Energy Economics 149 (2025) 108705

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Distribution of climate damages in convergence-consistent growth projections[☆]

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ARTICLE INFO

Dataset link: https://doi.org/10.7910/DVN/BFL5HZ

JEL classification:
Q54
O47
O44
C23
D63
Q56

Keywords:
Climate change
Economic growth
Convergence

ABSTRACT

Climate-econometric estimates assuming that climate changes affect economic growth result in larger projected damages than estimates restricting the effect to economic income levels. We show that the latter is consistent with neoclassical macroeconomic theory by explicitly accounting for income growth convergence in our empirical investigation. We show that accounting for convergence does not statistically change the point estimates capturing climate's macroeconomic effect, but it has significant implications for assessing the long-term economic consequences of climate change. The magnitude and spread of long-term losses from climate change are reduced. Aggregated damages are found to be convex in the extent of climate change and are projected to continuously increase over time with on-going climate change, in contrast to growth-effects-only estimates where the gains experienced by the winners of climate change eventually surpass the losses incurred by the losers. For example, projections of climate change damages based on climate-econometric estimates by Burke et al., 2015 find that global warming could reduce average global incomes by 20% and drastically increase intercountry income inequality, reflected by a 118% increase in the Gini coefficient in 2100 under RCP8.5. We reestimate and project climate damages under the same scenario accounting for convergence and find global climate damages around 8.5% of global incomes and an increase in intercountry income inequality by 8% in 2100.

1. Introduction

Projected climate damages based on reduced-form empirical climate impacts predict large impacts on income levels and an exacerbation of intercountry income inequality due to climate damages. This is particularly the case for estimates that consider persistent or semi-persistent impacts of climate on economic growth. For example, Burke et al. (2015) find that climate change has a heterogeneous impact on the growth of economic output across countries based on their climate. Climate change is projected to accelerate growth in colder countries, whereas it slows growth in hotter countries. By the end of the 21st century, due to the extreme dispersion in output following climate damages, the cumulative gains of the countries with accelerated growth begin to outweigh the, necessarily bounded, cumulative losses to those countries who lose from climate change. Thus, in the long run, this projection suggests that climate change can be economically beneficial, as it will increase global output.

This paper shows that the extreme dispersion in the distribution of projected climate change damages stems from a failure to account for neoclassical economic growth forces. We present 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 most Integrated Assessment Models (IAMs) and the methods employed in the broader empirical growth literature (Barro and Sala-i Martin, 1992;

☆ We thank Reyer Gerlagh and Mauricio Rodriguez Acosta for their comments and feedback.
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https://doi.org/10.1016/j.eneco.2025.108705
Received 23 April 2024; Received in revised form 3 June 2025; Accepted 25 June 2025
Available online 16 July 2025

Temple, 1999; Johnson and Papageorgiou, 2020). By adopting the foundational 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. 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, accounting for the interaction of climate impacts and convergence.

Our results are consistent with previous evidence for a non-linear effect of temperature on economic output levels, but we do not find evidence of enduring impacts on economic growth. When projecting economic damages from climate changes, we find that incorporating convergence effects considerably diminishes dispersion in the distribution of climate damages and reduces overall global climate damages. For example, Burke et al. (2015) estimates that climate change will reduce global average incomes by approximately 20% and increase inequality by around 118% as measured by the Gini coefficient. In contrast, our central specification indicates a reduction in global average incomes around 8.5% and an increase in intercountry inequality of less than 8%. This reconciles the discrepancies in climate damages between the climate-econometric approach and the IAM literature and shows climate change has a lesser impact on inter-country income inequality than previously found by some other climate-econometric studies, particularly those that build projections based on growth effects.

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). Yet, the empirical question whether climate has short-run or long-run effects on growth cannot be answered by an IAM. This has spurred a growing literature that uses empirical methods to inform whether climate impacts output levels or growth rates. The evidence has been mixed.

Predominantly, this literature leverages observed changes in climate variables and national economic growth rates to empirically estimate climate change damage functions and project future damages from climate change (e.g., Dell et al., 2014; Burke et al., 2015). Some researchers have found evidence of persistent, but sometimes not permanent, impacts on economic growth rates. Burke et al. (2015, 2018) find a persistent, non-linear effect of temperature on economic growth rates. More recently, Kotz et al. (2021, 2022, 2024) find evidence for persistent but not permanent impacts on economic growth rates, with impacts lasting up to 10 years in the case of Kotz et al. (2024). Using a low-pass filter to separate longer and shorter frequency temperature fluctuations, Bastien-Olvera et al. (2022) find that long-term temperature anomalies can have impacts comparable to short-term anomalies, suggesting evidence of persistent impacts on growth rates. On the other hand, studies such as Kalkuhl and Wenz (2020) and Newell et al. (2021) provide evidence that temperature impacts output levels, rather than growth rates. Bridging these, Nath et al. (2024) investigates the role of international technology diffusion in mediating climate impacts. By incorporating spillover effects across countries, Nath shows that local temperature shocks can generate output losses that exceed typical level-effect estimates, but still smaller than fully persistent growth impacts. Cross-country linkages amplify the economic consequences of climate change without requiring permanent changes in growth rates.

This empirical question continues to receive attention as researchers consider different methods, spatial resolutions, climate variables, and outcome variables. Burke and Tanutama (2019), Kotz et al. (2024), and Callahan and Mankin (2022) estimate climate impacts at the subnational level. This is particularly important for the effects of precipitation as effects are attenuated when spatial aggregation masks heterogeneity (Holtermann, 2020; Damania et al., 2020). Alternatively, Callahan and Mankin (2023) and Bilal and Känzig (2024) examine common global temperature shocks, which they find leads to higher estimates of climate impacts than local temperatures alone. Kotz et al. (2021) and Waidelich et al. (2024) examine the role of climate indicators beyond annual temperature. Kahn et al. (2021) estimate asymmetric impacts for deviations of temperature and precipitation from their trend. Mérel and Gammans (2021) examines how identifying variation constrains whether estimated impacts capture short-run versus long-run impacts. Letta and Tol (2019) examines impacts on total factor productivity. Moore et al. (2024) provides an extensive review of existing climate impact estimates decomposing variation based on methodological approaches. In this paper, we apply data and methods mirroring (Burke et al., 2015) to isolate how incorporating convergence effects estimates and projections of climate impacts.

Yet, this literature remains mostly silent about the effects of climate change on inter-country income inequality. Two notable exceptions are Dell et al. (2012) who provide evidence that temperature impacts country-level economic growth only in poor countries and Burke et al. (2018) who find the ratio between the highest- and lowest-decile of incomes increases by 25% in a warming world. This question of the distributional impacts of climate change, both inter-country (Pretis et al., 2018) and intra-country (Gilli et al., 2024), is an important one, with particular implications for the development of a loss and damage fund (Tavoni et al., 2024).

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. With the muted convergence effects in these projections, climate change has persistent differential effects on income across countries and leads to a strong divergence in incomes across countries, resulting in pronounced winners and losers. Closest to this paper, Casey et al. (2023) estimates climate impacts starting from a neoclassical model of economic growth to derive estimating equations. Different from Casey et al. (2023), our focus is the role of accounting for growth convergence and its effect on the distribution of climate damages and intercountry inequality.

Below, we show how accounting for such convergence effects can meaningfully guide projections of the economic impacts of climate changes. In Section 2, we build on a concise neo-classical growth model, derive an empirical model, factoring in convergence. In Section 3, we describe our empirical estimating equations and detail the data used for estimation. In Section 4, we present our findings. In Section 5, we draw our conclusions.

2. 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 indicates that the economy under consideration reaches a steady-state where per-capita output is described by[1]

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

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 and “reflects not just technology but resource endowments, climate, institutions” (Mankiw et al., 1992, p. 5).

[1] 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 as well as how (3) and (4) can be derived from (2).

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.[2]

In DICE, and most other IAMs, it is by assumption that climate impacts productivity levels, but not the long-run trend of technological change.[3] 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 Eq. (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 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.[4] Decreasing returns to man-made capital imply $1-\alpha > 0$. Here g_i, λ, and $y^*_{i,0}$ need to be estimated from observable 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.

3. Estimating growth effects with convergence

We estimate the transitory and permanent growth effects of climate channels in a manner consistent with theory following the approach of Bond et al. (2010).

As noted in Bond et al. (2010), a common empirical specification has the following form[5]

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

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, ν_t are year fixed effects, 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 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, which 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.[6]

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

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

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

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

[2] 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).

[3] There are a few notable exceptions that have examined other channels for climate impacts. For example, Moore and Diaz (2015), Dietz and Stern (2015), Lemoine and Kapnick (2016), Guivarch and Pottier (2018), and Bilal and Känzig (2024) have considered impacts through TFP levels, TFP growth, and capital depreciation.

[4] 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 $|1-\lambda| < 1$.

[5] See Appendix C.1 for a derivation of Eqs. (3) and (4) from Eq. (2).

[6] In Appendix B.2 we consider a flexible, non-linear, but still bounded time-trend specification given as $\gamma_i(t) = \gamma_{i1}\, t + \gamma_{2i}\, t\, \mathrm{e}^{-\frac{1}{\tau}(t-t_0)}$.

Unlike for Eq. (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 Eq. (4) capture the transitory growth effects of changes in climate, as in Eq. (3). By estimating Eq. (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.[7]

Dell et al. (2012) also follow this estimation approach, however, for estimation in the text of their paper they abstract from convergence, i.e. $\lambda = 0$. In their appendix, they test this assumption and find that fixing $\lambda = 0$ does not bias their estimates. Yet, while excluding 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 climate damages. Excluding the convergence term implies all growth effects become long-run effects when using the estimates in projections. However, evidence of growth convergence, i.e. $\lambda > 0$ or more generally $|1 - \lambda| < 1$, will moderate any climate impacts that exacerbate inter-country income inequality.

3.1. Data

We use the same sources for country-level economic data and climate data for our empirical analysis as Burke et al. (2015). The data on economic growth comes from the World Bank and covers 1960 to 2023 (World Bank Group, 2024). The climate data comes from monthly gridded interpolated weather station data and covers 1960 to 2017 (Willmott and Matsuura, 2018). 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. Thus, we let the data overlap with Burke et al. (2015) and Dell et al. (2012) as much as possible to ensure comparability with previous seminal work on this topic. In Supplementary Materials Section C.4 we analyze the effect of using updated climatological and economic data relative to the replication data of Burke et al. (2015) and find our takeaways are consistent whether using the replication or updated data. To measure common impacts from global temperature shocks, in addition to the effect of local temperatures, we use data on global mean temperature from NOAA National Centers for Environmental information (2024).

4. Results

4.1. Convergence-consistent regression results

We estimate Eqs. (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 $x_{i,t,k}$ we use linear and quadratic terms of country-level temperature and precipitation to allow for non-linearities in the relationship between climate and economic growth.[8,9] We estimate a single global relationship between climate variables and economic growth. But 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). It is also possible that common global temperature shocks have an effect above local temperature exposures à la (Bilal and Känzig, 2024), so in two model specifications we include contemporary and lagged temperature shocks. Temperature shocks are measured as the residual of two-period lead of global mean temperature regressed on contemporary and up to two-period lag of global mean temperature, following the process laid out in Bilal and Känzig (2024). We chose to include up to 5 lags after considering the statistical significance of additional lags and the strength of the instrument for lagged output. Table 1 shows the results across model specifications.

In columns (1)–(4) of Table 1 we estimate Eq. (3) assuming there is no convergence, i.e. $\lambda = 0$. As a reminder, by leaving out the convergence term, all climate effects are, by construction, permanent growth effects. 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), providing a benchmark for comparison. In particular, estimates in column (3) of Table 1 are identical to Burke et al. (2015)'s benchmark specification. Column (4) includes a linear time trend and considers the additional effect of global temperature shocks.

Across columns (1)–(4) of Table 1, we find statistically significant evidence that local temperature has a non-linear impact on economic growth (Figure 6). Our results indicate the existence of a "peak growth" temperature for countries, in which any deviations from this temperature result in a slowdown of economic growth. That is, if a country is typically colder than the peak growth temperature, a marginally warmer year will boost in economic growth. Alternatively, if a country is typically warmer than the peak growth temperature, a marginally warmer year will slow economic growth. 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). Column (4) suggests that global temperature shocks have a persisting effect on economic growth in addition to the effect of local temperatures.

In column (1) we estimate Eq. (3) without country-specific time-trends. We estimate peak growth temperature is 12.4 °C. In column (2) we add linear country-specific time-trends and find a higher 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) with quadratic country-specific time trends. We find the coefficients for climate variables are similar to those in column (2). But, as a quadratic trend is unbounded and inconsistent with the notion of convergence from our theoretical framework, we only report it here for comparison with the previous literature. We focus only on column (2) as our baseline for the remainder of the text.[10] In column (4) we augment the estimates of column (2) with global temperature

[7] Kahn et al. (2021) use an autoregressive distributed lag (ARDL) specification similar to Eq. (4) except that they exclude the level climate variable terms. Thus, they can only capture the short-run impacts of climate on economic output levels.

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

[9] It is possible that climate could interact with other determinants of economic growth, such as population growth or human capital formation (Casey et al., 2019). Future work could explore these interactions.

[10] Across these empirical specifications, we find no evidence of a statistically significant effect of precipitation on economic growth. As discussed in Damania et al. (2020) this is likely due to the aggregation of precipitation measures, which exhibit considerable spatial variation.

shocks. We find that including global temperature shocks does little to change the impact of local temperatures but augments with a lasting negative impact of global temperature shocks.

Next, in columns (5)–(7) of Table 1 we estimate Eq. (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 (5) we do not include country-specific time trends, i.e. we impose $\gamma_{1i} = 0$. In column (6) we estimate linear time-trends. Coefficients on these trends estimate γ_{1i}. In column (7) we augment the estimates of column (6) with global temperature shocks.

Note, while columns (1)–(4) can be estimated with OLS, when the lagged log of GDP per capita is considered as an independent variable, there are concerns of endogeneity. Thus, for columns (5)–(9) we follow the approaches of Bond et al. (2010) and Dell et al. (2012) and instrument using lagged income or income growth with two-period prior lags.

For the transitory effects of climate on economic growth, we again find significant evidence 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 columns (5) and (6) are comparable to those found in columns (2) and (3), if slightly higher, although the marginal effects at high and low temperatures are dampened. This suggests that including the convergence term has little effect on the precision of estimates of climate's growth effects, as found by Dell et al. (2012). Yet, it has important implications for the interpretation of the coefficients and their implications in projections of damages from climate changes which we illustrate in the next subsection.

Across columns (5)–(7), we find that the convergence term, $-\lambda$, is significant and negative, which indicates that lower output levels lead to faster economic growth. Moreover, one plus the point estimate for $1 - \lambda$ is less than one in absolute value, which indicates support for convergence. Our point estimates are consistent with previous estimates, such as those by Lee et al. (1998).

Supplementary Figure 7 shows estimates for the linear country-specific trends' for estimates in column (6). These coefficients measure countries' steady-state growth rates, γ_{1i}. We find that over 75% of countries have a steady-state growth rates between 0%–5%, and the majority around 1%–3%.

To test both channels by which climate can affect economic growth, both long-run and short-run, in columns (8)–(9) of Table 1 we estimate Eq. (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 (8) is a more general estimating equation than in column (6) by allowing for long-run growth effects and by nesting the previous specification. We find that this more general specification is consistent with the short-run only estimates in column (6). In column (9), we additionally explore the possibility of differential effects of climate between rich and poor countries.

Considering the first-differenced climate variables, we find significant evidence of a non-linear relationship between temperature and economic growth in the short-run, consistent with our previous estimates. However, in column (9), estimates are only statistically significant for rich countries. Compared with column (6), we estimate a lower peak growth temperature in column (8) and for poor countries in column (9), but comparable for rich countries in column (9). We find no significant evidence of a relationship between precipitation and economic growth.

Considering the leveled climate variables, we find no significant evidence of a relationship between temperature or precipitation and economic growth in the long run. This is consistent with recent results from Kalkuhl and Wenz (2020) and Newell et al. (2021) who find stronger evidence in support of climate having an effect on economic income levels rather than on long-run economic growth.[11]

For the estimating Eq. (4), the estimated coefficient for lagged growth measures $1 - \lambda$, or one minus the convergence rate. We find a faster convergence rate for this model specification than our estimates of Eq. (3). However, the difference in estimates of λ between columns (6) and (8) is not statistically significant. Our estimates for the implied value of λ are consistent with previous findings, such as in Bond et al. (2010).

4.2. Convergence consistent projections

We use our empirical estimates from the previous subsection to project country-level economic damages from climate change through the end of the century, and 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 construct a baseline no climate change projection of country-level economic growth using the Shared Socio-economic Pathways (SSPs) assuming that climate variables are static at 2010 levels in the SSPs, $x_{i,t,k} = x_{i,2010,k}$, $\forall t$ (O'Neill et al., 2014). Let $y^{SSP}_{i,t}$ 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:

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

Substituting this into Eq. (3) and letting $y^{CC}_{i,t}$ be the projected country-level income per capita with climate change, we can project per-capita income with climate change using the recursive equation:

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

where climate variables $x_{i,t,k}$ are updated based on a prescribed climate scenario and $\Delta y^{SSP}_{i,t}$ is taken as given by a prescribed SSP scenario for each year t (SSP5 in the text).

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

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

Eq. (7) shows that the growth projections with climate change are the growth projections from the SSPs, $\Delta y^{SSP}_{i,t}$, adjusted for the direct impacts of climate change and 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).[13]

We use RCP8.5, the extreme warming scenario, as our baseline climate change scenario. We choose this for comparability with previous studies (Burke et al., 2015; Kalkuhl and Wenz, 2020). In this scenario,

[11] Burke et al. (2015), following the approach of Dell et al. (2012), 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.

[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 Appendix shows a decline in inequality over the century, in support of this assumption.

[13] In Appendix C.2, we further derive an equation that expresses how convergence shows up in the long-run effect of climate changes on per capita income when climate variables reach a new steady-state.

Table 1
Regression results.

Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Estimating equation Restriction	(3) $\lambda = 0$	(3) $\lambda = 0$	(3) $\lambda = 0$	(3) $\lambda = 0$	(3)	(3)	(3)	(4)	(4)
Dependent variable	Δy_{it}	Δy_{it}	Δy_{it}	Δy_{it}	Δy_{it}	Δy_{it}	Δy_{it}	Δy_{it}	Δy_{it}^{Rich} | Δy_{it}^{Poor}
Level effects:									
Temperature					0.00916 (0.00319)	0.00901 (0.00363)	0.00745 (0.00394)		
Temperature^2					−0.000353 (0.0000908)	−0.000332 (0.000138)	−0.000271 (0.000157)		
Precipitation					0.00493 (0.00846)	0.000756 (0.00959)	0.00361 (0.00963)		
Precipitation^2					−0.00245 (0.00180)	−0.00149 (0.00198)	−0.00139 (0.00195)		
ΔTemperature								0.0131 (0.00307)	0.00990 | 0.0204 (0.00296) | (0.00869)
ΔTemperature^2								−0.000589 (0.000120)	−0.000422 | −0.000819 (0.000122) | (0.000217)
ΔPrecipitation								0.00132 (0.0112)	−0.00397 | 0.00717 (0.0108) | (0.0202)
ΔPrecipitation^2								−0.00133 (0.00254)	−0.000493 | −0.00241 (0.00295) | (0.00439)
Global temperature shock							0.00356 (0.00756)		
L.Global temperature shock							0.0142 (0.00544)		
L2.Global temperature shock							−0.00113 (0.00712)		
L3.Global temperature shock							−0.0166 (0.00561)		
L4.Global temperature shock							−0.0107 (0.00575)		
L5.Global temperature shock							−0.0132 (0.00722)		
Growth effects:									
Temperature	0.00574 (0.00330)	0.0139 (0.00425)	0.0136 (0.00360)	0.0132 (0.00439)				−0.00135 (0.00182)	−0.00162 | 0.00445 (0.00441) | (0.00728)
Temperature^2	−0.000231 (0.0000974)	−0.000491 (0.000130)	−0.000488 (0.000105)	−0.000412 (0.000131)				0.0000121 (0.0000576)	−0.0000281 | −0.0000687 (0.000157) | (0.000159)
Precipitation	0.000564 (0.00890)	−0.00718 (0.0103)	0.00169 (0.00957)	−0.00339 (0.0103)				−0.00684 (0.00737)	0.00257 | 0.00513 (0.0125) | (0.0154)
Precipitation^2	−0.00157 (0.00190)	0.000474 (0.00221)	−0.00202 (0.00201)	0.000128 (0.00216)				0.00123 (0.00195)	−0.00453 | −0.00133 (0.00296) | (0.00406)
Global temperature shock				−0.00269 (0.00720)					
L.Global temperature shock				0.00324 (0.00544)					
L2.Global temperature shock				−0.0114 (0.00669)					
L3.Global temperature shock				−0.0288 (0.00557)					
L4.Global temperature shock				−0.0204 (0.00637)					
L5.Global temperature shock				−0.0209 (0.00758)					
Convergence:									
Implied λ					0.0440 (0.00592)	0.149 (0.0112)	0.214 (0.0242)	0.180 (0.124)	0.283 | 0.005 (0.137) | (0.187)
Peak growth temperature	12.4	14.2	13.9	16.1	13	13.6	13.7	11.1	11.7 | 12.4
Country-specific time trend	None	Linear	Quadratic	Linear	None	Linear	Linear	None	None
Year FEs	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Obs.	8394	8394	8394	8394	8046	8046	7352	7871	7871
R sq.	0.118	0.174	0.237	0.125					
Adj. R sq.	0.0929	0.132	0.181	0.0857					

All models include country and year fixed effects. Standard Errors are clustered at the country level. Columns (1)–(4) are estimated using ordinary least squares. Addressing endogeneity, columns (5)–(9) are estimated instrumenting for lagged income or income growth with two-period prior lag. For regressions with level and first-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. Global temperature shocks are measured as innovations to global mean temperature constructed as the residual of two-period lead of global mean temperature regressed on contemporary and up to two-period lag of global mean temperature.

the mean global temperature rises around 3.6 °C over the century.[14] We focus on SSP5, a fossil-fueled development scenario with rapid economic growth and faster long-run convergence in inter-country income inequality, as our benchmark SSP. In the Appendix we consider projections for alternative SSPs and show that our findings are robust to the alternative SSP scenarios (Figures 8–11). Throughout this section we present results for no climate damages (represented by the SSP) and with climate damages for model specifications of columns (2), (4), (6), and (7) from Table 1. This promotes comparability to the seminal work by Burke et al. (2015), but theoretically consistent with growth convergence. Comparing estimates without convergence in Columns (2) and (4) to comparable estimates with convergence in Columns (6) and (7), respectively, also highlights the role of convergence in projections. In the Appendix we present results for all model specifications reported in Table 1.

Fig. 1 shows projected GDP per capita with and without climate damages. Independent of climate damages global average income rises exponentially over the 21st century (Fig. 1a). Projected global incomes with climate damages are consistently lower than without climate damages. This result is robust across model specifications and supports concerns about the negative global impacts of climate change. However, the size and characteristics of climate damages differ across the empirical specifications.

[14] Supplementary Figure 5 shows the change in country-level population-weighted mean annual temperatures.

Fig. 1b–c displays projections of global economic losses from climate change, measured as the difference between global average income for the baseline SSP scenario without climate change and projections with climate change. By the end of the 21st century incomes vary ranging from \$54,000/capita to \$84,000/capita (for SSP5, this range is from around \$54,000/capita to \$91,000/capita across all model specifications with the exception of column (4) which is \$0/capita). Comparing economic losses for Column (2) to Column (6) and Column (4) to Column (7), we find that convergence pressures moderate climate damages. Global losses by the end of the 21st century alter from 17% for Column (2) to 8.5% for Column (6) and from 100% for Column (4) to 41% for Column (7).

Including convergence also has important implications for the characteristics of economic losses from climate change. Economic losses without convergence pressures peak in the mid-2080s and then decline at an increasing rate (Fig. 1b). This inflection in the mid-2080s occurs predominantly due to the bounded nature of losses where a country cannot lose more than 100% of their incomes, thus the losses to those negatively affected by climate change become smaller than the gains to those positively affected by climate change. Alternatively, with convergence pressures, economic losses grow steadily as climate changes because countries never approach 100% losses. Thus, failing to account for income convergence overestimates medium-run impacts and underestimates long-run impacts of climate change.

This is mirrored in Fig. 1c, which plots the economic losses across models against changes in global mean temperature, capturing estimates of the climate damage function. Without convergence, the climate damage function, measured as the negative of economic losses, is concave with changes in global mean temperature. In contrast, including convergence effects, the climate damage function is convex in changes in global mean temperature. Here, we also compare the empirically estimated climate damage functions with the damage functions for three of the most commonly used IAMs. Damage functions in the IAMs are more consistent both in magnitude and shape with the empirical estimates that account for convergence. Projected climate damages for the column (2) specification – akin to the Burke et al. (2015) specification – are around 19%, greatly exceeding IAMs projections. At a 5 °C increase, income losses for our central model specification in column (6) are comparable to the DICE climate damages at a reduction in income of around 7% (Nordhaus, 2018).

To determine what drives the differences in the magnitude and characteristics of the estimated damage functions between estimates without and with convergence, we look at the country-level projection estimates. Across models, the identities of winners and losers from climate change are consistent, with the Global South typically suffering the worst losses while areas in the Global North benefit (Fig. 2). However, the intensity of gains and losses are considerably stronger for projections without convergence compared to projections with convergence. For projections using column (2), there is large spread in losses from climate changes ranging from −95% to 1850% difference in GDP per capita. For projections using column (6), which allow for convergence, the magnitude and spread of impacts are substantially smaller, ranging from just -23% to 30%. For column (7) it ranges from −48% to −24% This difference is due to a growing divergence in country-level growth rates in the absence of convergence pressures.

Fig. 3a shows the distribution of country-level growth rates at the beginning, middle, and end of the 21st century for the baseline SSP5 scenario and adjusted for impacts from climate change. Immediately apparent are differences in the spread of country-level growth rates over time and across model specifications. In the baseline SSP5 scenario, country-level growth slows and converges to an annual rate of around 3%, close to our empirical estimates of the steady-state growth rate for most countries (Supplementary Figure 7). Now consider the model specification without convergence effects of column (2). Here, growth again slows, 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. 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. When accounting for convergence effects, the spread of country-level growth rates shrinks over time and is more consistent with the baseline SSP5 projection.

Accounting for convergence in projections of climate change impacts has important implications for the distributional effects of climate change on cross-country inequality. Fig. 3b–c highlight how starkly different the effect of climate change on intercountry income inequality is between projections without and with convergence effects. In the SSP5 scenario without climate change, the Lorenz curve moves towards the 45° line over the century and, accordingly, the Gini coefficient decreases monotonically over time. Without convergence, intercountry income inequality decreases in the first half of the century, but then increases. By 2100, the Gini coefficient is around 118% higher with climate change than without (117% with global shocks). This mimics the U-shape of global GDP/capita in Fig. 1b and is the finding of Burke et al. (2018). But, when we account for convergence pressures, this finding that climate change causes income inequality to increase in the second half of the 21st century is reversed. Income inequality instead falls throughout the century. By 2100, the Gini coefficient is around 8% higher with climate change than without (5% with global shocks). This indicates that climate change will still amplify disparities in intercountry incomes, but not as much as previously thought.

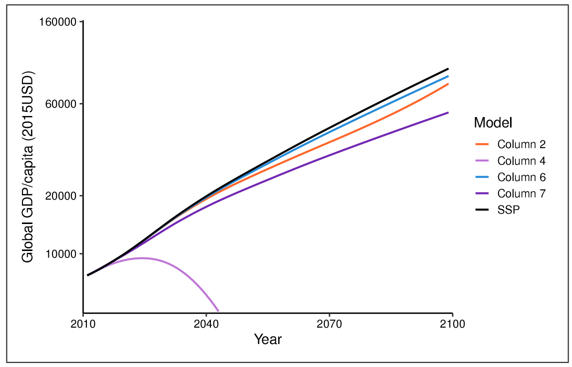
Putting together the country-level and global projections of climate losses, we find that, in the absence of convergence, the marginal impact of an increase in temperature decreases at higher temperatures because the gains from the winners outweigh the losses to the losers. This implies that, in the long run, climate change can become beneficial. However, with convergence, this result is reversed. Convergence tempers the benefits to winners and considerably dampens the losses to the losers of climate change. This highlights the importance of accounting for theoretically consistent convergence pressures in projections of losses from climate change.

5. Discussion and conclusion

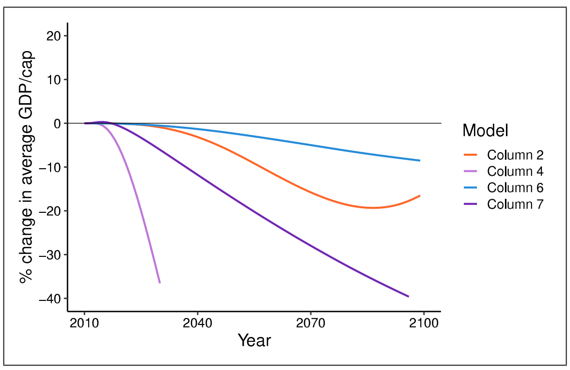
Climate econometrics play an essential role in providing an empirical foundation for understanding the potential macroeconomic costs of climate change. When estimating and, more importantly, employing these empirical approaches to project macroeconomic development, it is crucial to ensure consistency 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, and they report climate damages considerably larger than those in traditional IAMs. We demonstrate that these differences 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 magnitude and spread of long-term losses from climate change.

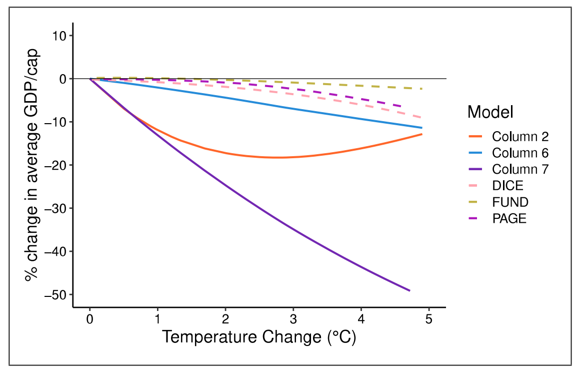
Drawing from neoclassical macroeconomic theory, we derive empirical models to estimate the economic impacts of climate changes, taking convergence into account. Additionally, we propose a test for distinguishing between transitory impacts on economic output levels and persistent impacts on underlying steady-state economic growth. Our 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 some previous studies (e.g., Dell et al., 2012), we find no evidence of persistent long-term growth impacts. Our estimates rather suggest that climate impacts in the long run can affect income levels, but not economic growth rates.



(a) Global GDP per capita projections

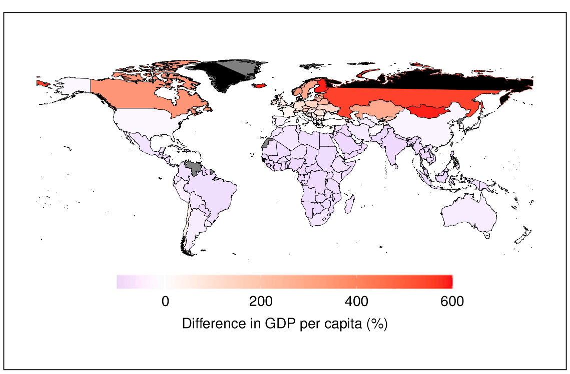


(b) Losses over time

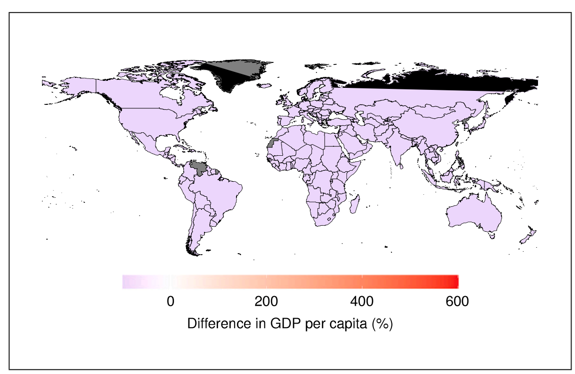


(c) Losses over temperature change

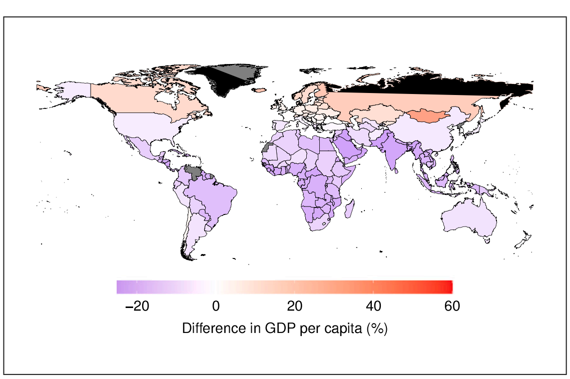
Fig. 1. Global GDP/capita projections. (a) Global GDP per capita projection for SSP5 and adjusted for climate damages under RCP 8.5 across empirical specifications in Table 1. Difference in projected average global GDP per capita between no climate change and with climate change against time (b) and against temperature change (c) for empirical specifications from Table 1 and three IAMs. Temperature change in (c) is relative to pre-industrial temperature. Subfigures (b) and (c) are relative to SSP5. We omit Column 4 from (c) because it is always -100% over the range of Temperature Changes plotted.



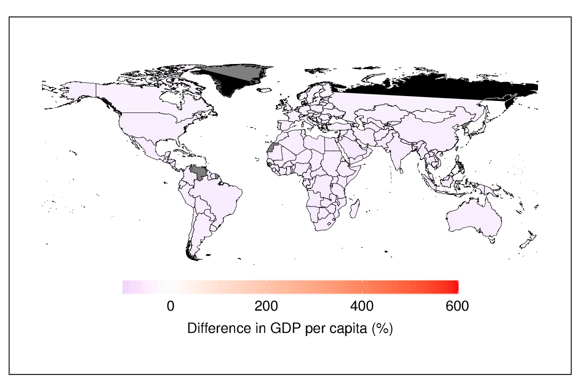
(a) Column 2



(b) Column 4

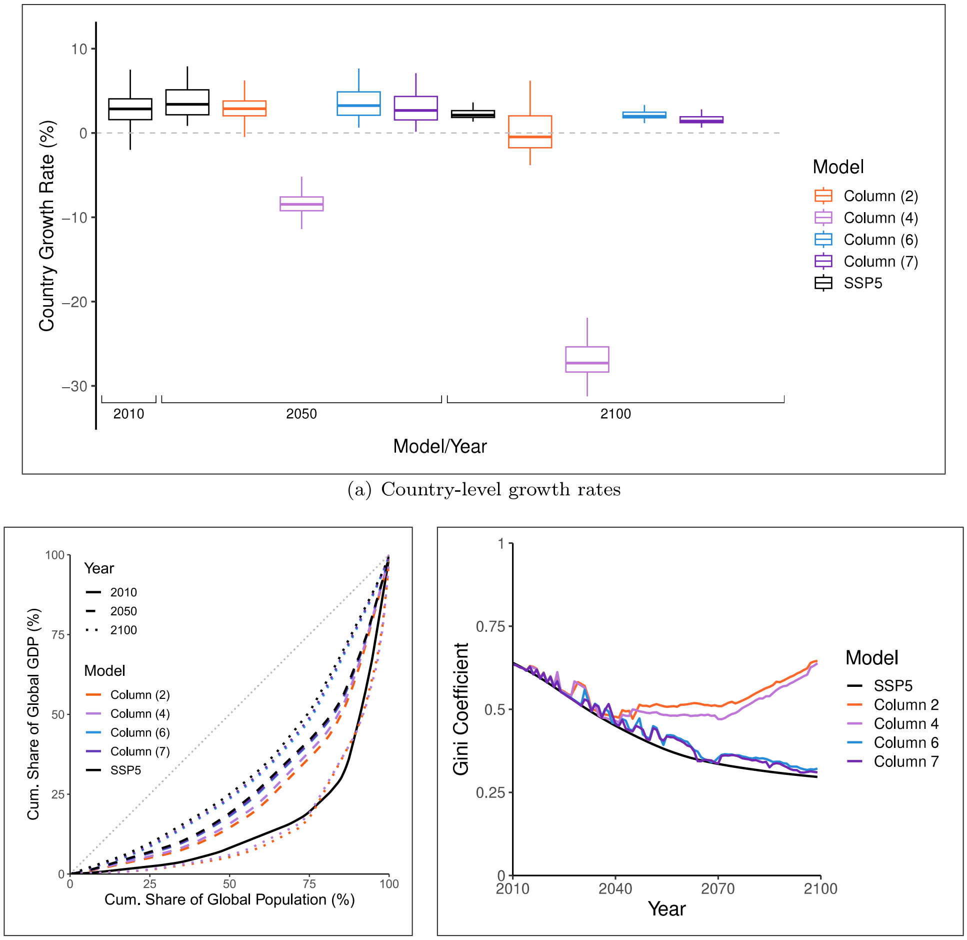


(c) Column 6



(d) Column 7

Fig. 2. 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.



(a) Country-level growth rates

(b) Inter-country income Lorenz curve

(c) Inter-country income Gini coefficient

Fig. 3. Distributional impacts from climate change. (a) Box-plots of projected country-level growth rates for SSP5 and adjusted for climate damages under RCP 8.5 across empirical specifications from Table 1. The horizontal line shows the median, the box shows the interquartile range, and the whiskers show the 5 to 95 percentile range. (b) Lorenz curve for inter-country income inequality for SSP5 and climate change projections for early, mid-, and end of 21st century. The gray dashed line at 45° represents perfect equality. (c) Gini coefficient of intercountry income inequality over time for SSP5 and climate change projections.

Consequently, when applying our findings to projections of economic growth under climate change, we observe that accounting for convergence considerably reduces 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 19%. Allowing for convergence reduces these losses to around 8.5%. 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 changes the distribution of impacts 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. 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. There is no aggregate gain from 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. Our focus is on bringing theoretical rigor to the estimation and interpretation of reduced-form model. Thus, we leave these questions for future research.

CRediT authorship contribution statement

Anthony Harding: Writing – original draft, Formal analysis, Writing – review & editing, Methodology, Visualization, Data curation. **Juan Moreno-Cruz:** Methodology, Writing – original draft, Writing – review & editing, Conceptualization. **Martin Quaas:** Writing – original draft, Writing – review & editing, Conceptualization, Methodology. **Wilfried Rickels:** Writing – review & editing, Conceptualization, Methodology, Writing – original draft. **Sjak Smulders:** Writing – review & editing, Formal analysis, Methodology, Writing – original draft, Conceptualization.

Funding

J.M.C. acknowledges the support of the Canada Research Chairs program. W.R. acknowledges funding from the Volkswagen AG as part of an endowed professorship via the Stifterverband.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2025.108705.

Data availability

Replication code and data for this study are available through Harvard Dataverse at https://doi.org/10.7910/DVN/BFL5HZ.

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