income, we can write (2) as $z_{it} = (1-\lambda)z_{i,t-1}$, which shows that $z_{it} \to 0$ i.e. $y_{it} \to y^*_{it}$ when $t \to \infty$, provided $|1-\lambda| < 1$.

determinants, *including climate variables*; combined with observed income $y_{i,t}$ they predict the growth process.

The model allows for two sources of growth. First, g_i captures long-run trend growth and is driven by continuous productivity improvements. Changes in trend growth g_i permanently affect income growth. Second, deviations from the trend, $y_{i,t} - y^*_{i,t}$, temporarily affect growth. This captures convergence growth. A fall in actual income without any corresponding change in trend growth creates temporarily faster growth so that the economy gradually returns to the old growth path. Similarly, an increase in the trend level of income, $y^*_{i,0}$, creates only temporarily faster growth so that the economy converges to income at a higher level but eventually grows at the old-growth rate.

This, in turn, suggests two channels by which changes in climate could impact economic growth. If changes in climate affect g_i, the long-run growth trend, these changes will have permanent effects on economic growth by changing steady-state growth rates. Impacts on growth rates would be the case if climate changes permanently impacted determinants of long-run economic growth, such as the rate of innovation. If climate changes only impact output levels, such as through a change in productivity, this will only have a transitory effect. In the long-run, convergence pressures will return growth to the steady-state. The pace at which this occurs depends on the speed of convergence, λ.

We analyze these two channels in a manner consistent with theory following the approach of Bond et al. (2010) to estimate both transitory and permanent growth effects of climate. To derive the corresponding empirical model, we first rewrite Equation (2) as

$$\Delta y_{i,t} = -\lambda y_{i,t-1} + \sum_k \beta_k x_{i,t,k} + \gamma_i(t) + \eta_i + \epsilon_{i,t} \tag{3}$$

where λ measures the speed of convergence, $x_{i,t,k}$ denotes explanatory variables k that may determine growth, $\gamma_i(t)$ are country-specific time trend functions representing the rates of steady-state growth, η_i are country-specific intercepts representing initial conditions, and $\epsilon_{i,t}$ is an error term. For analyzing the determinants of macroeconomic growth, the coefficients on $x_{i,t,k}$ are of main interest. This approach has been used to analyze explanatory variables such as population growth, human capital, or investment. Here, our interest is the partial effect of climate, so we use climate variables—temperature and precipitation—as the explanatory variables.

If $|1-\lambda| < 1$, $\lim_{t\to\infty} \gamma_i(t) = \gamma_{1i}t + \gamma_{2i}$, and explanatory variables $x_{i,t,k}$ – including climate variables – reach steady-state values such that eventually $x_{i,t,k} = x_{i,k}$, then, under this specification, the country-specific per capita income converges to an exponential growth path with growth rate

$$g_i = \frac{\gamma_{1i}}{\lambda}.$$

Notice, this steady-state growth rate does not depend on climate. Thus, while changes in climate can affect economic growth, the levels of climate variables, once stabilized, do not matter for the steady-state exponential growth path. Changes in climate in this model only have transitory impacts on economic growth as countries adjust to a new steady-state growth path at the same steady-state growth rate.

Notice also that income converges to an exponential growth path only if the (country-specific) time trends $\gamma_i(t)$ are bounded, i.e. at most linearly increasing (in absolute value) with t. Thus, for consistency with the underlying theoretical framework, when empirically estimating Equation (3), it is important that any country-specific time trends be bounded. In some previous empirical analyses of the growth effects of climate, estimates have used unbounded time trends. For example, Burke et al. (2015) estimate quadratic country-specific time trends. This assumption implies that countries will never converge to a steady-state growth path. In our empirical estimates, reported below, we rather estimate linear country-specific time trends.[4]

Next, we derive an empirical model that allows us to estimate persistent impacts of climate on economic growth. To this end, we rewrite Equation (3) as a levels equation, take first differences, and add additional lagged levels of the explanatory variables $x_{i,t,k}$. This gives

$$\Delta y_{i,t} = (1-\lambda)\Delta y_{i,t-1} + \sum_k \beta_k \Delta x_{i,t,k} + \sum_k \theta_k x_{i,t-1,k} + \Delta\gamma_i(t) + \Delta\epsilon_{i,t} \tag{4}$$

Again consider a steady-state, where explanatory variables remain stable, $x_{i,t,k} = x_{i,k}$. If $|1-\lambda| < 1$, and $\lim\limits_{t\to\infty} \gamma_i(t) = \gamma_{1i}t + \gamma_{2i}$, country-specific steady-state growth rates are given as

$$g_i = \frac{\gamma_{1i}}{\lambda} + \frac{\sum\limits_k \theta_k x_{i,k}}{\lambda}.$$

Unlike for Equation (3), here steady-state growth rates are a function of the explanatory variables, notably climate variables. Specifically, the steady-state growth rate depends on the coefficients θ_k of the lagged explanatory variable levels. By contrast, the coefficients β_k of the first-differenced explanatory variables in Equation (4) thus capture the transitory growth effects of changes in climate, as in Equation (3). By estimating Equation (4), which includes coefficients for both effects, we can test whether climate matters for long-run economic growth or if changes in climate only have a transitory effect on income levels.[5]

Dell et al. (2012) also follow this estimation approach, however, for econometric estimates in the text of their paper they assume $\lambda = 0$, i.e. they abstract from convergence. In the appendix of their paper, they test relaxing this assumption and find that fixing $\lambda = 0$ does not bias the coefficients on climate variables in their estimates. So, they opt to exclude the convergence term in the text. Whereas excluding

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[4] To consider an alternative non-linear country-specific time trend specification, in the Appendix we consider a more flexible but still bounded specification given as $\gamma_i(t) = \gamma_{i1}\, t + \gamma_{2i}\, t\, \mathbf{e}^{-\frac{1}{\tau}\,(t-t_0)}$.

[5] Kahn et al. (2021) use an autoregressive distributed lag (ARDL) specification similar to Equation (4) except that they exclude the level climate variable terms. By excluding the level terms, they can only capture the impacts of climate on economic output levels, not the long-run growth effects.

the convergence term does not affect the identification of the effects of changes in climate on growth, it has important implications in projections of long-run damages from climate changes, as we show below. In short, by ignoring convergence pressures by excluding the convergence term, all growth effects become long-run effects when using the estimates in projections.

2.2 Climate-growth effects in the literature

In IAMs, such as DICE, climate change reduces aggregate productivity and, by construction, does not affect long-run economic growth. When climate changes affect growth rates, the implications for optimal climate policy are significantly different (Moore and Diaz, 2015). It is an empirical question whether climate has short-run or long-run effects on growth, and as such it cannot be answered by an IAM.

Over the past decade there has been an expanding climate-econometrics literature applying cross-sectional and panel data estimation methods to identify how changing climate variables affect economic output and growth. The literature provides mixed evidence for level versus growth effects. Dell et al. (2012) provides evidence that temperature impacts country-level economic growth only in poor countries. Burke et al. (2015) provides further evidence of the growth effects of temperature, highlighting that the effect is non-linear due to differences in climate rather than income. Using a low-pass filter to separate longer and shorter frequency temperature fluctuations, Bastien-Olvera and Moore (2021) find that longer temperature anomalies can affect growth as much as shorter anomalies. They argue that this is indicative of persistent effects of climate change. On the other hand, Kalkuhl and Wenz (2020) and Newell et al. (2021) provide evidence that temperature impacts GDP levels, but they do not find effects on the growth rate.

Estimates from this climate-econometrics literature are frequently used to project the impacts of the climate outside the theoretical framework of IAMs by updating country-level socioeconomic projections to account for climate impacts (Burke et al., 2015, 2018; Diffenbaugh and Burke, 2019; Kalkuhl and Wenz, 2020; Newell et al., 2021). However, these empirical estimates do not account for diminishing returns to capital that bound the long-run impacts of climate change, as in Equations (3) and (4). Below, we show how accounting for such convergence effects can meaningfully guide projections of the economic impacts of climate changes.

3 Data

We use the same country-level economic and climate data for our empirical analysis as Burke et al. (2015). The data on economic growth comes from the World Bank and covers the years 1960 to 2010 (World Bank Group, 2012). The climate data comes from monthly gridded interpolated weather station data (Willmott and Matsuura, 2012). The monthly gridded climate data is aggregated to the country-level using population weights and then to the annual frequency taking the average of monthly temperatures and the sum of monthly precipitation. Recent empirical climate econometrics analyses have considered alternative datasets to address various potential issues or innovations. For example, some analyses have turned to sub-national economic growth data (Damania et al., 2020; Kalkuhl and Wenz, 2020) or considered alternative economic variables (Letta and Tol, 2019). Other analyses have considered alternative sources of climate data, such as using reanalysis data to address weather station bias (Auffhammer et al., 2013). Here our main interest is to assess the effects of using a convergence-consistent growth model as the basis for econometric analysis of climate impacts. To this end, we let the data overlap with Burke et al. (2015) as much as possible to ensure comparability with previous work on this topic.

4 Results

4.1 Convergence-Consistent Regression Results

Here we estimate a relationship between climate and economic activity based on the past global experience with climate change. Specifically, we estimate Equations (3) and (4) to study the effects of accounting for theoretically-founded convergence and the persistence of climate impacts on economic growth. For climate variables $x_{i,t,k}$, there is no theoretical guidance on the appropriate functional form or which climate variables should be included. We opt to use linear and quadratic terms of country-level temperature and precipitation to allow for non-linearities in the relationship between climate and economic growth.[6,7] We estimate a single global relationship between climate variables and economic growth. But, of course, it is possible this relationship depends on other factors, such as the level of economic development (Dell et al., 2012). So, in one model specification, we separately estimate effects for rich and poor countries, allowing for differential effects across levels of development. This functional form approach is consistent with Burke et al. (2015) and Dell et al. (2012). Table 1 shows the results across model specifications.

First, in columns (1)–(3) of Table 1 we estimate Equation (3) imposing the assumption that there is no convergence, i.e. $\lambda = 0$. Across columns (1)–(3), we change the country-specific time trend specification from no trends, to linear trends, to quadratic trends. These estimates reflect the estimates of Dell et al. (2012) and Burke et al. (2015) and provide a benchmark for comparison. In particular, estimates in column (3) of Table 1 are identical to Burke et al. (2015)'s estimate in column (1) of Extended Data

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[6] Lack of variation in climate changes, which occur on the scale of decades, makes empirical identification difficult. Thus, we follow the literature in using variations in weather, measured as annual temperature and precipitation as a proxy. Identification rests on the assumption that annual deviations in temperature and precipitation within countries are exogenous (Dell et al., 2014).

[7] We only consider temperature and precipitation as explanatory variables to capture the marginal effect of climate as a determinant of growth. It is of course possible that climate could interact with other determinants of economic growth, such as population growth or human capital formation. Future work could explore interactions between climate and other such determinants of economic growth.

Table 1, their benchmark specification. As a reminder, by leaving out the convergence term, all climate effects are, by construction, permanent growth effects.

Across columns (1)–(3) of Table 1 we find statistically significant evidence that temperature has a non-linear impact on economic growth. Our results indicate that if a cold country experiences a marginally warmer year, it will experience a boost in economic growth, ceteris paribus. And if a warmer country experiences a marginally warmer year, it will experience a slowdown in its economic growth, ceteris paribus. This is consistent with existing evidence of a non-linear effect of temperature on a variety of economic factors, such as agricultural yields, labor supply, and mortality (Schlenker and Roberts, 2009; Graff Zivin and Neidell, 2014; Carleton et al., 2022). In column (2) we estimate Equation (3) with linear country-level time-trends. We find a lower peak growth temperature and increased magnitude of the marginal effects at high and low temperatures. In column (3) we reproduce the estimates of Burke et al. (2015) which includes quadratic country-level time trends. We find the coefficient estimates for climate variables are similar to those in column (2). However, as a quadratic trend is unbounded and inconsistent with our theoretical framework, we only report them here for comparison with the previous literature and focus on column (2) in the text. Across these empirical specifications, we find no evidence of a statistically significant effect of precipitation on economic growth.[8]

Next, in columns (4)–(5) of Table 1 we estimate Equation (3) with the convergence term, i.e. relaxing the assumption $\lambda = 0$. This estimating equation, as discussed above, only captures transitory growth effects of climate. In the long-run, convergence pressures restore country-level growth rates to the steady-state level, so changes in climate only affect the level of output. In column (4) we do not include country-specific time trends, i.e. we impose $\gamma_{1i} = 0$. In column (5) we estimate linear time-trends. Coefficients on these trends estimate γ_{1i}.

For the transitory effects of climate on economic growth, we again find significant evidence in support of a non-linear effect of temperature, and we also find weakly significant evidence of a non-linear effect of precipitation. We find the peak-growth temperature in both columns (4) and (5) are comparable to those found in columns (2) and (3), if slightly higher, though the marginal effects at high and low temperatures are dampened.[9] As found by Dell et al. (2012), these results suggest that including the convergence term has little effect on the precision of the estimates of climate's growth effects. However, it has important implications for the interpretation of the coefficients and their implications in projections of damages from climate changes as we will explore in the next subsection.

Across columns (4)–(5), we find that the convergence term, $-\lambda$, is significant, negative, and one plus the point estimate is less than one in absolute value. The negative point estimate for $-\lambda$ indicates that lower current output leads to faster economic growth. Estimating an absolute value for $1 - \lambda$ of less than

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[8] As discussed in Damania et al. (2020) this is likely due to the aggregation of precipitation measures, which exhibit significant spatial variation.

[9] This is also true for a quadratic time trend with the lagged logarithmic income term though this specification prohibits convergence interpretation due to being unbounded.

one indicates support for convergence. Our point estimates are consistent with previous estimates, such as those by Lee et al. (1998).

In Supplementary Figure 7 we plot estimates for the linear country-specific trends' coefficients for estimates in column (5) of Table 1. These estimates measure the steady-state growth rates γ_{1i} for each country. We find that over 75% of countries have a steady-state annual growth of between 0-5%, and the majority around 2-3%.

To test both channels by which climate can affect economic growth, both long-run and short-run, in columns (6)–(7) of Table 1 we estimate Equation (4). As a reminder, coefficients on climate variable first differences capture the short-run impacts, and coefficients on climate variable levels capture the long-run impacts. Column (6) is a more general estimating equation than in column (5) by allowing for long-run growth effects and by nesting the previous specification. But we find that this more general specification is consistent with the short-run only estimates in column (5). In column (7), we additionally explore the possibility of differential effects of climate between rich and poor countries.

Let us first consider the short-run impacts of climate captured by coefficients on the first-differenced climate variables. As in each of our previous estimates, we find significant evidence of a non-linear relationship between temperature and economic growth. However, in column (7), estimates are only statistically significant for rich countries. Compared with column (5), we find that the peak growth temperature is lower in column (6) and for poor countries in column (7), but comparable for rich countries in column (7). We again find no significant evidence in support of a relationship between precipitation and economic growth.

Next, let us consider the long-run impacts of climate captured by the coefficients on the climate variable levels. We find no statistically significant evidence of a long-run effect, neither for temperature nor for precipitation.[10] This finding contrasts with Dell et al. (2012) who find evidence of long-run growth effects.[11] However, it is consistent with more recent results from Kalkuhl and Wenz (2020) and Newell et al. (2021) who find greater evidence in support of climate having an effect on economic income levels rather than on long-run economic growth.

For the estimating Equation (4), the estimated coefficient for lagged growth measures $1 - \lambda$, or one minus the convergence rate. Converting our estimates, we find a faster convergence rate for this model specification, both for the pooled model and for the model that distinguishes between rich and poor countries, than when estimating Equation (3). However, the difference in implied λ estimates between columns (5) and (6), which are directly comparable estimating equation, is not statistically significant. Again, our estimates for the implied value of λ are consistent with previous findings, such as the estimates

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[10] In the appendix we consider additional lagged climate terms. We find additional lags do not change this finding.

[11] Burke et al. (2015) follow the approach of Dell et al. (2012) and include lagged climate variables to test for short-run versus long-run growth effects. They find evidence of long-run growth effects. In the appendix, we analyze their findings in the context of our growth framework. When the regression includes lagged growth and, in particular, lagged growth is instrumented to correct for endogeneity, we find no evidence of a long-run growth effect.

in Bond et al. (2010).

4.2 Convergence Consistent Projections

In this section, we use our empirical estimates from the previous subsection to project country-level economic damages from climate change until the end of the century. We explore the consequences of incorporating convergence as guided by our theoretical framework. To project country-level climate damages, we follow the approach outlined in Burke et al. (2018). Specifically, we begin with initial projections of country-level economic growth for the 21st century from the Shared Socio-economic Pathways (SSPs) assuming that climate variables are static at 2010 levels in the SSPs, $x_{i,t,k} = x_{i,2010,k}$, for all t (O'Neill et al., 2014). This represents our baseline scenario without climate change. Let $y_{i,t}^{SSP}$ be the projected income per capita without climate change from the SSP. Then, we can write the projection of per-capita income in country i as the recursive equation:

$$\Delta y_{i,t}^{SSP} = -\lambda y_{i,t-1}^{SSP} + \sum_k \beta_k x_{i,2010,k} + \gamma_i(t) + \eta_i. \tag{5}$$

Substituting this into Equation (3) and letting $y_{i,t}^{CC}$ be the projected country-level income per capita with climate change, we find that the path of projected income under climate change can be generated recursively as follows

$$\Delta y_{i,t}^{CC} = \Delta y_{i,t}^{SSP} - \lambda(y_{i,t-1}^{CC} - y_{i,t-1}^{SSP}) + \sum_k \beta_k (x_{i,t,k} - x_{i,2010,k}), \tag{6}$$

where climate variables $x_{i,t,k}$ are obtained from the climate scenario.

Similarly, for econometric estimates following Equation (4), we project income per capita with climate change by recursively applying

$$\Delta y_{i,t}^{CC} = \Delta y_{i,t}^{SSP} + (1-\lambda)(\Delta y_{i,t-1}^{CC} - \Delta y_{i,t-1}^{SSP}) + \sum_k \beta_k \Delta x_{i,t,k} + \sum_k \theta_k (x_{i,t-1,k} - x_{i,2010,k}) \tag{7}$$

Equation (7) shows that the growth projections with climate change are the growth projections from the SSPs adjusted for not only the direct impacts of climate change but also the additional convergence effect induced by the impacts of climate change.[12] This convergence term is ignored in previous studies that use empirical estimates to project climate impacts, such as Burke et al. (2015). In Appendix C.2, we further derive an equation that expresses the long-run effect of climate changes on per capita income when climate variables reach a new steady-state.

We use the SSPs for our benchmark country-level economic growth projections. Here, we focus on

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[12] We assume that our baseline country-level growth scenarios already account for convergence pressures in the absence of climate changes. Figure 4 in the Supplementary Materials shows the changes in inter-country income inequality in the baseline growth projection illustrated as Lorenz Curves in 2010 and 2100. The decline in inequality over the century supports this assumption.

SSP5, a fossil-fueled development scenario with rapid economic growth. In the Supplementary Materials, we present results for alternative SSPs. While quantitative results vary, the qualitative takeaways are robust to the different SSPs. We use RCP8.5, the extreme warming scenario, as our climate change scenario for comparability with previous studies (Burke et al., 2015; Kalkuhl and Wenz, 2020). In this scenario, the mean global temperature rises around 3.6°C over the century. Supplementary Figure 5 shows the change in country-level population-weighted mean annual temperatures.

In Panel (a) of Figure 1, we show the projections of global average income for the SSP scenario without climate change, and for the RCP 8.5 climate change scenario across model specifications for columns (2), (4), and (5) from Table 1.[13] In each model specification projected average global incomes are lower by the end of the century with climate change than without climate change. This supports concerns about the negative global impacts of climate change. However, there is variation in projected incomes across model specifications, ranging from \$51,000/capita to \$58,000/capita at the end of the century (this range is from around \$35,000/capita to \$70,000/capita across all model specifications considered in the supporting material for SSP 5).

In Panel (b) of Figure 1 we show the distribution of projected country-level growth rates by the end of the century. Immediately apparent are the differences in the spread of country-level growth rates across model specifications. First, consider the SSP5 scenario without climate change. Over the century, in this baseline scenario, country-level growth slows and converges to an annual growth rate of around 3%, which is close to our empirical estimates of the steady-state growth rate for most countries (Figure 7 in the Supplementary Materials). Alternatively, consider the spread in country-level growth rates at the end of the century for the model specification of column (2). Here, growth rates again slow, but the spread of projected country-level growth rates increases over time. Notably, losses to hotter countries amplify over time until their incomes are eventually shrinking over time. That is, their growth rates become negative. This is due to the long-run persistence in the growth effects of climate for this model specification. Alternatively, when accounting for convergence effects in model specifications of column (4) and column (5), the spread of country-level growth rates shrinks over time and is more consistent with the baseline SSP5 projection.

In Figure 2 we compare the projected global average incomes in the baseline SSP scenario without climate change to projections with climate change, to measure the global economic losses from climate change. More precisely, we measure the losses as the percentage difference in projected global average GDP per capita between the scenarios with and without climate change. We again focus on model specifications for columns (2), (4), and (5) of Table 1 to examine the effect of accounting for convergence

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[13] Throughout this section we present results only for model specifications for columns (2), (4), and (5) from Table 1. Results for all model specifications reported in Table 1 can be found in the Supplementary Materials. In the text, we focus on these model specifications to compare a model specification similar to the model in Burke et al. (2015), but theoretically consistent, to a comparable model with the convergence term. We do not show results for the long-run model specifications, columns (6)-(7), because we find no evidence of persistent growth effects captured by those models.

pressures.

In Panel (a) we show the projected losses from climate change against time. This figure shows that accounting for convergence significantly reduces the projected losses from climate change. By 2100, for empirical estimates of column (4) and column (5), which account for convergence, we find losses from climate change are around 6% to 13%. For empirical estimates of column (2), which does not account for convergence, we find losses from climate change are around 16%. This result follows because in model specifications for columns (4) and (5), climate change's growth effects are not as persistent in the long-run. While climate impacts reduce economic growth, convergence counters these effects, limiting the long-run losses in per capita income.

The implications of accounting for convergence for the magnitude and distribution of long-run losses from climate change are also apparent at the country level. In Figure 3 we show the country-level difference in GDP per capita in 2100 between the scenarios with and without climate change. For the column (2) model specification, the specification without convergence, the negative impacts of climate change are large and apparent for the hotter tropical countries. There is also a considerable spread in impacts ranging from -95% to 1,491% difference in GDP per capita. This implies a considerable range of winners and losers from climate change. For model specifications for columns (4) and (5), which allow for convergence, the magnitude of impacts and the spread are smaller, ranging from just -18% to 22%.

In Panel (a) of Figure 2 the projection of global economic losses under the column (2) specification, which is similar to the Burke et al. (2015) specification, displays a U-shape towards the end of the century. This shape suggests that peak economic losses from climate change would occur in 2090, after which climate damages would start to decline. Neglecting convergence thus suggests that the gains to climate change winners—due to persistent per capita growth without convergence—would start dominating the losses of climate change losers around 2090. Thus, failing to account for income convergence overestimates medium-run impacts and underestimates long-term impacts.

Incorporating convergence pressures is consistent with the approach used by IAMs. In Panel (b) of Figure 2 we compare the economic damages of climate change based on projections using regression estimates for model specifications for columns (2), (4), and (5) of Table 1 to the results from three of the most commonly used IAMs for different mean global temperature changes. The projected damages from climate change under the column (2) specification, which is akin to the Burke et al. (2015) specification and does not account for convergence, greatly exceeds damages obtained from the IAMs, particularly at moderate to extreme temperature changes. Global average income losses for the IAMs range from around 2% to 7% for a 5°C increase in temperature, whereas income losses under the column (2) specification are projected to be around 17%. For the IAMs, the marginal damages of an increase in temperature rises with higher temperatures. This convexity in losses for IAMs is consistent with the expectation that the damages from climate change will increase convexly with deviations from the pre-industrial state of the climate. However, under the column (2) specification, we find that the marginal impact of an increase in temperature decreases at higher temperatures because the gains from the winners outweigh the losses to the losers. Once we account for convergence, as in model specifications for columns (4) and (5) of Table 1, projected climate damages are much closer to the IAM results, both in shape and in magnitude. At a 5°C increase, income losses for our central model specification in column (5) are close to the climate damage obtained from DICE, which is a reduction of output by around 7%.

5 Discussion

Climate-econometrics play an essential role in providing an empirical foundation for understanding the potential costs of climate change. When estimating and, more importantly, implementing these empirical approaches, it is crucial to ensure consistency with fundamental economic theories, such as the neoclassical growth theory that serves as the basis for Integrated Assessment Models.

Previous studies, such as Burke et al. (2015), have employed econometric estimates to project the economic impacts of climate change over extended periods, for instance, throughout the 21st century. They report climate damages significantly larger than those in traditional IAMs. In this paper, we demonstrate that these projected magnitudes can be reconciled by adopting an empirical approach consistent with the macroeconomic models underlying most IAMs. In particular, we show that factoring in the convergence growth effect, a key feature of neoclassical macroeconomic theory, substantially reduces the projected long-term impacts of climate change. A main result from our study is that ignoring growth convergence may lead to artificially high estimates for the long-term economic consequences of climate change.

Drawing from neoclassical macroeconomic theory, we derive empirical models to estimate the economic impacts of climate shocks, taking convergence into account. Additionally, we propose a test for distinguishing between transitory impacts on economic output levels and persistent impacts on underlying steady-state economic growth. Our empirical regression results reveal that, while accounting for convergence hardly changes the point estimates capturing climate's macroeconomic impact, it has significant implications for assessing the long-term economic consequences of climate change. Contrary to Dell et al. (2012), we uncover no evidence of persistent long-term growth impacts. Our estimates rather suggest that climate impacts in the long-run should only influence income levels, but not economic growth rates.

Consequently, when applying our findings to projections of economic growth under climate change, we observe that accounting for convergence considerably mitigates the damages from climate change. Ignoring convergence, as done in most of the climate-econometric literature, we find average global income losses by the end of the century that reach 16%. Allowing for convergence reduces these losses to around 6%. This estimate is in line with climate damages in prominent IAMs, such as the DICE model, which are also based on macroeconomic model that includes diminishing returns to man-made capital and thus convergence. Further, accounting for convergence influences the implications of climate change. For instance, without convergence, the gains experienced by the winners of climate change eventually surpass the losses incurred by the losers; thus, from a utilitarian welfare perspective climate change is projected to be beneficial in the long run, i.e., starting in the 22nd century. Moreover, without convergence, damages are estimated to be concave in climate deviations from pre-industrial levels. Including convergence reverses both findings and lead to conclusions more in line with expectations informed by environmental-macroeconomic theory: aggregate damages are convex in the extent of climate change and are projected to continuously increase over time with on-going climate change.

Despite the panel approach enabling the disentanglement of historical, institutional, and technological country-fixed effects from changes in climate conditions, our empirical approach still faces fundamental limitations inherent in most current climate-econometric approaches. For instance, the approach overlooks feedback from trade and price effects, implying that countries like Canada and Russia continue to benefit from climate change as their regional temperature approaches the optimum, even though there may be few viable trading partners left in the rest of the world. Considering these effects, the overall impact of climate change on countries GDP might differ from the one resulting from the direct climate impacts within the country (Calzadilla et al. 2013, Aaheim et al. 2015). Moreover, while our model aligns empirical estimates with the convergence effect in the neo-classical model of economic growth, it does not necessarily capture all the mechanisms of more intricate growth models. We leave these questions for future research.

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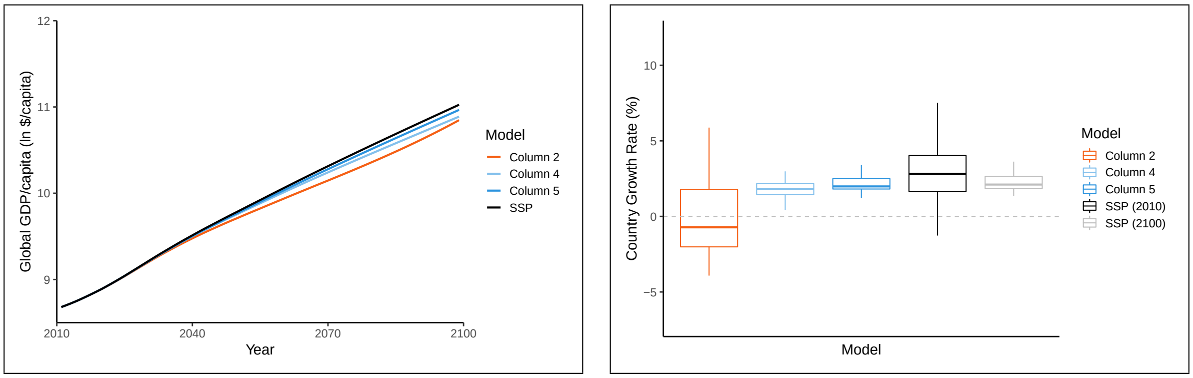
Tables and Figures

Table 1: Regression Results

Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Estimating equation	(3)	(3)	(3)	(3)	(4)	(4)	(4)
Restriction	$\lambda = 0$	$\lambda = 0$	$\lambda = 0$				
Dependent variable	Δy_{it}	Δy_{it}	Δy_{it}	Δy_{it}	Δy_{it}	Δy_{it}	$\Delta y_{it}^{\text{Rich}}/\Delta y_{it}^{\text{Poor}}$
Level effects:							
Temperature	0.00844	0.0128	0.0127	0.0108	0.00836		
	(0.00404)	(0.00423)	(0.00374)	(0.00360)	(0.00394)		
Temperature^2	-0.000249	-0.000477	-0.000487	-0.000380	-0.000316		
	(0.000106)	(0.000139)	(0.000117)	(0.000101)	(0.000149)		
Precipitation	0.0190	0.0137	0.0145	0.0203	0.0215		
	(0.00934)	(0.00987)	(0.00990)	(0.00913)	(0.0104)		
Precipitation^2	-0.00500	-0.00352	-0.00475	-0.00536	-0.00614		
	(0.00213)	(0.00223)	(0.00252)	(0.00212)	(0.00248)		
ΔTemperature						0.0131	0.0145/0.0104
						(0.00318)	(0.00323)/(0.0115)
ΔTemperature^2						-0.000566	-0.000539/-0.000520
						(0.000119)	(0.000139)/(0.000274)
ΔPrecipitation						0.00867	-0.00468/-0.00468
						(0.0107)	(0.00962)/(0.00962)
ΔPrecipitation^2						-0.00200	0.00277/0.00277
						(0.00302)	(0.00221)/(0.00221)
Growth effects:							
Temperature						-0.00113	-0.00162/0.00445
						(0.00292)	(0.00441)/(0.00728)
Temperature^2						0.00000952	-0.0000281/-0.0000687
						(0.0000775)	(0.000157)/(0.000159)
Precipitation						0.00590	0.00257/0.00513
						(0.00951)	(0.0125)/(0.0154)
Precipitation^2						-0.00253	-0.00453/-0.00133
						(0.00256)	(0.00296)/(0.00406)
Convergence:							
Implied λ				0.0471	0.192	0.375	0.585/0.235
				(0.00758)	(0.0109)	(0.153)	(0.193)/(0.184)
Max GDP/capita Growth Temp	16.9	13.4	13.1	14.2	13.2	11.5	13.5/10.0
Country-Specific Time Trend	None	Linear	Quadratic	None	Linear	None	None
Obs.	6584	6584	6584	6187	6187	6086	5963
R sq.	0.153	0.219	0.286				
Adj. R sq.	0.124	0.170	0.221				

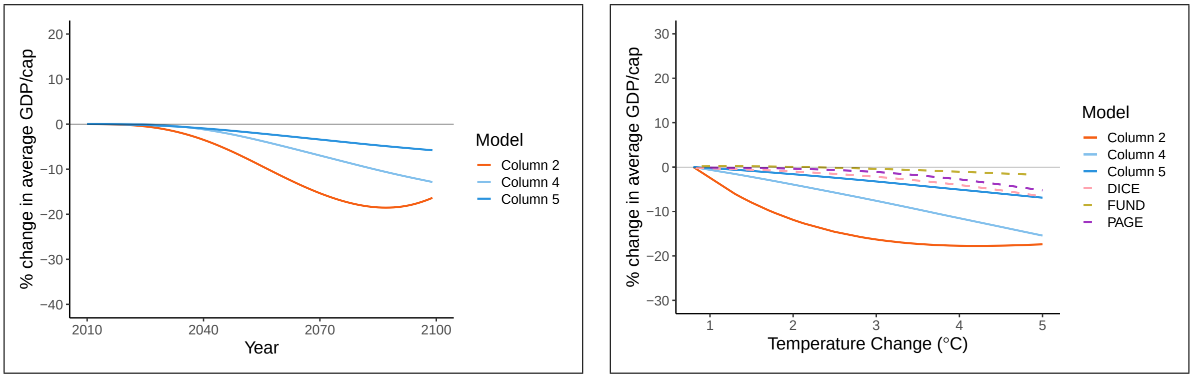
All models include country and year fixed effects. Standard Errors are clustered at the country level. Columns (1)-(3) are estimated using ordinary least squares. Addressing endogeneity, columns (4)-(7) are estimated instrumenting for lagged income or income growth with two-period prior lag. For regressions with level and differenced climate variables, max GDP/capita temperatures are calculated using the coefficients on the differenced variables. For the rich/poor specification, max GDP/capita temperatures is given for rich/poor countries. Temperature is measured in °C. Precipitation is measured in μm/year.



(a) Global GDP per capita projections

(b) Country-level growth rates (2099)

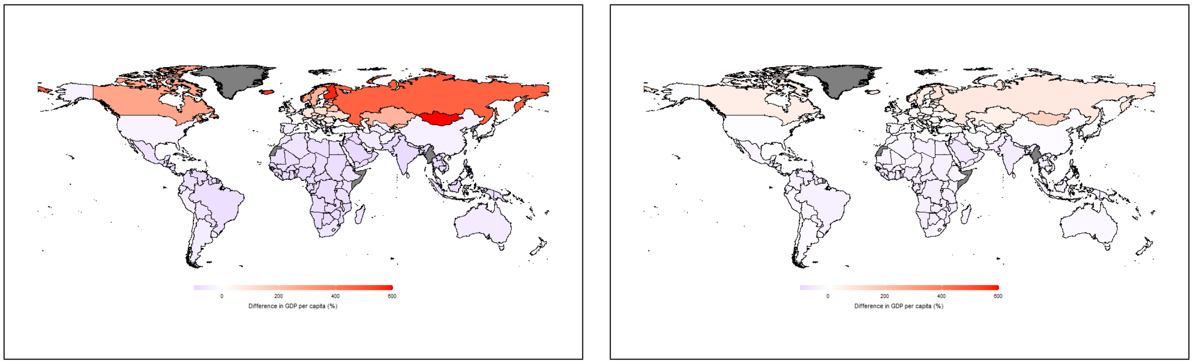
Figure 1: **GDP per capita projections**. (a) Global GDP per capita projection for SSP5 and adjusted for climate damages under RCP 8.5 across empirical specifications in Table 1. (b) Box-plots of projected country-level growth rates for SSP5 and adjusted for climate damages under RCP 8.5 across empirical specifications in Table 1. For the box-plots, the horizontal line shows the median, the box shows the interquartile range, and the whiskers show the 5 to 95 percentile range.



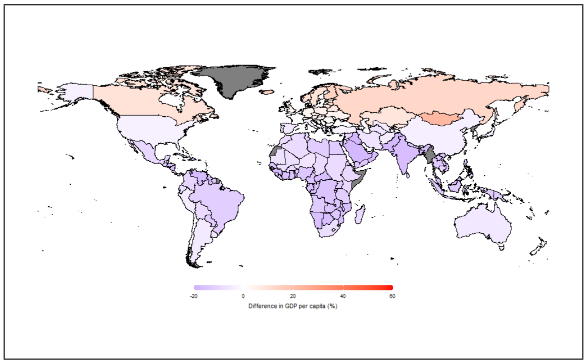
(a) Losses over time

(b) Losses over temperature change

Figure 2: **Global losses from climate change**. Difference in projected average global GDP per capita between no climate change and with climate change against time (a) and against temperature change (b) for empirical specifications from Table 1 and three IAMs. Temperature change in (b) is relative to pre-industrial temperature. Both figures are for SSP5.



(a) Column 2 (b) Column 4



(c) Column 5

Figure 3: **Country-level losses from climate change.** Difference in projected country-level GDP per capita between no climate change and with climate change in the year 2100. Figures are for SSP5 and empirical specifications from Table 1.

Appendix

A Additional Data Figures

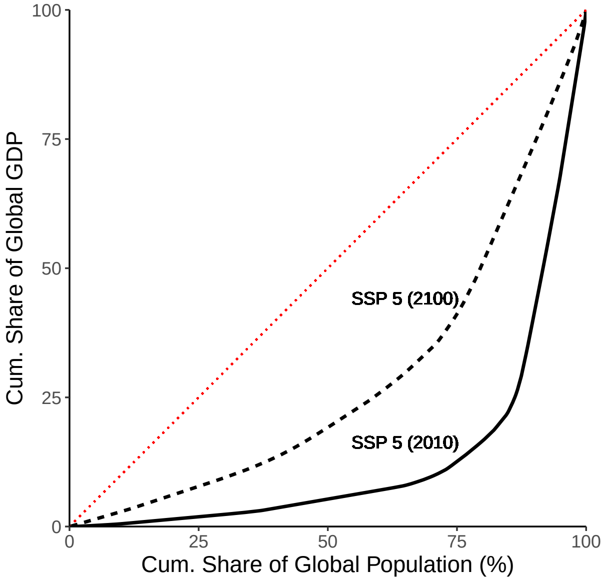


Figure 4: **Lorenz curves.** Lorenz Curve of country-level population and income for SSP5 in 2010 and 2100.

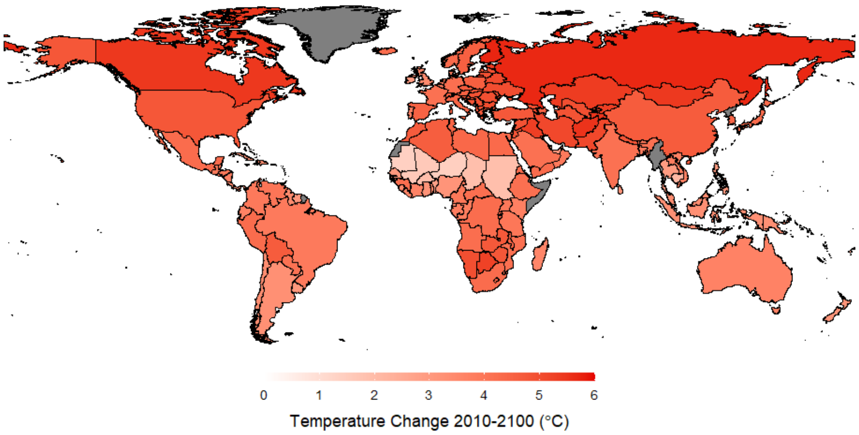


Figure 5: **Climate changes** Change in country-level annual population-weighted mean temperature over the 21st Century under RCP 8.5 forcings.

B Additional Regression Results

B.1 Additional Figures

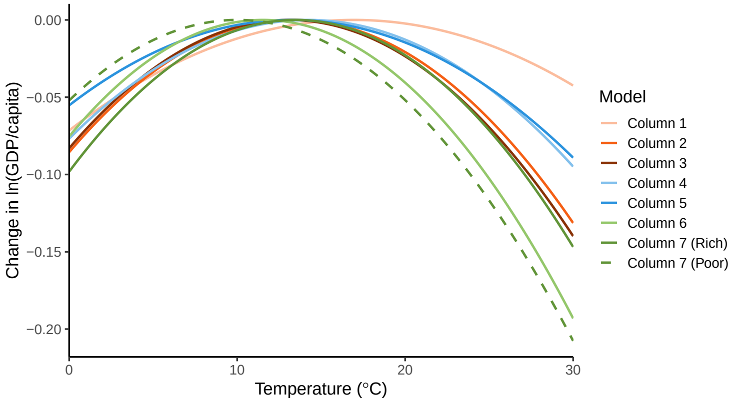


Figure 6: **Peak growth temperatures for alternative models.** Displays the marginal effects of temperature for each model specifications. For models that estimate with both level and first-differenced climate variables, we plot marginal effects of the first-differenced variables.

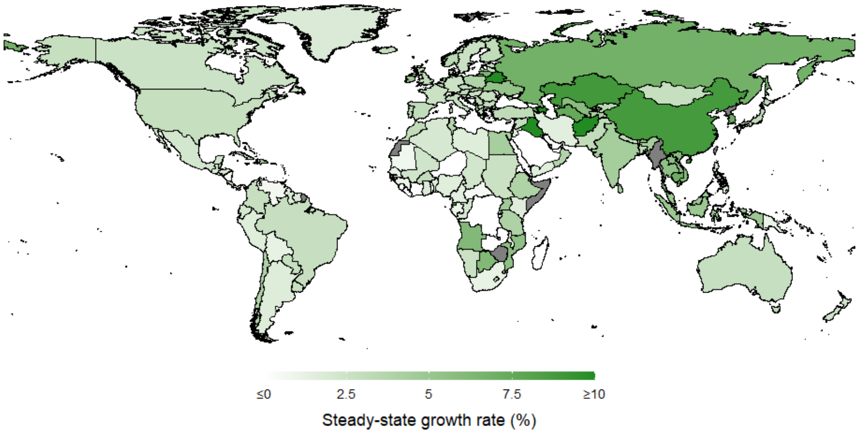
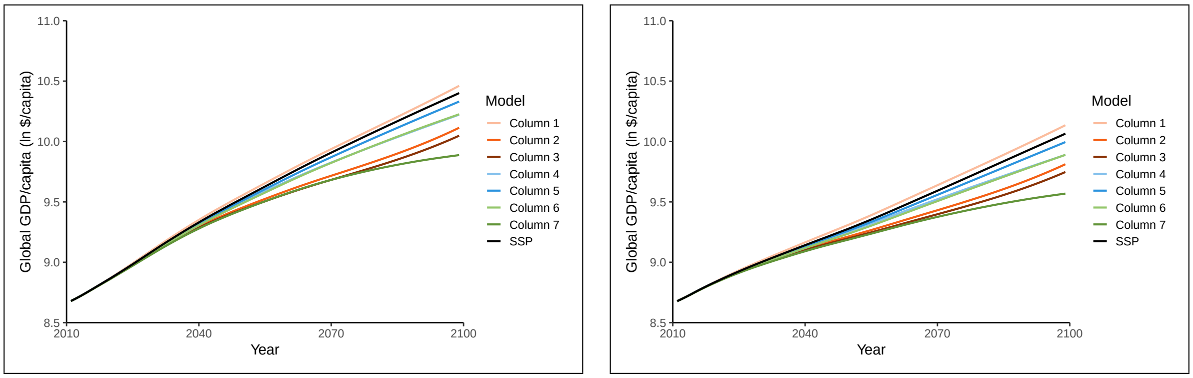
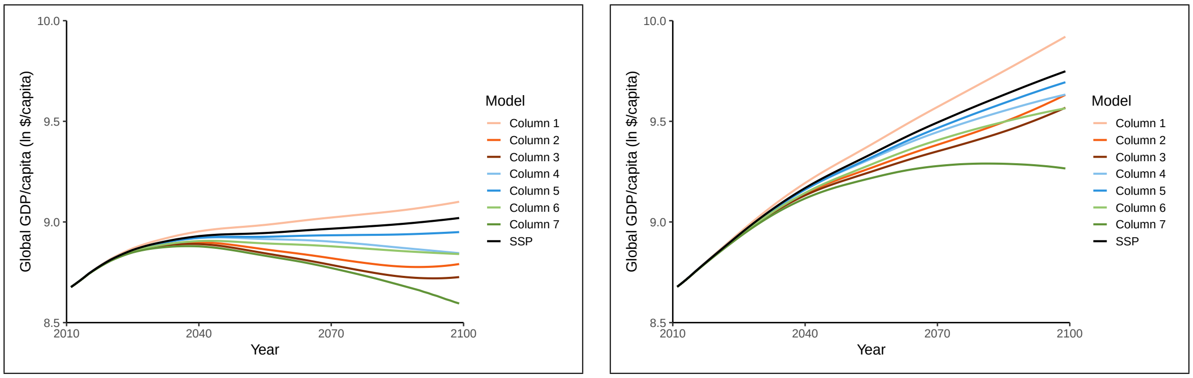


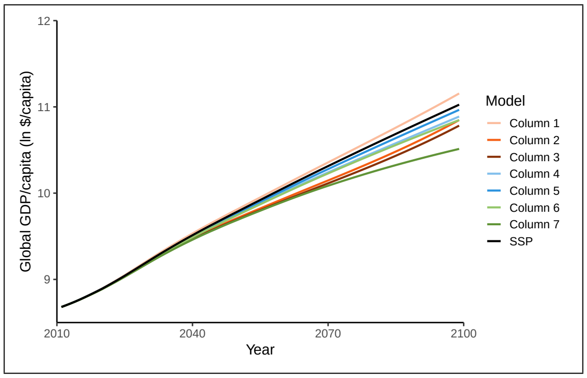
Figure 7: **Steady state growth** Estimates of country-level steady-state growth rates for column (5) empirical model.



(a) SSP1 (b) SSP2

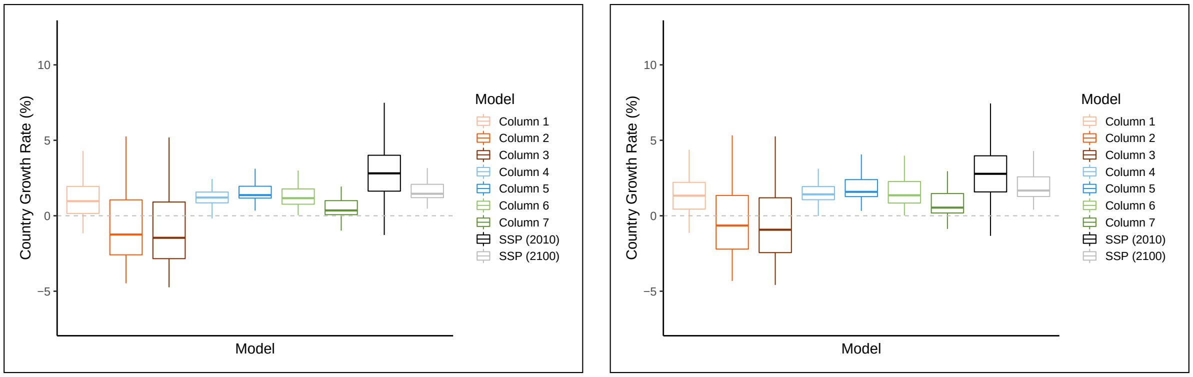


(c) SSP3 (d) SSP4

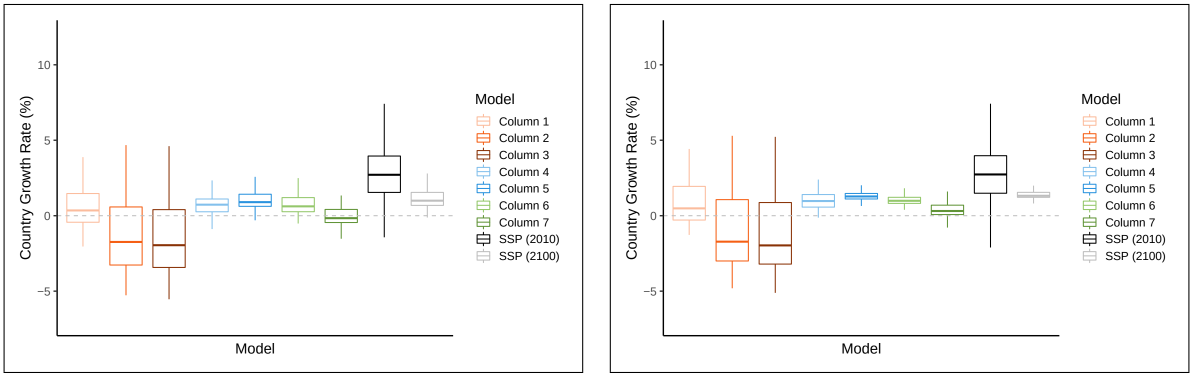


(e) SSP5

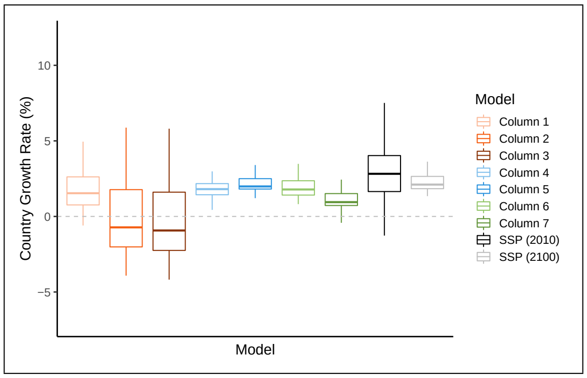
Figure 8: **Projections.** Projections of average global income for each model.



(a) SSP1 (b) SSP2

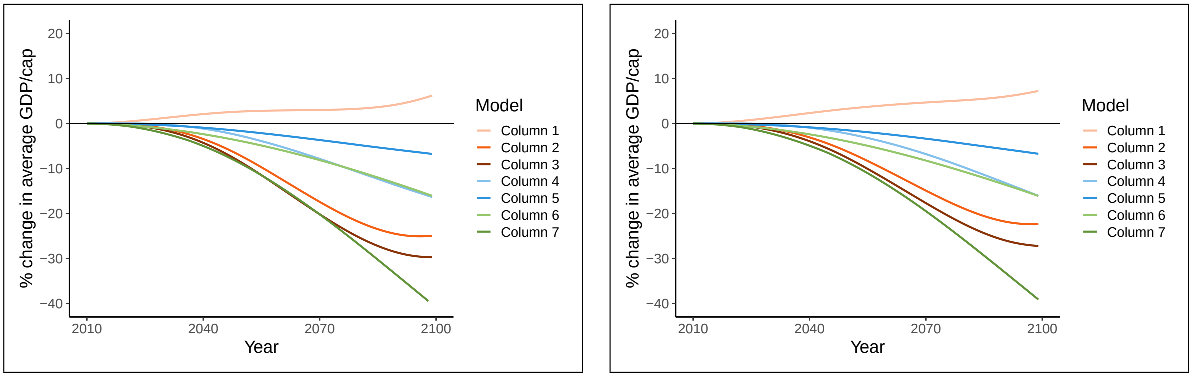


(c) SSP3 (d) SSP4

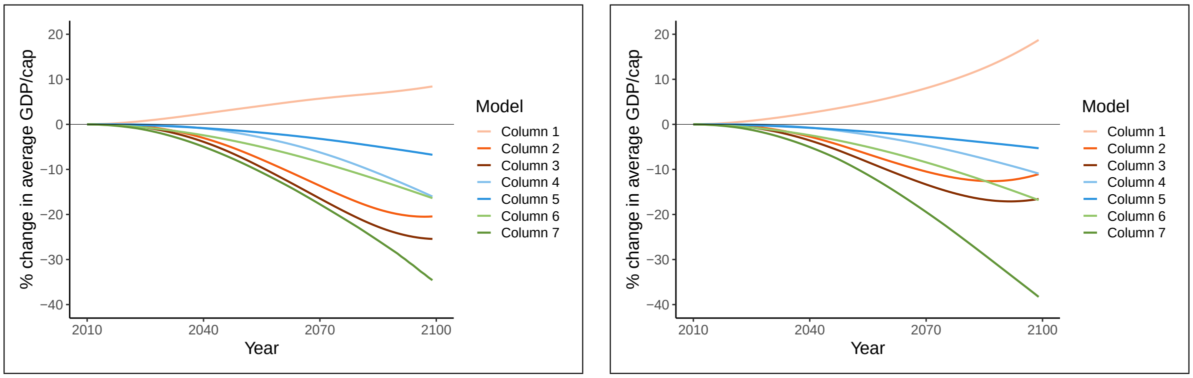


(e) SSP5

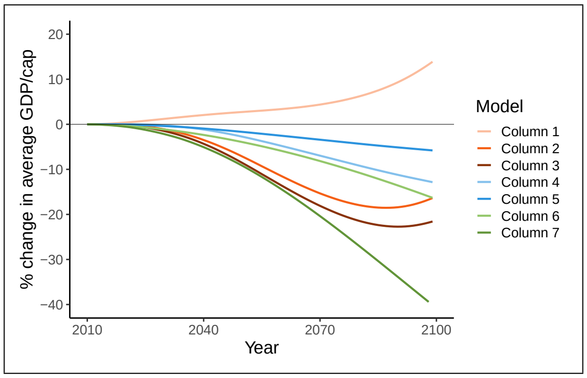
Figure 9: **Convergence of growth rates.** Box plot of projected country-level growth rates in 2099 for each of the models. Horizontal line represent median, box represents interquartile range, and whiskers represent 5 to 95 percentile range.



(a) SSP1 (b) SSP2

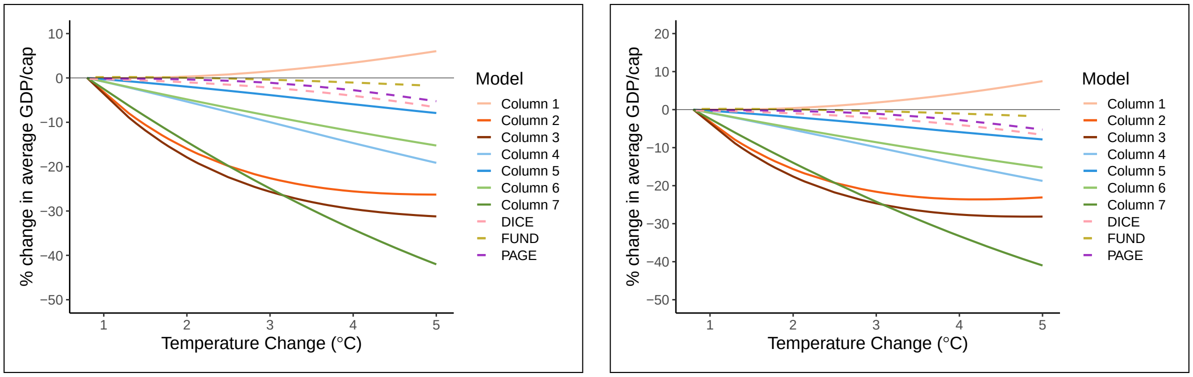


(c) SSP3 (d) SSP4

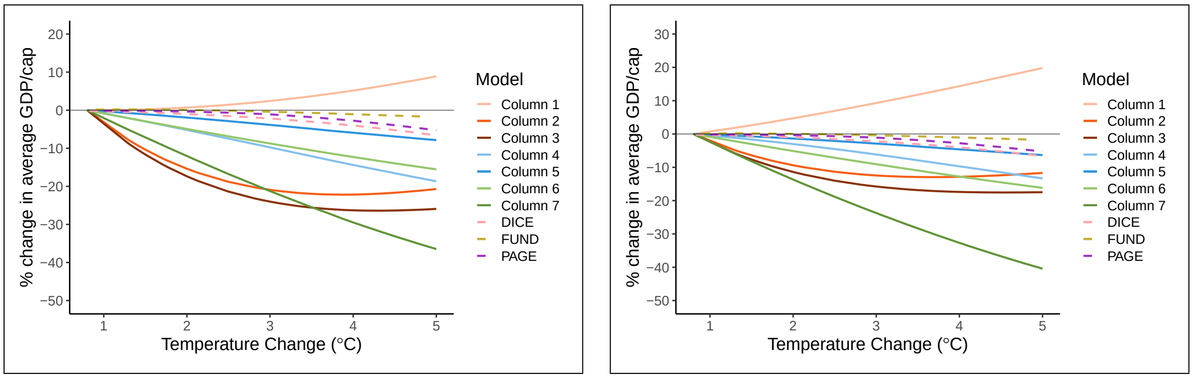


(e) SSP5

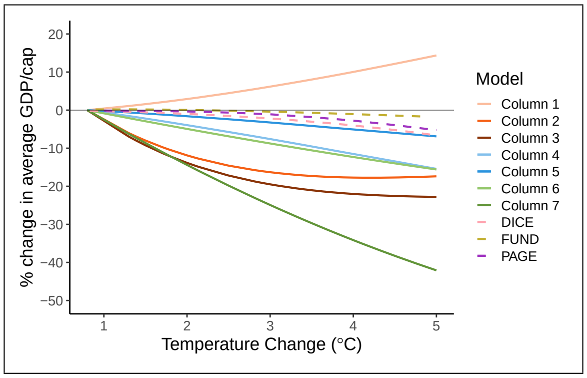
Figure 10: **Climate damages over time** Global damages of climate change over time measured as percentage difference in global average income.



(a) SSP1 (b) SSP2



(c) SSP3 (d) SSP4



(e) SSP5

Figure 11: **Climate damages over temperature** Global damages from climate change measured as percentage difference in global average income versus change in global average temperature

B.2 Non-linear country-level time trends

We estimate the following equation including non-linear, but bounded, country-specific time trends.

$$\Delta y_{i,t} = -\lambda y_{i,t-1} + \sum_k \beta_k x_{i,t,k} + \gamma_i^1 t + \gamma_i^2 t e^{-(t-t0)/\tau}. \tag{8}$$

There is no good justification for using any specific value of τ, which controls the rate at which the non-linear time trend term approaches 0, so we consider a range of possible values. Below, we plot the estimated marginal effects of temperature for each of the estimated values of τ as well as the corresponding projections of climate damages over time. It is clear that the climate impacts are sensitive to the τ parameter. We find that this is due to changes in the estimated temperature and precipitation coefficients when using an IV regression approach. For low values of τ, for which the non-linear term approaches 0 more quickly, we find damages are similar to the linear time trends model.

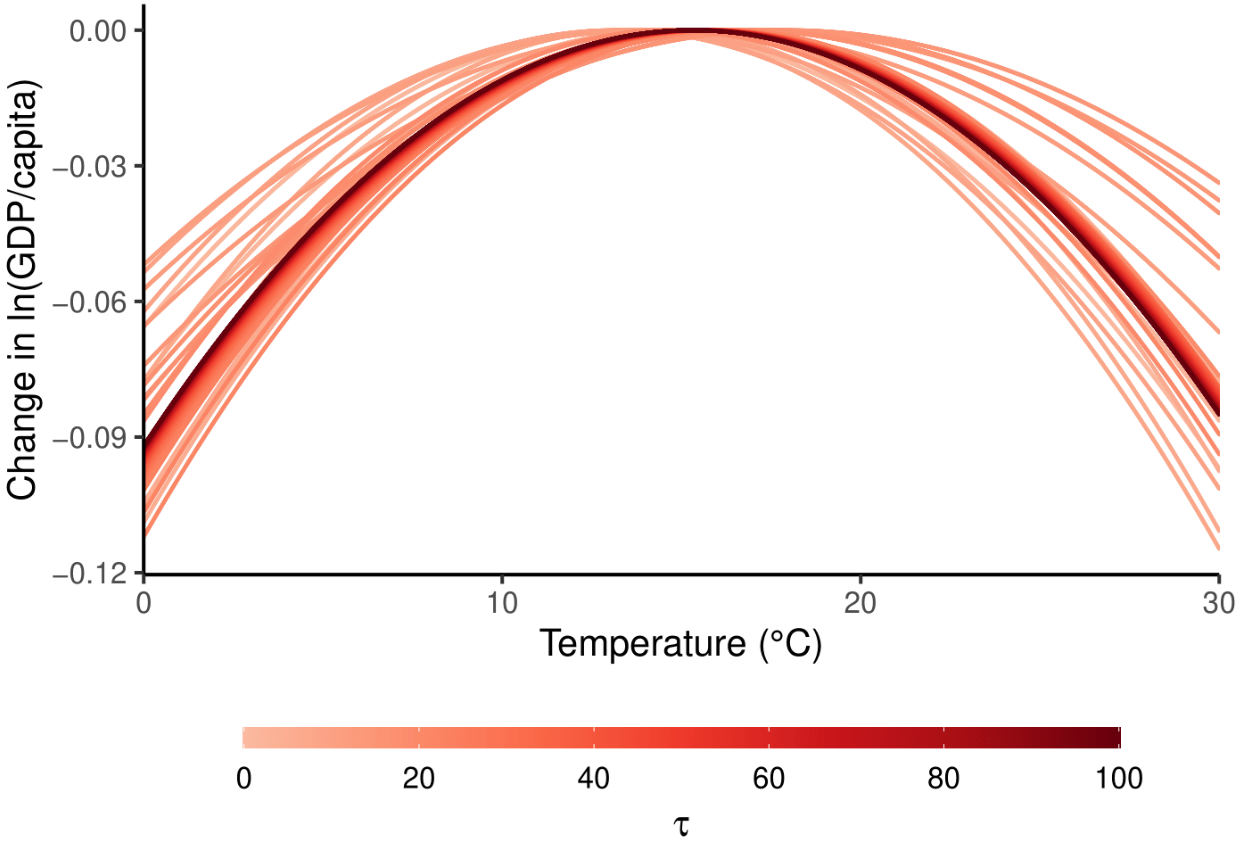


Figure 12: Marginal effects of temperature by τ value

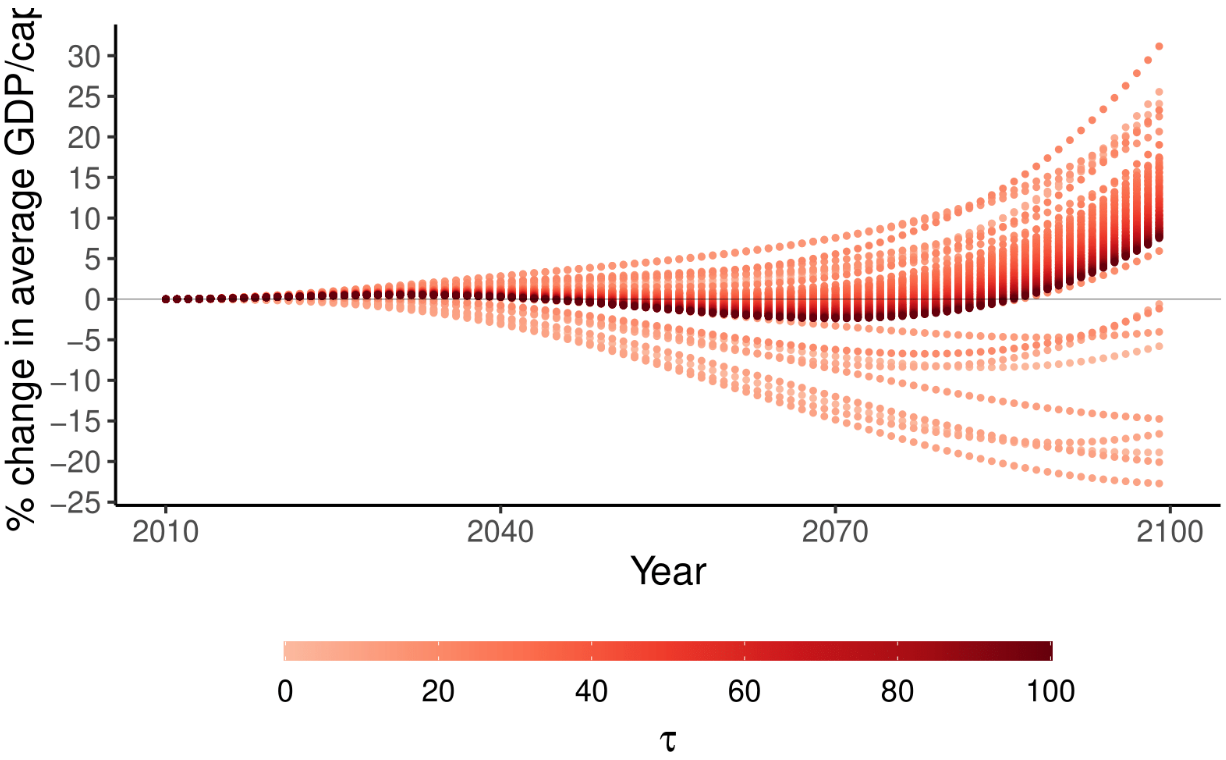


Figure 13: Global costs of climate change over time by tau value.

C Additional Theory and Modeling

C.1 Deriving the steady state and dynamics of the Solow model

The (Cobb-Douglas) Solow model can be presented and solved in a few lines. Let the time-dependent variables Y, K, L, A be output, capital, labor input (as well as population size), and technology, respectively; and let the constants $s \in (0,1), \delta > 0$, $\alpha \in (0,1)$, $g = \Delta \ln A$, and $n = \Delta \ln L$ be the savings rate, depreciation rate, production elasticity of capital, growth rate of technology, and growth rate of population, respectively. Output follows from a constant returns Cobb-Douglas production function

$$Y = K^{\alpha}(AL)^{1-\alpha}. \tag{9}$$

Capital accumulates according to

$$\Delta K/K = sY/K - \delta. \tag{10}$$

We rewrite these two equations in terms of the capital-output ratio $q \equiv K/Y$ and the log of per capita income $y \equiv \ln Y/L$. Using these definitions in the production function (9) gives for per capita income

$$y = \ln A + \frac{\alpha}{1-\alpha} \ln q. \tag{11}$$

Taking logs and first differencing the production function (9), and substituting the definition of q, we find

$$\Delta \ln q = (1-\alpha)(\Delta \ln K - n - g).$$

In (10) we approximate $\Delta K/K \approx \Delta \ln K$ and substitute in the above equation to find

$$\Delta \ln q = \lambda(q^*/q - 1), \tag{12}$$

where $q^* \equiv s/(n+g+\delta)$ and $\lambda \equiv (1-\alpha)(n+g+\delta)$. This shows that the steady state value of q is q^* and its adjustment speed is λ. Substituting $q = q^*$ into (11) gives (1) in the main text.
To derive (2), we note that for q close to q^* we have the first-order Taylor expansion $\ln(q^*/q) \approx q^*/q - 1$, so that we can approximate (12) by:

$$\Delta \ln q = \lambda(\ln q^* - \ln q).$$

Substituting this result into the first difference of (11), we find (2).

C.2 SSP-based growth

The assumption is that the climate variables are static at the 2010 levels in the SSPs, $x_{itk} = x_{i2010k}, \forall t$. Thus, we adjust the country-level economic growth in each year to account for changes in the climate variable from the 2010 level. Let y^{CC} be the predicted value (for log per capita income) with climate change and y^{SSP} the predicted value without climate change from SSP:

$$\Delta y_{i,t}^{SSP} = \sum_k \beta_k x_{i,2010,k} + \gamma_i(t) + \eta_i - \lambda y_{i,t-1}^{SSP}.$$

Substituting this into (3), we find

$$\Delta y_{i,t}^{CC} = \Delta y_{i,t}^{SSP} + \sum_k \beta_k (x_{i,t-1,k} - x_{i,2010,k}) - \lambda(y_{i,t-1}^{CC} - y_{i,t-1}^{SSP}).$$

This shows that the growth projections with climate change are the growth predictions from SSP adjusted for not only the impact of climate change, but also the additional convergence effect, i.e. the additional temporary growth because the level of income is lower (or higher) because of climate change. Solving the difference equation, we can express the climate effect on per capita income as

$$y_{i,t}^{CC} - y_{i,t}^{SSP} = \sum_{s=0}^{t-1} (1-\lambda)^s \sum_k \beta_k (x_{i,t-1-s,k} - x_{i,2010,k}).$$

If climate variables reach a steady state $x_{i,t,k} \rightarrow \bar{x}_{i,k}$, the long-run climate effect is

$$\lim_{t\to\infty} y_{i,t}^{CC} - y_{i,t}^{SSP} = \frac{1}{\lambda} \sum_k \beta_k (\bar{x}_{i,k} - x_{i,2010,k}).$$

C.3 Understanding BHM Long run specification

Following the approach of Dell et al. (2012), Burke et al. (2015) test for long-run or persistent impacts of climate on economic growth by using additional lags. Following the Appendix of Dell et al. (2012), Equation (4) can be rewritten as

$$\begin{aligned}
\Delta y_{i,t} &= (1-\lambda)\Delta y_{i,t-1} + \sum_k \beta_k \Delta x_{i,t,k} + \sum_k \theta_k x_{i,t,k} + \gamma_i + \Delta\epsilon_{i,t} \\
&= (1-\lambda)\Delta y_{i,t-1} + \sum_k \beta_k x_{i,t,k} - \sum_k \beta_k x_{i,t-1,k} + \sum_k \theta_k x_{i,t,k} + \gamma_i + \Delta\epsilon_{i,t} \\
&= (1-\lambda)\Delta y_{i,t-1} + \sum_k (\beta_k + \theta_k) x_{i,t,k} - \sum_k \beta_k x_{i,t-1,k} + \gamma_i + \Delta\epsilon_{i,t} \\
&= (1-\lambda)\Delta y_{i,t-1} + \sum_k \rho_k^t x_{i,t,k} - \sum_k \rho_k^{t-1} x_{i,t-1,k} + \gamma_i + \Delta\epsilon_{i,t}.
\end{aligned} \tag{13}$$

Estimating this equation using the levels of climate variables, rather than a mixture of levels and first-differences one can test for long-run growth effects, that is $\theta_k = 0$, as $\rho_k^t = -\rho_k^{t-1}$. If the coefficient on the lagged level climate variable is equal in magnitude but opposite in sign to the current period climate variable, then climate there is no evidence that climate has a persistent impact on long-run growth.

Here we estimate such a model first using the Burke et al. (2015) specification and then adjusting the model specification to make the model consistent with ours. The regression results are shown in Table 2. Column (1) shows the results for a quadratic country-specific time trend and no lagged growth term. Considering the coefficients on the current and lagged temperature terms, we can reject the null hypothesis that the coefficients are equal in magnitude but opposite in sign. This suggests that there is evidence of the long-run impacts of climate on economic growth. In the next column, we add lagged growth and consider only a linear country-specific time trend. In column (3) we estimate the model instrumenting for the lagged growth term. Finally, in column (4) we remove the country-specific trends, giving a model consistent with our theory. Considering the coefficients on the temperature terms in column (4), the current and lagged terms are significantly closer in magnitude and we can no longer reject the null hypothesis that their sum is statistically significant from zero. This shows that after adjusting the model specification to be consistent with the underlying theory and account for endogeneity, the persistence of climate impacts on growth disappears.

Table 2: Additional Regression Results

	(1) Δy_{it}	(2) Δy_{it}	(3) Δy_{it}	(4) Δy_{it}
$\text{Temperature}_{i,t}$	0.0151	0.0136	0.0113	0.0119
	(0.00387)	(0.00377)	(0.00330)	(0.00297)
$\text{Temperature}_{i,t-1}$	-0.00515	-0.00929	-0.0108	-0.0131
	(0.00350)	(0.00345)	(0.00528)	(0.00318)
$\text{Temperature}^2_{i,t}$	-0.000574	-0.000550	-0.000531	-0.000557
	(0.000126)	(0.000127)	(0.000132)	(0.000119)
$\text{Temperature}^2_{i,t-1}$	0.000193	0.000346	0.000463	0.000566
	(0.000106)	(0.000107)	(0.000209)	(0.000119)
$\text{Precipitation}_{i,t}$	0.0129	0.0109	0.0132	0.0146
	(0.0102)	(0.00852)	(0.00912)	(0.00886)
$\text{Precipitation}_{i,t-1}$	0.00433	0.000680	-0.00618	-0.00867
	(0.0102)	(0.0110)	(0.0120)	(0.0107)
$\text{Precipitation}^2_{i,t}$	-0.00432	-0.00339	-0.00414	-0.00453
	(0.00260)	(0.00192)	(0.00229)	(0.00217)
$\text{Precipitation}^2_{i,t-1}$	-0.00179	-0.000149	0.00123	0.00200
	(0.00258)	(0.00317)	(0.00365)	(0.00302)
Δy_{it-1}		0.238	0.433	0.625
		(0.0401)	(0.378)	(0.153)
Marginal Effect at 5°C	0.0062	0.0023	-0.0003	-0.0010
Marginal Effect at 25°C	-0.0090	-0.0059	-0.0030	-0.0006
Country-Specific Time Trend	Quadratic	Linear	Linear	None
Obs.	6,519	6,418	6,086	6,086
Estimation Method	OLS	OLS	IV	IV

All models include country and year fixed effects. Standard Errors are clustered at the country level. Columns (1)-(2) are estimated using ordinary least squares. Columns (3)-(4) are estimated instrumenting for lagged income growth with two-period prior lag. Marginal effects are evaluated by summing over the lagged coefficients which is equivalent to assuming a stable climate. Temperature is measured in °C. Precipitation is measured in μm/year.