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Long-term macroeconomic effects of climate change: A cross-country analysis☆

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ABSTRACT

We study the *long-term* impact of climate change on economic activity across countries, using a stochastic growth model where productivity is affected by deviations of temperature and precipitation from their long-term moving average historical norms. Using a panel data set of 174 countries over the years 1960 to 2014, we find that per-capita real output growth is adversely affected by persistent changes in the temperature above or below its historical norm, but we do not obtain any statistically significant effects for changes in precipitation. We also show that the marginal effects of temperature shocks vary across climates and income groups. Our counterfactual analysis suggests that a persistent increase in average global temperature by 0.04 °C per year, in the absence of mitigation policies, reduces world real GDP per capita by more than 7 percent by 2100. On the other hand, abiding by the Paris Agreement goals, thereby limiting the temperature increase to 0.01 °C per annum, reduces the loss substantially to about 1 percent. These effects vary significantly across countries depending on the pace of temperature increases and variability of climate conditions. The estimated losses would increase to 13 percent globally if country-specific variability of climate conditions were to rise commensurate with annual temperature increases of 0.04 °C.

1. Introduction

Global temperatures have increased significantly in the past half century possibly causing a wide range of impacts, including cold snaps and heat waves, droughts and floods, hurricanes, higher sea levels, and weather whiplash; see IPCC (2021) for details. These changes in the distribution of weather patterns (i.e., climate change[2]) are not only affecting low-income countries and emerging markets, but also advanced economies. A persistent rise in temperatures, changes in precipitation patterns and/or more volatile weather events can have long-term macroeconomic effects by adversely affecting labour productivity, slowing investment and damaging human health.

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1 All co-authors of this manuscript have contributed equally to every aspect of the work.

2 Weather refers to atmospheric conditions over short periods of time (e.g., temperature and precipitation). Climate refers to the long-term average and variability of weather. Climate change is a shift "in the state of the climate that can be identified (e.g., via statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer" (IPCC, 2014).

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This paper investigates the *long-term* macroeconomic effects of weather patterns transformed by climate change across 174 countries over the period 1960 to 2014. While weather could affect the level of output across climates, for example, by changing agricultural yields, climate change, by shifting the long-term average and variability of weather, could impact an economy's ability to grow in the long-term, through reduced investment and lower labour productivity. We focus on both of these issues and develop a theoretical growth model that links deviations of temperature and precipitation (weather) from their long-term moving-average historical norms (climate) to per capita real output growth (Appendix A.1).

In our empirical application, we allow for dynamics and feedback effects in the interconnections of climatic and macroeconomic variables, distinguish between level and growth effects – including for long-term –, consider asymmetric weather effects, and test for differential impact of weather shocks across climates. Also, by using deviations of temperature and precipitation from their respective historical norms, while allowing for nonlinearity[3] and an implicit model for adaptation, we avoid the econometric pitfalls associated with the use of trended variables, such as temperature, in output growth equations. As it is well known, and is also documented in our paper, temperature has been trending upward strongly in almost all countries in the world, and its use as a regressor in growth regressions can lead to spurious results. A detailed analysis of how trends in temperature can lead to spurious trends in output growth in regressions used in the literature is provided in Appendix A.2.

The literature which attempts to quantify the effects of weather and/or climate on economic performance (agricultural production, labour productivity, commodity prices, health, conflict, and economic growth) is growing fast—see Stern (2007), IPCC (2014), Hsiang (2016), Cashin et al. (2017), Letta and Tol (2019), Henseler and Schumacher (2019), and recent surveys by Tol (2009), Dell et al. (2014), and Tol (2018). There are a number of grounds on which the econometric evidence of climate impacts on the economy may be questioned. Firstly, the literature that relies on the cross-sectional approach (e.g., Sachs and Warner, 1997, Gallup et al., 1999, Nordhaus, 2006, and Kalkuhl and Wenz, 2020) is hindered by the temporal invariance of climate over the studied time-frames and by important omitted variables that affect economic performance (e.g., institutions). The more recent literature largely uses panel data models to estimate the economic effects of weather shocks. See, for example, Burke et al. (2015), Dell et al. (2009, 2012, 2014), and Hsiang (2016). There is, however, some disagreement in the literature as to whether temperature affects the level of economic output or its growth. See Schlenker and Auffhammer (2018) and Newell et al. (2021) for a discussion.

Secondly, econometric specifications of the weather–macroeconomic relation are often written in terms of GDP per capita growth and the level of temperature, T_{it}, and in some cases also T_{it}^2;[4] see, for instance, Dell et al. (2012), Burke et al. (2015) , and Kalkuhl and Wenz (2020). But if T_{it} is trended, which is the case in almost all countries in the world (see Appendix A.3), its inclusion in the regression will introduce a linear trend in per capita output growth which is spurious and is not supported by the data (see Table A.1), and can in turn lead to biased estimates. The prevalence of this issue in the econometric specifications used in the literature is demonstrated in Appendix A.2. Indeed, Mendelsohn (2016) and Tol (2021) argue that researchers should focus on the deviation of T_{it} from its long-term average to estimate unbiased weather effects in panel data studies. As well, this transformation would allow for an implicit model of adaptation. Also, current panel models do not explicitly model climate variability in the estimation of long-term damage functions.

Thirdly, the fixed effects (FE) estimators used in panel-data studies assume that climate variables are strictly exogenous. At the heart of the Dynamic Integrated Climate-Economy (DICE) model of Nordhaus is the need to account for bi-directional feedback effects between growth and climate change (see Nordhaus, 1992). In his work, Nordhaus accounts for the fact that faster economic activity increases the stock of greenhouse gas (GHG) emissions and thereby the average temperature (possibly with a long lag). At the same time, rising average temperature could reduce real economic activity. Consequently, when estimating the impact of temperature on economic growth, T_{it} may not be considered as strictly exogenous, but merely weakly exogenous/predetermined to income growth; in other words economic growth in the past might have feedback effects on future temperature. While it is well known that the FE estimator suffers from small-T bias in dynamic panels (see Nickell, 1981) with N (the cross-section dimension) larger than T (the time series dimension), Chudik et al. (2018) show that this bias exists regardless of whether the lags of the dependent variable are included or not, so long as one or more regressors are not strictly exogenous. In such cases, inference based on the standard FE estimator will be invalid and can result in large size distortions unless $N/T \to 0$, as $N, T \to \infty$ jointly.

We contribute to the literature along the following dimensions. Firstly, we explicitly model and test for level or growth effects of weather shocks and estimate the long-term macroeconomic impact of persistent increases in temperature. Secondly, we use the half-panel Jackknife FE (HPJ-FE) estimator proposed in Chudik et al. (2018) to deal with the possible bias and size distortion of the commonly-used FE estimator (given that T_{it} is weakly exogenous). When the time dimension of the panel is moderate relative to N, the HPJ-FE estimator effectively corrects the Nickel-type bias if regressors are weakly exogenous, and is robust to possible feedback effects from aggregate economic activity to the climate variables. Thirdly, we test the predictions of our theoretical growth model using cross-country data on per-capita GDP growth and deviations of temperature and precipitation from their moving average historical norms over the past fifty-five years (1960–2014). Our focus on "deviations" is a departure from the literature, as changes in the distribution of weather patterns (not only averages of temperature and precipitation but also their variability) are modelled explicitly; an implicit model of adaptation is introduced; and the econometric pitfalls of including trended variables (that is, T_{it}) in growth regressions are avoided (see Appendix A.2 for details). Moreover, rather than assuming a common climate threshold across countries, we allow for country-specific and time-varying climate thresholds and also test for asymmetric effects.[5] Finally, we estimate the differential impact of weather shocks across climates (e.g., hot and cold) and income groups (rich and poor) using a heterogeneous panel data model.

Our results suggest that a series of positive (or negative) weather shocks has a long-term negative effect on per capita GDP growth. Since we are measuring an integral of marginal weather effects in our

[3] Non-linearity arises because growth is only affected when temperature (or precipitation) goes above or below a time-varying and country-specific historical threshold (i.e., the norm). It is due to this feature that future growth is affected not only by warming (or cooling if that was the case) but also by its variability.

[4] It is argued that this quadratic specification would account for the global nonlinear relationship between temperature and growth; i.e., a common temperature threshold.

[5] Assuming common climate thresholds, as is done in the literature, leads to important oddities in individual country estimates. For example, Burke et al. (2015) estimate that per capita GDP will be 63, 210, 247, 419, 516, 1413 percent larger in Germany, Sweden, Canada, Russia, Finland, and Mongolia as a result of climate change by 2100. Similarly, it is estimated that many countries (including Brazil, India, and most African and South East Asian countries) will experience per capita GDP losses of more than 80 percent which is hard to imagine barring climate disasters (which cannot be modelled within a stochastic growth framework as we document in Appendix A.1). See https://web.stanford.edu/\char126\relaxmburke/climate/map.php for the mentioned individual country results.

regressions, we can cautiously link them to climate change. Specifically, we show that if temperature rises (falls) above (below) its historical norm by 0.01 °C annually for a long period of time, income growth will be lower by 0.0543 percentage points per year. We could not detect any significant evidence of an asymmetric long-term growth impact from persistent positive and negative deviations of temperature from its norms. Furthermore, we show that our empirical findings pertain to poor or rich, and hot or cold countries alike (albeit to varying degrees) as economic growth is affected not only by persistent increases in temperatures (and the pace with which they are rising) but also by the degree of climate variability.[6] One of the reasons that cold countries are also affected by climate change is the faster pace with which temperatures are rising in these regions than in hot countries. Suppose that the pace of temperature increases was the same across hot and cold climates, then our heterogeneous panel estimations would suggest a smaller, but still negative, marginal weather effect in cold countries. Most papers in the literature find that temperature increases have had uneven macroeconomic effects, with adverse consequences *only* in countries with hot climates or low-income countries; see, for instance, Sachs and Warner (1997), Jones and Olken (2010), Dell et al. (2012), International Monetary Fund (2017), and Mejia et al. (2018). We estimate that the marginal effects of weather shocks are larger in low-income countries because they have lower capacity to deal with the consequences of climate change. However, this does not mean that rich nations are immune from the effects of climate change.

To contribute to climate change policy discussions, we perform a number of counterfactual exercises where we investigate the cumulative income effects of annual increases in temperatures over the period 2015–2100 (when compared to a baseline scenario under which temperature in each country increases according to its historical trend of 1960–2014). We show that an increase in average global temperature of 0.04 °C per year – corresponding to the Representative Concentration Pathway (RCP) 8.5 scenario (see Fig. 1), which assumes higher greenhouse gas emissions in the absence of mitigation policies – reduces world's real GDP per capita by 7.22 percent by 2100. The estimated losses under the RCP 8.5 scenario would almost double (to 13.11 percent globally by 2100) if country-specific variability of climate conditions were to rise commensurate to temperature increases (see Fig. 2 and Table 7). Limiting the increase to 0.01 °C per annum, which corresponds to the December 2015 Paris Agreement objective, reduces the output loss substantially to 1.07 percent.[7]

To put our results into perspective, Fig. 2 compares our economic loss estimates with those from select papers in the literature. Our counterfactual estimates are relatively large. They suggest that all countries would experience a fall in GDP per capita by 2100 in the absence of climate change policies (i.e., under a high-emission scenario or RCP 8.5). However, the size of these income effects varies across countries and regions depending on the pace with which temperatures increase over the century and the historical variability of climate conditions in each country and their evolution going forward (see Figs. 3, 6 and 7); for instance, for the U.S. the losses are relatively large at 10.52 percent under the RCP 8.5 scenario in year 2100 (reflecting a sharp increase in

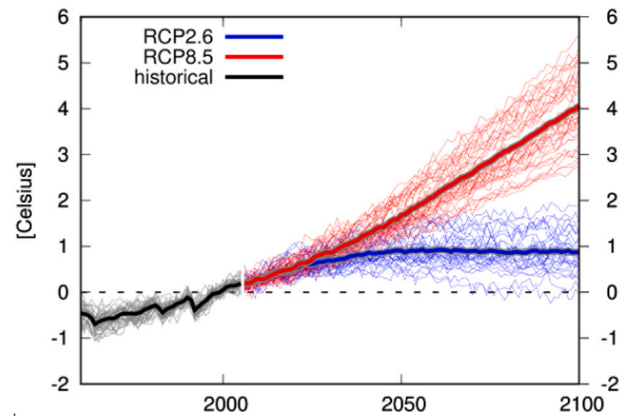

Fig. 1. Global Temperature Projections (Deviations from 1984–2014). Notes: The thin lines represent each of the 40 models in the IPCC WG1 AR5 Annex I Atlas. The thick lines represent the multimodel mean. Representative Concentration Pathways (RCP) are scenarios of greenhouse gas concentrations, constructed by the IPCC. RCP 2.6 corresponds to the Paris Agreement which aims to hold the increase in the global average temperature to below 2 degrees Celsius above pre-industrial levels. RCP 8.5 is an unmitigated scenario in which emissions continue to rise throughout the 21st century.
Source: Intergovernmental Panel on Climate Change (IPCC) Coupled Model Intercomparison Project Phase Five AR5 Atlas Subset.

its average temperatures), but would be limited to 1.88 percent under the Paris Agreement objective. Moreover, the speed with which the historical norms change (20-, 30-, or 40 year moving averages)– that is how fast countries adapt to global warming or new climate conditions – affects the size of income losses.[8] Overall, while adaptation to climate change can reduce these negative long-run growth effects, it is highly unlikely to offset them entirely.

The rest of the paper is organized as follows. Section 2 discusses the long-run macroeconomic effects of weather patterns transformed by climate change. Counterfactuals in Section 3 investigate the cumulative income effects of annual increases in temperatures under an unmitigated path as well as the Paris Agreement objective up to the year 2100. Section 4 concludes. The paper also contains four appendices. Appendix A.1 develops a multi-country stochastic growth model with weather and climate effects. Appendix A.2 discusses a number of key growth regressions used in macroeconomy-climate research, and how they relate to our approach. Appendix A.3 provides detailed evidence on the historical patterns of climate change across 174 countries. Finally, Appendix A.4 provides additional empirical results.

2. Empirical results

In the empirical application, we use annual population-weighted climate data and real GDP per capita. For the climate variables we consider temperature (measured in degrees Celsius, °C) and precipitation (measured in metres). We construct population-weighted climate data for each country and year between 1900 and 2014 using the terrestrial air temperature and precipitation observations from Matsuura and Willmott (2015) (containing 0.5 degree gridded monthly time series), and the gridded population of the world collection from CIESIN (2016), for which we use the population density in 2010.[9] We obtain the real GDP

[6] For example, while the level of temperature in Canada is low, the country is warming up twice as fast as the rest of the world and therefore is being affected by climate change (including from damages to its physical infrastructure, coastal and northern communities, human health and wellness, ecosystems and fisheries).

[7] The Paris Agreement, reached within the United Nations Framework Convention on Climate Change (UNFCCC), aims to keep the increase in the global average temperature to below 2 degrees Celsius above pre-industrial levels over the 21st century. The average global temperature is already 1 °C above the pre-industrial levels. For most countries, the Nationally Determined Contributions pledged under the Paris Agreement are deemed insufficient to meet either the 1.5 °C or the 2 °C target, and, judging by current policies, unlikely to be met in the first place.

[8] Another way to assess adaptation is to test how the elasticity of per capita GDP to climate variables evolves over time.

[9] We follow the literature in applying constant weights to create population-weighted temperatures, therefore abstracting from changes in the distribution of population over time and/or population trends (see Tol, 2017 for details). Nonetheless, in our empirical analysis we use deviations of temperature and precipitation from their historical norms, which are not trended.

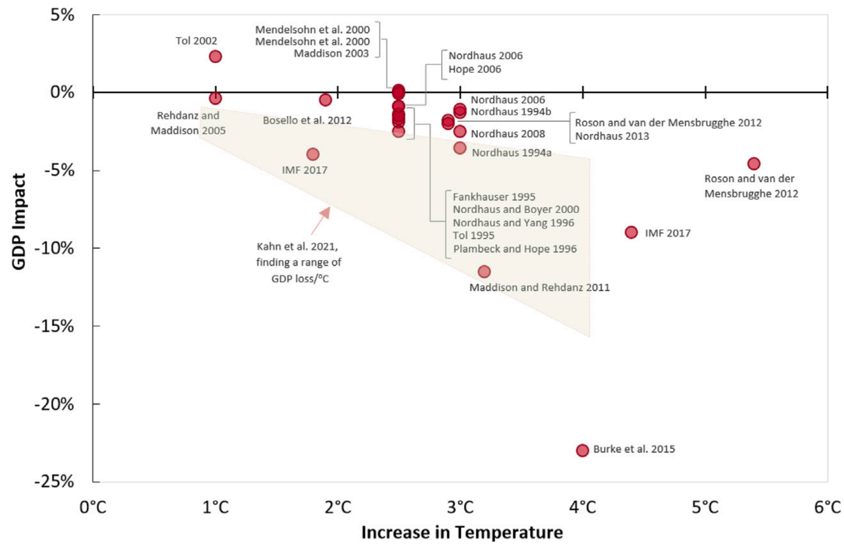

Fig. 2. GDP Impact of Increases in Temperature. Notes: Projected GDP impact is for some future year, typically 2100. The shaded area represents the GDP per capita losses from our counterfactual exercise in Section 3 with the upper bound based on $m = 20$ and the lower bound based on $m = 40$ (with increased climate variability). See Tables 6 and 7 for details.
Source: Tol (2009, 2014), Burke et al. (2015), International Monetary Fund (2017) and authors' estimates (shown as the grey area in the chart).

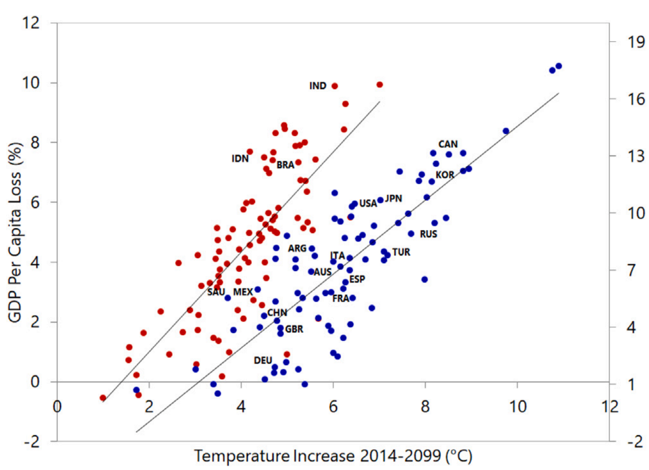

Fig. 3. GDP Per Capita Losses from Increases in Temperature: Cold vs. Hot. Notes: GDP per capita losses by 2100 from our baseline counterfactual exercise in Section 4 for hot (on left axis and in red) and cold (on right axis and in blue) countries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

per capita data between 1960 and 2014 from the *World Development Indicators* database of the World Bank. Combining the GDP per capita and the climate data, we end up with an unbalanced panel, which is very rich both in terms of the time dimension (T), with maximum $T = 55$ and average $T \approx 39$, and the cross-sectional dimension (N), containing 174 countries.

2.1. Long-term impact of climate change on economic growth

Considering strong evidence of an upward trend in temperatures worldwide (see Appendix A.3), and guided by the theoretical growth model with weather and climate variables in Appendix A.1, we base our empirical analysis on the following panel ARDL model:

$$\Delta y_{it} = a_i + \sum_{\ell=1}^{p} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p} \beta'_\ell \Delta \tilde{\mathbf{x}}_{i,t-\ell}(m) + \varepsilon_{it}, \quad (1)$$

where y_{it} is the log of real GDP per capita of country i in year t, a_i is the country-specific fixed effect, $\tilde{\mathbf{x}}_{it}(m) = [\tilde{T}_{it}(m)^+, \tilde{T}_{it}(m)^-, \tilde{P}_{it}(m)^+, \tilde{P}_{it}(m)^-]'$, $\tilde{T}_{it}(m) = \left(\frac{2}{m+1}\right)\left[T_{it} - T^*_{i,t-1}(m)\right]$ and $\tilde{P}_{it}(m) = \left(\frac{2}{m+1}\right)\left[P_{it} - P^*_{i,t-1}(m)\right]$ are measures of temperature and precipitation relative to their historical norms per annum, T_{it} and P_{it} are the population-weighted average temperature and precipitation of country i in year t, and $T^*_{i,t-1}(m) = \frac{1}{m}\sum_{\ell=1}^{m} T_{i,t-\ell}$ and $P^*_{i,t-1}(m) = \frac{1}{m}\sum_{\ell=1}^{m} P_{i,t-\ell}$ are the time-varying historical norms of temperature and precipitation over the preceding m years in each t. Climate norms are typically computed using 30 year moving averages (see, for instance, Arguez et al., 2012 and Vose et al., 2014), but to check the robustness of our results, we also consider historical norms computed using moving averages with $m = 20$ and 40.[10] With $\tilde{T}_{it}(m)$ and $\tilde{P}_{it}(m)$ separated into positive and negative values, we account for the potential asymmetrical effects of climate change on growth around the threshold. The (average) long-run effects, θ, are calculated from the OLS estimates of the short-run coefficients in Eq. (1): $\theta = \phi^{-1}\sum_{\ell=0}^{p}\beta_\ell$, where $\phi = 1 - \sum_{\ell=1}^{p}\varphi_\ell$.

The reasons for using ARDL growth regressions in deviations form (i.e., temperature and precipitation relative to their long-term moving average historical norms), rather than in levels and/or squares of climate variables, are discussed in some detail in Appendix A.2, where it is shown that including T_{it} and T^2_{it} will introduce trends in Δy_{it}, which is not present in the data. As documented in Table A.1, we find that at the 5% significance level, output growth is upward trended in only 21 countries out of 174 under consideration, and in fact 9 (174×0.05) of the 21 countries with statistically significant trend coefficients could have arisen by pure chance given the large number of multiple tests being carried out.

Other important econometric considerations behind the use of ARDL regressions are set out in Pesaran and Smith (1995), Pesaran (1997), and Pesaran and Shin (1999) who show that the traditional ARDL approach can be used for long-run analysis; it is valid regardless of whether the underlying variables are $I(0)$ or $I(1)$; and it is robust to omitted variables bias and bi-directional feedback effects between economic growth and its determinants. These features of the panel ARDL approach are clearly appealing in our empirical application. For validity of this technique, however, the dynamic specification of the model needs to be augmented with a sufficient number of lagged effects so that regressors become weakly exogenous. Specifically, Chudik et al.

[10] $m = 30$ also corresponds to the official World Meteorological Organization definition of climate (i.e., norm).

(2016), show that sufficiently long lags are necessary for the consistency of the panel ARDL approach.[11] Since we are interested in studying the growth effects of climate change (a long-term phenomenon), the lag order should be long enough, and as such we set $p = 4$ for all the variables/countries. Using the same lag order across all the variables and countries help reduce the possible adverse effects of data mining that could accompany the use of country and variable specific lag order selection procedures such as Akaike or Schwarz criteria. Note also that our primary focus here is on the long-run estimates rather than the specific dynamics that might be relevant for a particular country.

Table 1 presents the estimation results for two specifications of the panel ARDL regression in (1) and different adaptation speeds ($m = 20, 30$ and 40). We report the fixed effects (FE) estimates of the long-run impact of changes in temperature and precipitation variables on GDP per capita growth ($\hat{\theta}$), and the estimated coefficients of the error correction term ($\hat{\phi}$) in columns (a). When the cross-sectional dimension of the panel is larger than the time dimension (in our panel, $N = 174$ and the average $T \approx 38$, see Table 1), the standard FE estimator suffers from small-T bias regardless of whether the lags of the dependent variable are included or not, so long as one or more of the regressors are not strictly exogenous (see Chudik et al., 2018). Since the lagged values of growth and temperature/precipitation can be correlated with the lagged values of the error term ε_{it}, the regressors (climate variables) are weakly exogenous, and hence, inference based on the standard FE estimator is invalid and can result in large size distortions. To deal with these issues, we use the half-panel Jackknife FE (HPJ-FE) estimator of Chudik et al. (2018) and report the results in columns (b) of Table 1 alongside the estimated coefficients of the error correction term ($\hat{\phi}$). The jackknife bias correction requires $N, T \to \infty$, but it allows T to rise at a much slower rate than N.

Specification 1 of Table 1 for $m = 30$ reports the baseline results. The FE and HPJ-FE estimated coefficients of the precipitation variables, $\hat{\theta}_{\Delta \tilde{P}_{it}(m)^+}$ and $\hat{\theta}_{\Delta \tilde{P}_{it}(m)^-}$, are not statistically significant. However, long-run economic growth is adversely affected when temperature deviates from its time-varying historical norm persistently, as $\hat{\theta}_{\Delta \tilde{T}_{it}(m)^+}$ and $\hat{\theta}_{\Delta \tilde{T}_{it}(m)^-}$ are both statistically significant. The HPJ-FE estimates suggest that a 0.01 °C annual increase in the temperature above its historical norm reduces real GDP per capita growth by 0.0577 percentage points per year – calculated as $-0.894 \times \left(\frac{2}{m+1}\right)$ – and a 0.01 °C annual decrease in the temperature below its historical norm reduces real GDP per capita growth by 0.0505 percentage points per year—calculated as $-0.783 \times \left(\frac{2}{m+1}\right)$. As expected, the FE estimates (which are widely used in the literature) are smaller than their HPJ-FE counterparts in absolute values.[12] Therefore, bias correction is important, including for the counterfactual exercises in Section 3; otherwise the cumulative effects of climate change could be underestimated.

Since the baseline estimates of deviations of precipitation variables from their historical norms (both above and below) are not statistically significant for $m = 30$, we re-estimate Eq. (1) without them; setting $\tilde{\mathbf{x}}_{it}(m) = [\tilde{T}_{it}(m)^+, \tilde{T}_{it}(m)^-]'$ in specification 2. The results show that persistent deviations of temperature above or below its historical norm, $\tilde{T}_{it}(m)^+$ or $\tilde{T}_{it}(m)^-$, have negative effects on long-run economic growth. Specifically, the HPJ-FE estimates suggest that a persistent 0.01 °C increase in the temperature above its historical norm reduces real GDP per capita growth by 0.0586 percentage points per annum in the long run (being statistically significant at the 1% level) – calculated as $-0.908 \times \left(\frac{2}{m+1}\right)$ – and a 0.01 °C annual decrease in the temperature below its historical norm reduces real GDP per capita growth by 0.0520 percentage points per year (being statistically significant at the 5% level)—calculated as $-0.806 \times \left(\frac{2}{m+1}\right)$. To make sure that our results are robust to the choice of historical norms, Table 2 also reports the estimation results with climate norms constructed as moving averages of the past 20 ($m = 20$) and 40 ($m = 40$) years, respectively. As in the case with $m = 30$, we note that the estimated coefficients of the precipitation variables, $\hat{\theta}_{\Delta \tilde{P}_{it}(m)^+}$ and $\hat{\theta}_{\Delta \tilde{P}_{it}(m)^-}$, are not statistically significant (specification 1). However, the estimated coefficients of the deviations of temperature from its historical norm are statistically significant in both specifications. The speed of adjustment to long-run equilibrium ($\hat{\phi}$) is quick in both specifications and for different values of m. However, this does not mean that the effects of changes in $\tilde{T}_{it}(m)^+$ and $\tilde{T}_{it}(m)^-$ are short lived.

As discussed above, estimates of the coefficients of $\tilde{T}_{it}(m)^+$ and $\tilde{T}_{it}(m)^-$ are very similar in magnitude. There is, therefore, little evidence of asymmetry in the long-run relationship between output growth and positive or negative deviations of temperature from its historical norm (or the country-specific threshold). This lack of asymmetry suggests that a simpler specification might be preferred and we therefore re-estimate Eq. (1) by replacing $\tilde{\mathbf{x}}_{it}(m) = [\tilde{T}_{it}(m)^+, \tilde{T}_{it}(m)^-, \tilde{P}_{it}(m)^+, \tilde{P}_{it}(m)^-]'$ with $\tilde{\mathbf{x}}_{it}(m) = \left(\left|\tilde{T}_{it}(m)\right|, \left|\tilde{P}_{it}(m)\right|\right)'$. The FE and HPJ-FE results are reported in Table 2. Like our earlier results, permanent deviations of precipitation from their historical norms do not affect long-term growth, but permanent deviations of temperature from their time-varying historical norms have a negative effect on long-run GDP growth, with the magnitudes of the coefficient of $\left|\tilde{T}_{it}(m)\right|$ being similar to those reported for $\tilde{T}_{it}(m)^+$ and $\tilde{T}_{it}(m)^-$ in Table 1. Focusing on Specification 2 with $\tilde{x}_{it}(m) = \left|\tilde{T}_{it}(m)\right|$ and the HPJ-FE estimates (our preferred model and estimator), we observe that $\hat{\theta}_{\Delta\left|\tilde{T}_{it}(m)\right|}$ is robust to alternative ways of measuring $T^*_{i,t-1}(m)$.

To put our results into perspective, note that models that relate temperature to GDP levels yield income loss estimates that are relatively small—consistent with damage functions embedded in major integrated assessment models (IAMs). Specifically, most such models find that when a poor (hot) country gets 1 °C warmer, the level of its GDP per capita falls by 1–3 percent; (ii) when a rich (temperate) country gets 1 °C warmer, there is little impact on its economic activity. The IAMs have been extensively used in the past few decades to investigate the welfare effects of temperature increases by relying on aggregation of sector-specific effects, see Tol (2014); they have also been used as tools for policy analyses (including by the Obama administration, see Obama, 2017, and at international forums). More recent studies, that relate temperature to GDP growth (possibly nonlinearly), arguably show that a shift to a higher (but nonincreasing) temperature level reduces per capita output growth substantially (with compounding effects over time). For example, Burke et al. (2015) consider a panel specification that includes quadratic climate variables in regressions and detect: (i) non-linearity in the relationship with a universal optimal temperature level of 13 °C; (ii) differential impact on hot versus cold countries with opposite sign; and (iii) weak lagged effects—their higher lag order (between 1 and 5) estimates reported in Supplementary Table S2, show that only 3 out of 18 estimates are statistically significant. However, our results show that an increase in temperature above its historical norm for an extended period of time is associated with lower economic growth in the long run – suggesting that a temporary temperature shock will only have short-term growth effects but climate change – by shifting the long-term average and variability of weather—could impact an economy's ability to grow in the long-term. Moreover, the marginal impact of weather shocks are estimated to be larger than most papers in the literature and vary across hot and cold climates. Therefore, our findings call for a more forceful policy response to climate change.

If the world economy were adapting to climate change, ceteris paribus, should we not expect the impact of temperature increases to be shrinking over time? To investigate this hypothesis, we re-estimate our preferred model (with $m = 30$ and $\tilde{x}_{it}(m) = \left|\tilde{T}_{it}(m)\right|$) over different time windows using real GDP per capita growth as the

[11] See also Chudik et al. (2013) and Chudik et al. (2017).

[12] Since the half-panel Jackknife procedure splits the data set into two halves, for countries with an odd number of time observations, we drop the first observation. Thus, the number of observations in Columns (a) and (b) are somewhat different.

Table 1
Long-run effects of climate change on per capita real GDP growth, 1960–2014.

	Specification 1						Specification 2					
	$m=20$		$m=30$		$m=40$		$m=20$		$m=30$		$m=40$	
	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE
$\hat{\theta}_{\Delta\tilde{T}_{it}(m)^+}$	−0.373***	−0.566***	−0.583***	−0.894***	−0.701***	−1.072***	−0.378***	−0.572***	−0.586***	−0.908***	−0.709***	−1.105***
	(0.141)	(0.209)	(0.195)	(0.291)	(0.248)	(0.373)	(0.141)	(0.208)	(0.196)	(0.290)	(0.249)	(0.372)
$\hat{\theta}_{\Delta\tilde{T}_{it}(m)^-}$	−0.441**	−0.500**	−0.699**	−0.783**	−0.834*	−0.909*	−0.451**	−0.508**	−0.712**	−0.806**	−0.851*	−0.954**
	(0.217)	(0.249)	(0.346)	(0.380)	(0.445)	(0.485)	(0.217)	(0.249)	(0.346)	(0.380)	(0.446)	(0.485)
$\hat{\theta}_{\Delta\tilde{P}_{it}(m)^+}$	−0.044	−0.031	0.104	0.122	−0.058	−0.005	–	–	–	–	–	–
	(0.289)	(0.357)	(0.485)	(0.556)	(0.684)	(0.766)						
$\hat{\theta}_{\Delta\tilde{P}_{it}(m)^-}$	−0.072	−0.175	−0.132	−0.320	−0.382	−0.595	–	–	–	–	–	–
	(0.323)	(0.431)	(0.576)	(0.660)	(0.754)	(0.857)						
$\hat{\phi}$	0.671***	0.603***	0.671***	0.603***	0.671***	0.602***	0.672***	0.604***	0.671***	0.604***	0.671***	0.604***
	(0.049)	(0.045)	(0.049)	(0.045)	(0.049)	(0.045)	(0.049)	(0.045)	(0.049)	(0.045)	(0.049)	(0.045)
N	174	174	174	174	174	174	174	174	174	174	174	174
max T	50	50	50	50	50	50	50	50	50	50	50	50
avg T	38.59	38.36	38.59	38.36	38.59	38.36	38.59	38.36	38.59	38.36	38.59	38.36
min T	2	2	2	2	2	2	2	2	2	2	2	2
$N \times T$	6714	6674	6714	6674	6714	6674	6714	6674	6714	6674	6714	6674

Notes: Specification 1 (the baseline) is given by $\Delta y_{it} = a_i + \sum_{\ell=1}^{p} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p} \beta_\ell' \Delta \tilde{\mathbf{x}}_{i,t-\ell} + \varepsilon_{it}$, where y_{it} is the log of real GDP per capita of country i in year t, $\tilde{\mathbf{x}}_{it}(m) = [\tilde{T}_{it}(m)^+, \tilde{T}_{it}(m)^-, \tilde{P}_{it}(m)^+, \tilde{P}_{it}(m)^-]'$, $\tilde{T}_{it}(m) = \left(\frac{2}{m+1}\right)\left[T_{it} - T_{i,t-1}^*(m)\right]$ and $\tilde{P}_{it}(m) = \left(\frac{2}{m+1}\right)\left[P_{it} - P_{i,t-1}^*(m)\right]$ are measures of temperature and precipitation relative to their historical norms per annum, T_{it} and P_{it} are the population-weighted average temperature and of precipitation country i in year t, and $T_{i,t-1}^*(m) = \frac{1}{m}\sum_{\ell=1}^{m} T_{i,t-\ell}$ and $P_{i,t-1}^*(m) = \frac{1}{m}\sum_{\ell=1}^{m} P_{i,t-\ell}$ are the time-varying historical norms of temperature and precipitation over the preceding m years. $z^+ = zI(z \geq 0)$, and $z^- = -zI(z < 0)$. The long-run effects, θ_i, are calculated from the OLS estimates of the short-run coefficients in Eq. (1): $\theta = \phi^{-1}\sum_{\ell=0}^{p}\beta_\ell$, where $\phi = 1 - \sum_{\ell=1}^{p}\varphi_\ell$. Specification 2 drops the precipitation variables from the baseline model: $\tilde{\mathbf{x}}_{it}(m) = \left[\tilde{T}_{it}(m)^+, \tilde{T}_{it}(m)^-\right]'$. Columns labelled ($a$) report the FE estimates and columns labelled (b) report the half-panel Jackknife FE (HPJ-FE) estimates, which corrects the bias in columns (a). The standard errors are estimated by the estimator proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 1% (***), 5% (**), and 10% (*) levels.

Table 2
Long-run effects of climate change on per capita real GDP growth, 1960–2014 (using absolute value of deviations of climate variables from their historical norm).

	Specification 1						Specification 2					
	$m=20$		$m=30$		$m=40$		$m=20$		$m=30$		$m=40$	
	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE
$\hat{\theta}_{\Delta\lvert\tilde{T}_{it}(m)\rvert}$	−0.375***	−0.523***	−0.582***	−0.836***	−0.702***	−0.981***	−0.379***	−0.529***	−0.583***	−0.841***	−0.706***	−0.996***
	(0.142)	(0.201)	(0.199)	(0.284)	(0.252)	(0.361)	(0.142)	(0.201)	(0.199)	(0.284)	(0.253)	(0.361)
$\hat{\theta}_{\Delta\lvert\tilde{P}_{it}(m)\rvert}$	−0.070	−0.125	−0.032	−0.131	−0.259	−0.404	–	–	–	–	–	–
	(0.237)	(0.335)	(0.473)	(0.527)	(0.646)	(0.709)	–	–	–	–	–	–
$\hat{\phi}$	0.671***	0.604***	0.671***	0.604***	0.671***	0.603***	0.672***	0.604***	0.672***	0.604***	0.672***	0.604***
	(0.049)	(0.045)	(0.049)	(0.045)	(0.049)	(0.045)	(0.049)	(0.045)	(0.049)	(0.045)	(0.049)	(0.045)
N	174	174	174	174	174	174	174	174	174	174	174	174
max T	50	50	50	50	50	50	50	50	50	50	50	50
avg T	38.36	38.36	38.36	38.36	38.36	38.36	38.36	38.36	38.36	38.36	38.36	38.36
min T	2	2	2	2	2	2	2	2	2	2	2	2
$N \times T$	6714	6674	6714	6674	6714	6674	6714	6674	6714	6674	6714	6674

Notes: Specification 1 (the baseline) is given by $\Delta y_{it} = a_i + \sum_{\ell=1}^{p} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p} \beta_\ell' \Delta \tilde{\mathbf{x}}_{i,t-\ell} + \varepsilon_{it}$, where y_{it} is the log of real GDP per capita of country i in year t, $\tilde{\mathbf{x}}_{it}(m) = [\lvert\tilde{T}_{it}(m)\rvert, \lvert\tilde{P}_{it}(m)\rvert]'$, $\tilde{T}_{it}(m) = \left(\frac{2}{m+1}\right)\left[T_{it} - T_{i,t-1}^*(m)\right]$ and $\tilde{P}_{it}(m) = \left(\frac{2}{m+1}\right)\left[P_{it} - P_{i,t-1}^*(m)\right]$ are measures of temperature and precipitation relative to their historical norms per annum, T_{it} and P_{it} are the population-weighted average temperature and of precipitation country i in year t, and $T_{i,t-1}^*(m) = \frac{1}{m}\sum_{\ell=1}^{m} T_{i,t-\ell}$ and $P_{i,t-1}^*(m) = \frac{1}{m}\sum_{\ell=1}^{m} P_{i,t-\ell}$ are the time-varying historical norms of temperature and precipitation over the preceding m years in each t. The long-run effects, θ_i, are calculated from the OLS estimates of the short-run coefficients in Eq. (1): $\theta = \phi^{-1}\sum_{\ell=0}^{p}\beta_\ell$, where $\phi = 1 - \sum_{\ell=1}^{p}\varphi_\ell$. Specification 2 drops the precipitation variable from the baseline model. The standard errors are estimated by the estimator proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 1% (***), 5% (**), and 10% (*) levels.

dependent variable. We start with the full sample, 1960–2014, and then drop a year at a time (with the last estimation being carried out for the sub-sample 1983–2014). The results are plotted in Fig. 4, showing that the estimated coefficients on $\Delta\left|\tilde{T}_{it-\ell}(m)\right|$ are becoming larger (in absolute value) over time. Do these results cast doubt on the efficacy of adaptation efforts over the last five decades? *Ceteris paribus*, while it is expected that adaptation weakens the relationship between temperature and economic growth over time, we cannot conclude that the world economy has not been adapting to climate change based on Fig. 4. First, adaptation efforts might be concentrated in certain countries (typically advanced economies) and certain sectors. Second, it may be the case that adaptation is not keeping pace with the climate change; i.e., global temperatures have increased at an unprecedented pace over the past 40 years. Third, the effects of adaptation might have been offset by structural changes to the economy (that is a shift of value added to sectors that are more exposed to climate change). Fourth, if firms underestimate the likelihood or severity of future weather events, they may not adapt sufficiently; i.e. adaptation technologies are readily available but the take-up so far has been limited by firms. In a survey of private sector organizations across multiple industries within the Organization for Economic Cooperation and Development (OECD) countries, Agrawala et al. (2011) find that only few firms have taken sufficient steps to assess and manage the risks from climate change. Fifth, according to Deryugina and Hsiang (2014) firms tend to under-invest in adaptation owing to its high cost.[13] Overall, the evidence appears to suggest that (at least for now) adaptation has so far had

[13] Other reasons for underinvestment include knowledge spillovers and networks externalities.

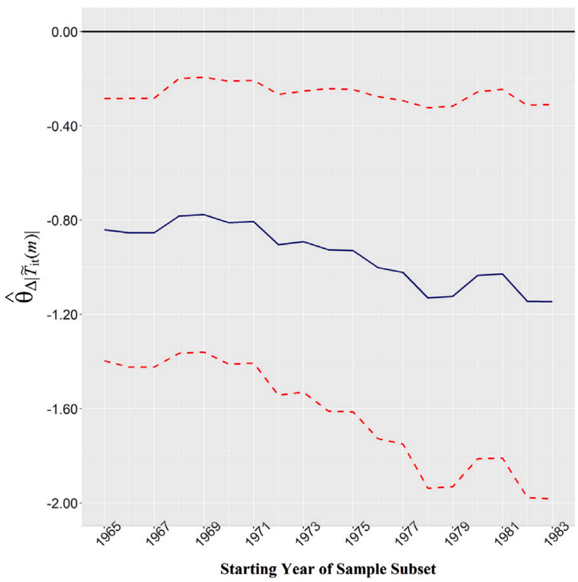

Fig. 4. Rolling Estimates of the Long-Run Effects of Temperature Increases on per capita Real GDP Growth. Notes: Figure shows the long-run effects (and their 95% standard error bands) of temperature increases on per capita real GDP growth over different time windows, using the ARDL specification in (1). We start the estimation with the full sample (1960–2014) and then drop one year at a time, ending with the final estimates based on the 1983–2014 sub-sample.

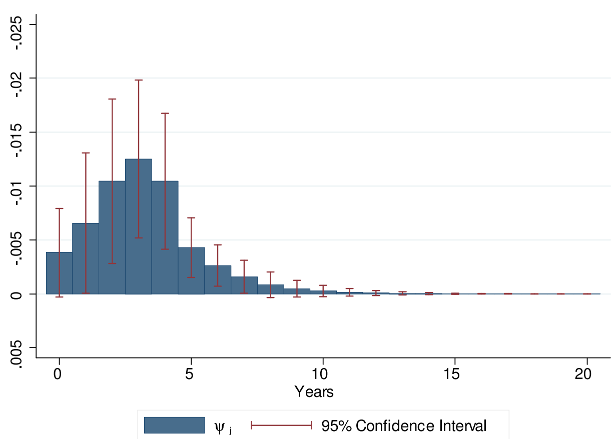

Fig. 5. $\{\psi_j\}$ for $j = 0, 1, 2, \ldots, 20$.

limited impact in dampening the negative effects of climate change globally. But it is possible that with greater public awareness and government efforts, we will be seeing a much faster rate of adaptation in the future. Our analysis is counterfactual given the current state of the world, and outcomes could, and hopefully will, deviate from our counterfactual with better and more forceful environmental polices (both mitigation and adaptation).

2.2. Weather effects across climates and income groups

The literature provides evidence for uneven effects of temperature shocks, with worse adverse consequences in economies with hot climates and/or in low-income countries; see, for instance, Sachs and Warner (1997), Jones and Olken (2010), Dell et al. (2012), Burke et al. (2015) and Mejia et al. (2018). In other words, when a rich (temperate) country gets warmer, there will be little impact on its economic activity. There are intuitive reasons and anecdotal evidence for this, including adaptation that has taken place particularly in advanced economies; they are more urbanized and much of the economic activity takes place indoors. For instance, Singapore has attempted to insulate its economy from the heat by extensively engaging in economic activity in places with air conditioning. Therefore, if individuals are aware of how extreme heat affects their economic performance, they can invest in self protection to reduce their exposure to such risks.[14] Mendelsohn (2016) also argues that economic effects of weather shocks are likely to be very different in cold versus hot climates.

Given our heterogeneous sample of 174 countries and motivated by above studies, an immediate question is whether the estimated adverse long-run growth effects of weather shocks in Specifications 1 and 2 of Table 2 are driven by poor countries. We, therefore, follow Dell et al. (2012) and Burke et al. (2015) and augment Specification 2 with an interactive term, $\Delta\tilde{\mathbf{x}}_{i,t-\ell}(m) \times \mathbb{I}(\text{country } i \text{ is poor})$, to capture any possible differential effects of temperature changes from the moving-average norm for the rich and poor countries:

$$\Delta y_{it} = a_i + \sum_{\ell=1}^{p} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p} \boldsymbol{\beta}'_\ell \Delta\tilde{\mathbf{x}}_{i,t-\ell}(m) + \sum_{\ell=0}^{p} \boldsymbol{\zeta}'_\ell \Delta\tilde{\mathbf{x}}_{i,t-\ell}(m) \times \mathbb{I}(\text{country } i \text{ is poor}) + \varepsilon_{it}, \tag{2}$$

where, as in Burke et al. (2015), we define country i as poor (rich) if its purchasing-power-parity-adjusted (PPP) GDP per capita was below (above) the global median in 1980. Moreover, to investigate whether temperature increases affect hotter countries more than colder ones, we estimated the following panel data model

$$\Delta y_{it} = a_i + \sum_{\ell=1}^{p} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p} \boldsymbol{\beta}'_\ell \Delta\tilde{\mathbf{x}}_{i,t-\ell}(m) + \sum_{\ell=0}^{p} \boldsymbol{\xi}'_\ell \Delta\tilde{\mathbf{x}}_{i,t-\ell}(m) \times \mathbb{I}(\text{country } i \text{ is hot}) + \varepsilon_{it}, \tag{3}$$

where a country is defined as cold (hot) if its historical average temperature is below (above) the global median. The results from estimating specifications (2) and (3) are reported in Table 3 where the estimated coefficients of the interactive terms are not statistically significant—hence, we cannot reject the hypothesis that there are no differential effects of climate change on poor versus rich nations or hot versus cold countries.

The statistical insignificance of estimated coefficients of the interactive terms in Table 3 may be due to lack of statistical power. In what follows, we attempt to explore the heterogeneity issue further by relying on the half-panel Jackknife Mean Group (HPJ-MG) estimator in the context of the following heterogeneous panel data model:

$$\Delta y_{it} = a_i + \omega_i \Delta\bar{y}_{w,t-1} + \varphi_i \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p_{\tilde{T}}} \beta_{i\ell} \Delta\left|\tilde{T}_{it-\ell}(m)\right| + \varepsilon_{it}. \tag{4}$$

Unlike pooled estimation techniques such as FE where only intercept heterogeneity is taken into account, the above specification allows for the marginal effects of weather shocks to vary across countries or sub-group of countries. Under this more general specification, country-specific marginal effects can be estimated by running least squares regressions for each country i separately, and then considering averages or medians of the estimated coefficients across countries or regions, for example cold versus hot climates, or rich versus poor countries. Pesaran and Smith (1995) show that simple averages of the estimated coefficients (known as mean group, MG, estimates) result in consistent estimates of the underlying population means of the parameters when the time-series dimension of the data is sufficiently large. Whilst it is not possible to be sure about when T is sufficiently large, Monte Carlo evidence suggests that reliable estimates can be obtained with $T \geq 30$

[14] For a survey of the literature on heat and productivity, see Heal and Park (2016).

Table 3
Long-run effects of climate change on per capita real GDP growth of poor and hot countries, 1960–2014 (using absolute value of deviations of climate variables from their historical norm).

	Specification 3		Specification 4	
$m = 30$	(a) FE	(b) HPJ-FE	(a) FE	(b) HPJ-FE
$\hat{\theta}_{\Delta\lvert\tilde{T}_{it}(m)\rvert}$	−0.551**	−0.836**	−0.754***	−1.029***
	(0.235)	(0.368)	(0.200)	(0.287)
$\hat{\theta}_{\Delta\lvert\tilde{T}_{it}(m)\rvert\times\mathbb{I}(i\text{ is poor})}$	−0.156	−0.137	–	–
	(0.396)	(0.586)	–	–
$\hat{\theta}_{\Delta\lvert\tilde{T}_{it}(m)\rvert\times\mathbb{I}(i\text{ is hot})}$	–	–	0.496	0.562
	–	–	(0.420)	(0.656)
$\hat{\phi}$	0.661***	0.596***	0.672***	0.605***
	(0.050)	(0.047)	(0.049)	(0.045)
N	165	165	174	174
max T	50	50	50	50
avg T	38.76	38.76	38.36	38.36
min T	8	8	2	2
$N \times T$	6431	6396	6714	6674

Notes: See notes to Table 2. Specifications 3 and 4 interact the temperature variables with dummies for poor and hot countries, respectively (see Eqs. (2) and (3)). The standard errors are estimated by the estimator proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 1% (***), 5% (**), and 10% (*) levels.

and $N \geq 20$, when output growth is not very persistent, which is the case in our applications. We, therefore, select countries for which we have at least 30 years of observations for GDP growth, resulting in a sample of 130 countries. To explore heterogeneous responses across regions, we define a country as cold if its historical average temperature is among the bottom third of the temperature distribution. Other countries fall into temperate or hot climates. Poor and rich countries are selected based on International Monetary Fund's classifications. The results from estimating equation (4) with and without lagged world output growth, $\Delta\bar{y}_{w,t-1}$, are reported in Table 4. The inclusion of $\Delta\bar{y}_{w,t-1}$ serves two purposes: (1) it accounts for unobserved global factors, and (2) it renders the errors of the regressions across countries weakly (rather than strongly) correlated.

Key findings are as follows: First, the HPJ-MG estimation results for the sample of all 130 countries are similar (in sign and statistical significance) to those reported in Table 2. Specifically, persistent temperature deviations from their historical norms (owing to climate change) are estimated to have a negative effect on long-run per capita GDP growth (especially when $\Delta\bar{y}_{w,t-1}$ is included as an additional regressor). The mean group estimates for all 130 countries can be viewed as the weighted average of the estimates for cold and hot countries, and the weighted average of the estimates for poor and rich economies. Second, there is some evidence that negative growth effects of weather shocks are less severe in cold climates. For example, using the reported standard errors for the average estimated coefficients on cold and hot countries in regressions featuring $\Delta\bar{y}_{w,t-1}$ and $m = 30$ (see Column 6 of Table 4), the 95% range estimates can be calculated as $(-0.342 - 1.96 * 0.1509 = -0.64$ to $-0.342 + 1.96 * 0.1509 = -0.05)$ for cold countries and $(-1.180 - 1.96 * 0.3713 = -1.91$ to $-1.180 + 1.96 * 0.3713 = -0.45)$ for hot countries. As can be seen, the 95% interval for cold climates largely falls outside the 95% interval for hot climates, suggesting more severe growth effects of weather shocks in hot countries. Nevertheless, the impact of persistent changes in $\lvert\tilde{T}_{it}(m)\rvert$ on GDP growth in cold climates is still negative, statistically significant, and increasing with m (namely depends on how fast adaptation is taking place). Third, while poor countries are found to be disproportionately affected by weather shocks, rich countries are by no means immune to climate change. Note that lagged world output growth, $\Delta\bar{y}_{w,t-1}$, plays a crucial role in accounting for global output trends that likely interact with global climate conditions. The weather effects are generally weaker when $\Delta\bar{y}_{w,t-1}$ is excluded from regressions.

3. Counterfactual analysis

We perform a number of counterfactual exercises to measure the cumulative output per capita effects of persistent increases in annual temperatures above their norms (or thresholds) over the period 2015–2100. We carry out this analysis using the HPJ-FE estimates based on the ARDL specification given by (1), which we write equivalently as

$$\varphi(L)\,\Delta y_{it} = a_i + \beta(L)\Delta x_{it}(m) + \varepsilon_{it},$$

where $x_{it}(m) = \left|T_{it} - T^{*}_{it-1}(m)\right|$, $\varphi(L) = 1 - \sum_{\ell=1}^{4}\varphi_\ell L^l$, $\beta(L) = \sum_{\ell=0}^{4}\beta_\ell L^l$, and L is the lag operator. Pre-multiplying both sides of the above equation by the inverse of $\varphi(L)$ yields

$$\Delta y_{it} = \tilde{a}_i + \psi(L)\Delta x_{it} + \vartheta(L)\varepsilon_{it}, \tag{5}$$

where $\tilde{a}_i = \varphi(1)^{-1}a_i$, $\vartheta(L) = \vartheta_0 + \vartheta_1 L + \vartheta_2 L^2 + \cdots$ and $\psi(L) = \varphi(L)^{-1}\beta(L) = \psi_0 + \psi_1 L + \psi_2 L^2 + \cdots$ for $j = 0, 1, 2, \ldots$.[15]

The counterfactual effects of climate change can now be derived by comparing the output trajectory of country i over the period $T+1$ to $T+h$ under the no change scenario denoted by $b^0_{T_i}$ and $\sigma^0_{T_i}$, with an alternative expected trajectory having the counterfactual values of $b^1_{T_i}$ and $\sigma^1_{T_i}$. Denoting the values of x_{it} for $t = T+1, T+2, \ldots, T+h$ under these two scenarios by $\mathbf{x}^0_{i,T+1,T+h} = \left\{x^0_{i,T+1}, x^0_{i,T+2}, \ldots, x^0_{i,T+h}\right\}$, and $\mathbf{x}^1_{i,T+1,T+h} = \left\{x^1_{i,T+1}, x^1_{i,T+2}, \ldots, x^1_{i,T+h}\right\}$, the counterfactual output change can be written as

$$\xi_{i,T+h} = \mathbb{E}\left(y_{i,T+h}\left|\mathcal{F}_{i,T}, \mathbf{x}^1_{i,T+1,T+h}\right.\right) - \mathbb{E}\left(y_{i,T+h}\left|\mathcal{F}_{i,T}, \mathbf{x}^0_{i,T+1,T+h}\right.\right),$$

where $\mathcal{F}_{iT} = (y_{iT}, y_{i,T-1}, y_{i,T-2}, \ldots; x_{iT}, x_{i,T-1}, x_{i,T-2}, \ldots)$. Cumulating both sides of (5) from $t = T+1$ to $T+h$ and taking conditional expectations under the two scenarios we have

$$\xi_{i,T+h} = \sum_{j=1}^{h}\psi_{h-j}\left(x^1_{i,T+j} - x^0_{i,T+j}\right), \tag{6}$$

The impact of climate change clearly depends on the magnitude of $x^1_{i,T+j} - x^0_{i,T+j}$.

We consider the output effects of country-specific average annual increases in temperatures over the period 2015–2100 as predicted under RCP 2.6 and RCP 8.5 scenarios, and compare them with a baseline scenario under which temperature in each country increases according to its historical trend of 1960–2014.[16] However, owing to the non-linear nature of our output-growth specification, changes in trend temperature do not translate on a one-to-one basis to absolute changes in temperature. In line with (A.34), future temperature changes over the counterfactual horizon, $T+j,\ j = 1, 2, \ldots$. can be represented by

$$T_{i,T+j} = a_{Ti} + b_{Ti,j}(T+j) + \upsilon_{Ti,T+j}, \text{ for } j = 1, 2, \ldots, \tag{7}$$

where we allow for the trend change in the temperature to vary over time. The above equation reduces to (A.34) if we set $b_{Ti,j} = b_{Ti}$ for all j. Suppose also that, as before, the historical norm variable associated with $T_{i,T+j}$, namely $T^{*}_{i,T+j-1}(m)$, is constructed using the past m years. Then it is easy to show that

$$T_{i,T+j} - T^{*}_{i,T+j-1}(m) = \left(\frac{m+1}{2}\right)b_{Ti,j} + \left(\upsilon_{Ti,T+j} - \bar{\upsilon}_{Ti,T+j-1,m}\right),\ j = 1, 2, \ldots, h, \tag{8}$$

where $\bar{\upsilon}_{Ti,T+j-1,m} = m^{-1}\sum_{s=1}^{m}\upsilon_{Ti,T+j-s}$. The realized values of $\left|T_{i,T+j} - T^{*}_{i,T+j-1}(m)\right|$ depend on the probability distribution of weather shocks, $\upsilon_{Ti,T+j}$, as well as the trend change in temperature, given by $b_{Ti,j}$. As a first order approximation, and in order to obtain analytic

[15] We are suppressing the dependence of x_{it} on m to simplify the exposition.
[16] A similar analysis can also be carried out in terms of changes in precipitation. For brevity and given the empirical results in Section 2, we focus on the counterfactual effects of changes in temperature only.

Table 4
Mean group estimates of the long-run effects of climate change on per capita real GDP growth, 1960–2014.

	Excluding $\Delta\bar{y}_{w,t-1}$			Including $\Delta\bar{y}_{w,t-1}$		
Historical norm:	$m = 20$	$m = 30$	$m = 40$	$m = 20$	$m = 30$	$m = 40$
(a) All 130 countries						
$\hat{\theta}_{\Delta\lvert\tilde{T}_{it}(m)\rvert}$	−0.447* (0.234)	−0.487 (0.367)	−0.521 (0.473)	−0.706*** (0.237)	−0.918** (0.393)	−1.051** (0.519)
$N \times T$	6198	6198	6198	6020	6020	6020
(b) Cold ($\bar{T}_i < 33th$ *Percentile*)						
$\hat{\theta}_{\Delta\lvert\tilde{T}_{it}(m)\rvert}$	−0.227** (0.101)	−0.230* (0.128)	−0.198 (0.175)	−0.238** (0.105)	−0.342** (0.151)	−0.457*** (0.169)
$N \times T$	2090	2090	2090	1964	1964	1964
(c) Temperate or hot ($\bar{T}_i \geq 33th$ *Percentile*)						
$\hat{\theta}_{\Delta\lvert\tilde{T}_{it}(m)\rvert}$	−0.665*** (0.193)	−0.780*** (0.302)	−0.613 (0.431)	−0.842*** (0.222)	−1.180*** (0.371)	−1.212** (0.504)
$N \times T$	4108	4108	4108	3990	3990	3990
(d) Poor (Low-income developing countries)						
$\hat{\theta}_{\Delta\lvert\tilde{T}_{it}(m)\rvert}$	−0.603** (0.270)	−0.759* (0.406)	−0.855* (0.488)	−1.020*** (0.262)	−1.463*** (0.429)	−1.703*** (0.547)
$N \times T$	3140	3140	3140	3048	3048	3048
(e) Rich (Advanced economies and G20 emerging markets)						
$\hat{\theta}_{\Delta\lvert\tilde{T}_{it}(m)\rvert}$	−0.586*** (0.195)	−0.849*** (0.272)	−1.047*** (0.373)	−0.587*** (0.209)	−1.003*** (0.310)	−1.280*** (0.392)
$N \times T$	1794	1794	1794	1734	1734	1734

Notes: Specification 1 is given by $\Delta y_{it} = a_i + \varphi_i \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p_T} \beta_{i\ell} \Delta\left|\tilde{T}_{it-\ell}(m)\right| + \varepsilon_{it}$, where y_{it} is the log of real GDP per capita of country i in year t, $\tilde{T}_{it}(m) = \left(\frac{2}{m+1}\right)\left[T_{it} - T^*_{i,t-1}(m)\right]$ is a measure of temperature relative to its historical norm per annum, T_{it} is the population-weighted average temperature of country i in year t, and $T^*_{i,t-1}(m) = \frac{1}{m}\sum_{\ell=1}^{m} T_{i,t-\ell}$ is the time-varying historical norm of temperature over the preceding m years in each t. Specification 2 is given by $\Delta y_{it} = a_i + \omega_i \Delta\bar{y}_{w,t-1} + \varphi_i \Delta y_{i,t-\ell} + \sum_{\ell=0}^{p_T} \beta_{i\ell} \Delta\left|\tilde{T}_{it-\ell}(m)\right| + \varepsilon_{it}$, where $\bar{y}_{wt}$ is the log of world's real GDP per capita in year t and the other variables are as before. The models are estimated using the half-panel Jackknife mean-group estimator. Asterisks indicate statistical significance at the 1% (***), 5% (**), and 10% (*) levels.

expressions, we assume that temperature shocks, $\upsilon_{Ti,T+j}$, over $j = 1, 2, \ldots$, are serially uncorrelated, Gaussian random variables with zero means and variances, σ^2_{Ti}. Under these assumptions and using the results in Lemma 3.1 of Dhyne et al. (2011), we have

$$\mathbb{E}\left|T_{i,T+j} - T^*_{i,T+j-1}(m)\right| = \mu_{Ti,j}\left[\Phi\left(\frac{\mu_{Ti,j}}{\omega_{Ti}}\right) - \Phi\left(\frac{-\mu_{Ti,j}}{\omega_{Ti}}\right)\right] + 2\omega_{Ti}\phi\left(\frac{\mu_{Ti,j}}{\omega_{Ti}}\right) = g_{Ti}(m, b_{Ti,j}, \sigma_{Ti}) \quad (9)$$

where $\Phi(\cdot)$ and $\phi(\cdot)$ are the cumulative and density distribution functions of a standard Normal variate, respectively, and

$\mu_{Ti,j} = \left(\frac{m+1}{2}\right) b_{Ti,j}$, and $\omega^2_{Ti} = \sigma^2_{Ti}\left(1 + \frac{1}{m}\right)$.

It is clear from the above expressions that the responses of our climate variables to a postulated rise in temperature most crucially depend on the volatility of temperature around its trend, σ_{Ti}, which differs markedly across countries.[17]

For the baseline scenario, we set $m = 30$ and consider the following counterfactual *country-specific* changes in the trend temperature over the period $T + j$, for $j = 1, 2, \ldots, H$, as compared to the historical trend rise in temperature (namely b^0_{Ti}):

$$b^1_{Ti,j} = T_{i,T+j} - T_{i,T+j-1} = b^0_{Ti} + jd_i, \text{ for all } j = 1, 2 \ldots, H, \quad (10)$$

where d_i is the average incremental change in the trend rise in temperature for country i. We set d_i to ensure that the average rise in temperature over the counterfactual period in country i is equal to the hypothesized value of b^1_{Ti}, and note that

$$b^1_{Ti} = H^{-1}\sum_{j=1}^{H} b^1_{Ti,j} = H^{-1}\sum_{j=1}^{H}\left(T_{i,T+j} - T_{i,T+j-1}\right) = \frac{T_{i,T+H} - T_{i,T}}{H}, \quad (11)$$

where $T_{i,T+H}$ denotes the level of temperature at the end of the counterfactual period. Averaging (10) over j we have

$$d_i = \frac{2\left(b^1_{Ti} - b^0_{Ti}\right)}{H + 1}. \quad (12)$$

In our empirical application, we set $T_{i,T+H} = T_{i,2099}$ and $T_{i,T+1} = T_{i,2015}$, with implied $H = 85$. For $T_{i,2099}$, for $i = 1, 2, \ldots, N$, we consider two sets of values based on IPCC's projections under the RCP 2.6 and RCP 8.5 scenarios (see Table A.7). In effect, this specification assumes that over the counterfactual period temperature in country i increases by jd_i per annum over the period $T + 1$ to $T + j$, relative to its historical trend value of b^0_{Ti}.

We also assume that the postulated trend rise in temperature, specified in (10), does not affect the volatility of temperature shocks, and set σ^1_{Ti} to its pre-counterfactual value of σ^0_{Ti}. This is a conservative assumption and most likely will result in an under-estimation of the adverse effects of temperature increases, since one would expect rising temperature to be associated with an increase in volatility.[18] With these considerations in mind, and using (6), the mean counterfactual impact of the temperature change on output is given by

$$\Delta_{ih}(d_i) = \mathbb{E}\left(y^1_{i,T+h}\left|\mathcal{F}_{i,T}\right.\right) - \mathbb{E}\left(y^0_{i,T+h}\left|\mathcal{F}_{i,T}\right.\right) = \sum_{j=1}^{h}\psi_{h-j}\left[g_{Ti}(m, b^0_{Ti} + jd_i, \sigma^0_{Ti}) - g_{Ti}(m, b^0_{Ti}, \sigma^0_{Ti})\right], \quad (13)$$

[17] For estimates of σ_{Ti} across countries see Table A.7.

[18] Moreover, accounting for international spillover effects of climate change, individual countries' long-term growth effects could be larger.

Table 5
Effects of climate change on per capita real GDP growth, 1960–2014.

$\hat{\beta}_0$	−0.0038*	$\hat{\varphi}_1$	0.2643***	No. of countries (N)	174
	(0.0021)		(0.0500)	$\max T$	50
$\hat{\beta}_1$	−0.0056*	$\hat{\varphi}_2$	0.0785***	avg T	38.36
	(0.0029)		(0.0266)	$\min T$	2
$\hat{\beta}_2$	−0.0084***	$\hat{\varphi}_3$	0.0547**	No. of obs. $(N \times T)$	6674
	(0.0031)		(0.0216)		
$\hat{\beta}_3$	−0.0090***	$\hat{\varphi}_4$	−0.0016		
	(0.0026)		(0.0327)		
$\hat{\beta}_4$	−0.0060***				
	(0.0021)				

Notes: Estimates are based on $\Delta y_{it} = a_i + \sum_{\ell=1}^{4} \varphi_\ell \Delta y_{i,t-\ell} + \sum_{\ell=0}^{4} \beta_\ell' \Delta x_{i,t-\ell}(m) + \varepsilon_{it}$, where y_{it} is the log of real GDP per capita of country i in year t, $x_{it}(m) = \left|T_{it} - T_{i,t-1}^*(m)\right|$, T_{it} is the population-weighted average temperature of country i in year t, and $T_{i,t-1}^*(m)$ is the historical temperature norm of country i (based on moving averages of the past 30 years). The coefficients are estimated by the half-panel Jackknife FE (HPJ-FE) procedure and the standard errors are based on the estimator proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at 1% (***), 5% (**), and 10% (*) levels.

where we base the estimates of b_{Ti}^0 and σ_{Ti}^0 on the pre-counterfactual period 1960–2014 (see Table A.7), and use

$$g_{Ti}^1(m, b_{Ti,j}^1, \sigma_{Ti}^0) = \mu_{Ti,j}^1 \left[\Phi\left(\frac{\mu_{Ti,j}^1}{\omega_{Ti}^0}\right) - \Phi\left(\frac{-\mu_{Ti,j}^1}{\omega_{Ti}^0}\right) \right] + 2\omega_{Ti}^0 \phi\left(\frac{\mu_{Ti,j}^1}{\omega_{Ti}^0}\right), \tag{14}$$

$$g_{Ti}^0(m, b_{Ti}^0, \sigma_{Ti}^0) = \mu_{Ti}^0 \left[\Phi\left(\frac{\mu_{Ti}^0}{\omega_{Ti}^0}\right) - \Phi\left(\frac{-\mu_{Ti}^0}{\omega_{Ti}^0}\right) \right] + 2\omega_{Ti}^0 \phi\left(\frac{\mu_{Ti}^0}{\omega_{Ti}^0}\right), \tag{15}$$

$$\mu_{Ti,j}^1 = \left(\frac{m+1}{2}\right)\left(b_{Ti,j}^1\right), \ \mu_{Ti}^0 = \left(\frac{m+1}{2}\right) b_{Ti}^0, \tag{16}$$

and $\omega_{Ti}^0 = \sigma_{Ti}^0 \left(1 + \frac{1}{m}\right)^{1/2}$. To obtain $\{\hat{\psi}_j\}$, we use the HPJ-FE estimates of $\{\beta_\ell\}_{l=0}^4$ and $\{\varphi_l\}_{l=1}^4$ from the ARDL equation with $\left|T_{it} - T_{i,t-1}^*(m)\right|$ as the climate variable. These estimates and their standard errors are reported in Table 5. Fig. 5 plots the estimates of ψ_j for $j = 0, 1, 2, \ldots, 20$, for which the estimated mean lag is $\frac{\sum_{j=1}^{\infty} j\hat{\psi}_j}{\sum_{j=0}^{\infty} \hat{\psi}_j} = 3.1943$ years.

We report the real GDP per capita losses from global warming under the RCP 2.6 and RCP 8.5 scenarios, compared to the reference case, in country heat maps and for the year 2100 only, but make all of the 174 country-specific estimates over various horizons (by year 2030, 2050, and 2100) available in Table A.7. Fig. 6 shows that in the absence of climate change policies (under the RCP 8.5 Scenario with $m = 30$), the percent losses in per-capita incomes by 2100 are sizable, regardless of whether a country is rich or poor, and hot or cold. Nonetheless, the losses vary significantly across countries depending on the country-specific projected paths of temperatures. Fig. 7 shows that if we managed to limit the increase in average global temperatures to 0.01 °C per annum (the RCP 2.6 scenario), in line with the Paris Agreement objective, we would be able to substantially reduce these losses.

Table 6 reports the real GDP per capita losses for China, the European Union, India, Russia, and the United States, over various time horizons. As in Fig. 6, income effects are substantially larger under an unmitigated path (i.e., RCP 8.5). Nonetheless, under both scenarios, the cross-country heterogeneity is significant. Focusing on the RCP 8.5 scenario (with $m = 30$) we observe that the losses vary between 0.50 and 1.20 percent, 1.53 and 3.77 percent, and 4.35 and 10.52 percent in 2030, 2050 and 2100, respectively; with a relatively large impact estimated for the United States in 2100 (reflecting IPCC's projections of a sharp increase in the country's average temperature in the absence of mitigation efforts).

Averaging the losses across countries, using PPP-GDP weights, we report the global income effects of climate change under the RCP 2.6 and RCP 8.5 scenarios in Table 6. Under the Paris agreement objective, and assuming $m = 30$, our results indicate that the world could actually benefit from mitigation policies in year 2030 (compared to a reference case in which temperatures increase according to their historical trends of 1960–2014), while limiting the economic losses of climate change to 0.11 and 1.07 percent over the next 36 and 86 years, respectively. However, a persistent above-norm increase in average global temperature by 0.04 °C per year (based on RCP 8.5) leads to substantial output losses, reducing real per capita output by 0.80, 2.51 and 7.22 percent in 2030, 2050 and 2100, respectively. Overall these economic effects are somewhat larger than those obtained in existing studies in the literature and what is generally discussed in policy circles (see Fig. 2).

Can adaptation help offset these negative income effects? Repeating the counterfactual exercise for different values of m highlights the role of adaptation. The shorter the m, the faster agents treat higher temperatures as the new norm. Table 6 shows the effects of global warming over time for various values of m. The results indicate that per-capita output losses are lower for $m = 20$ but significantly higher if it takes longer to adapt to climate change ($m = 40$). Overall, we argue that while climate change adaptation could reduce these negative economic effects, it is highly unlikely to offset them entirely. More forceful mitigation policies are needed to limit the damage from climate change.

Prior research projects the GDP impact of temperature increases for some future year, typically 2100, assuming a "no further warming" counterfactual (e.g., Burke et al., 2015; Kalkuhl and Wenz, 2020). Since there are no pathways to a scenario in which baseline temperatures remain constant, we compared the per capita GDP impact of temperature increases under RCP2.6 and RCP8.5 to a baseline scenario under which temperature in each country rises according to its historical trend of 1960–2014. However, to have a better comparability to previous papers, we also performed a counterfactual exercise where temperature increases under RCP8.5 are compared to a baseline scenario in which historical temperatures are assumed to remain constant. As expected, the analysis results in higher per capita income losses in 2100 (4.64 percent for $m = 20$; 7.64 percent for $m = 30$; and 10.67 percent for $m = 40$) than those reported in Table 6 under RCP8.5 (4.44, 7.22, and 9.96 percent, respectively).

We showed that economic growth is affected not only by higher temperatures but also by the degree of climate variability. To study the role of climate volatility in determining GDP per capita losses, instead of setting $\sigma_{Ti}^1 = \sigma_{Ti}^0$, we allow temperature increases to affect the variability of temperature shocks commensurately. That is, we keep the coefficient of variation unchanged, and therefore set $\sigma_{Ti}^1 = \left(\mu_{Ti,j}^1/\mu_{Ti}^0\right)\sigma_{Ti}^0$. The results are reported in Table 7 for the RCP 8.5 scenario and $m = 30$. As expected, the estimated GDP per capita losses become significantly larger, almost doubling at the global level by 2100 to 13.11 percent. For the United States, the losses are likely to be 70 percent higher compared to the baseline counterfactual scenario reported in Table 6. In terms of the channels of impact, the increase in the degree of climate variability affects economies by reducing labour productivity, increasing health problems (e.g., heat-related health issues or drought-related water and food shortages), damaging infrastructure (e.g., from flooding in river basins and coasts and landslides), and disruptions in supply chains—see IPCC (2014) for details.

4. Concluding remarks

Using data on 174 countries over the period 1960 to 2014, and a novel econometric strategy (that differentiates between level and growth effects including over the long term; accounts for bi-directional feedbacks between economic growth and climate change; considers

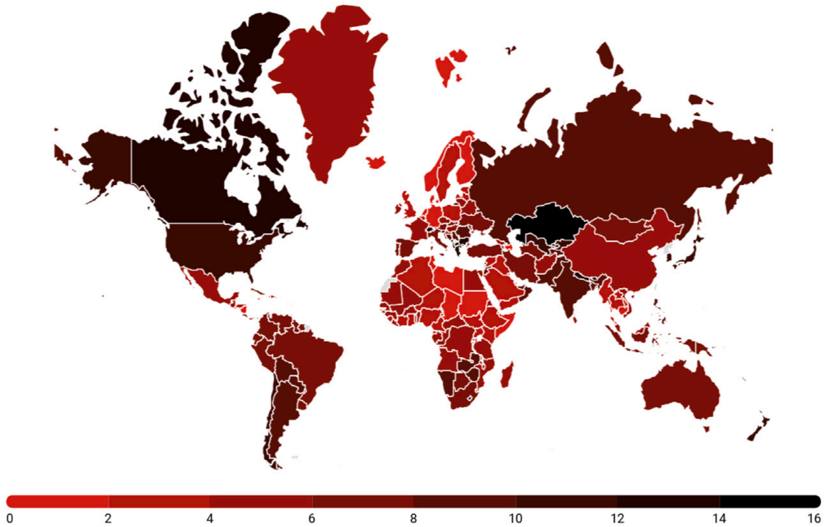

Fig. 6. Percent Loss in GDP per capita by 2100 in the Absence of Climate Change Policies (RCP 8.5 Scenario). Notes: The heat map shows $\Delta_{ih}(d_i)$, see Eq. (13), in year 2100 with $m = 30$, based on the RCP 8.5 scenario. The Mercator projection exaggerates areas far from the equator.

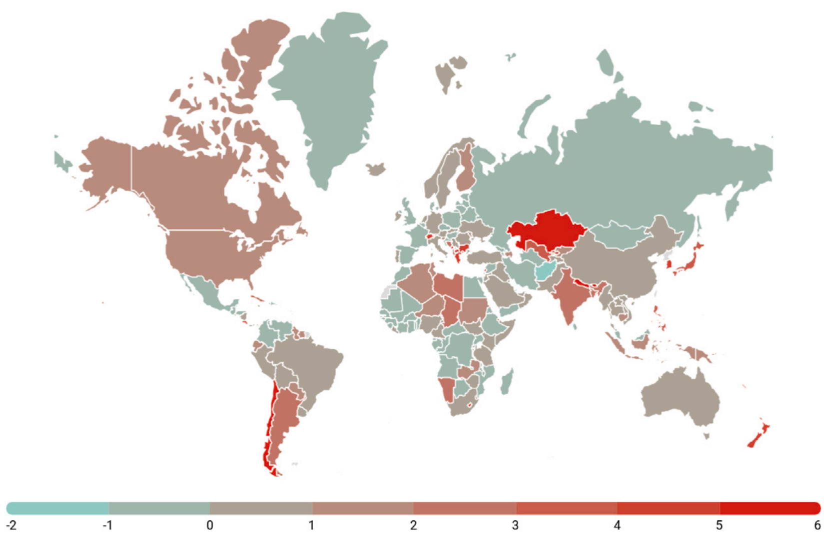

Fig. 7. Percent loss in GDP per capita by 2100 Abiding by the Paris Agreement Objective (RCP 2.6 Scenario). Notes: The heat map shows $\Delta_{ih}(d_i)$, see Eq. (13), in year 2100 with $m = 30$, based on the RCP 2.6 scenario. The Mercator projection exaggerates areas far from the equator.

asymmetric weather effects; allows for nonlinearity and an implicit model of adaptation; and deals with temperature being trended), we showed that persistent changes in temperature above time-varying norms has long-term negative impacts on economic growth. If temperature deviates from its historical norm by 0.01 °C annually for an extended period of time, long-term income growth will be lower by 0.0543 percentage points per year. Furthermore, we illustrated that these negative long-run growth effects are prevalent in all countries but to different degrees across climates and income groups. In particular, our heterogeneous panel data estimates suggested a lower marginal weather effects in cold and/or rich countries (i.e., slope coefficients were smaller). Nevertheless, we find that income losses are sizable even in cold climates either because they are warming up much faster than temperate or hot regions or climate variability is becoming more pronounced in line with faster temperature increases.

We performed a number of counterfactual exercises where we investigated the output effects of annual increases in temperatures under mitigated and unmitigated scenarios during 2015–2100. We showed that keeping the increase in the global average temperature to below 2 degrees Celsius above pre-industrial levels as agreed by 190 parties in Paris in December 2015, will reduce global income by 1 percent by 2100. However, an increase in average global temperatures of 0.04 °C (corresponding to the RCP 8.5 scenario, which assumes higher greenhouse gas emissions in absence of climate change mitigation policies) reduces world's real GDP per capita by 7 percent by 2100, with the size of these income effects varying significantly across countries depending on the pace of temperature increases and variability of climate conditions in each country. The estimated global per capita GDP losses under a high-emissions scenario with no policy action (that is RCP 8.5) would almost double if country-specific climate variability were to rise commensurate to temperature increases in each country (with global income losses amounting to 13 percent by 2100). Overall, abiding by the Paris Agreement objective would go a long way in limiting economic losses from climate change across almost all countries. We also illustrated that while adaptation to climate change could reduce these negative long-run growth effects, it is highly unlikely to offset them entirely. Therefore, our findings call for more forceful policy responses to the threat of climate change, including more ambitious mitigation and adaptation efforts.

Table 6
Percent loss in GDP per capita by 2030, 2050, and 2100 under the RCP 2.6 and RCP 8.5 scenarios.

	Year 2030 ($h = 16$)			Year 2050 ($h = 36$)			Year 2100 ($h = 86$)		
	$m = 20$	$m = 30$	$m = 40$	$m = 20$	$m = 30$	$m = 40$	$m = 20$	$m = 30$	$m = 40$
World									
RCP 2.6	−0.01	−0.01	−0.02	0.06	0.11	0.16	0.58	1.07	1.57
RCP 8.5	0.40	0.80	1.25	1.39	2.51	3.67	4.44	7.22	9.96
China									
RCP 2.6	−0.22	−0.45	−0.71	−0.38	−0.80	−1.31	0.24	0.45	0.67
RCP 8.5	0.31	0.58	0.87	0.90	1.62	2.30	2.67	4.35	5.93
European Union									
RCP 2.6	−0.04	−0.08	−0.13	−0.06	−0.13	−0.22	0.05	0.09	0.13
RCP 8.5	0.24	0.50	0.80	0.79	1.53	2.35	2.67	4.66	6.69
India									
RCP 2.6	0.12	0.26	0.42	0.41	0.81	1.27	1.44	2.57	3.69
RCP 8.5	0.60	1.16	1.78	2.13	3.62	5.08	6.37	9.90	13.39
Russia									
RCP 2.6	−0.07	−0.14	−0.23	−0.16	−0.34	−0.56	−0.33	−0.71	−1.19
RCP 8.5	0.51	1.03	1.63	1.62	3.08	4.61	5.28	8.93	12.46
United States									
RCP 2.6	0.10	0.20	0.33	0.29	0.60	0.96	0.98	1.88	2.84
RCP 8.5	0.60	1.20	1.86	2.13	3.77	5.39	6.66	10.52	14.32

Notes: We consider persistent increases in temperatures based on the RCP 2.6 and RCP 8.5 scenarios. Numbers are PPP GDP weighted averages of $\Delta_{ih}\left(d_i\right)$, see Eq. (13), with $h = 16$, 36 , and 86 (corresponding to the year 2030, 2050, and 2100, respectively) and $m = 20$, 30, and 40.

Table 7
Percent loss in GDP per capita by 2030, 2050, and 2100 under the RCP 8.5 scenario: the role of climate variability.

	Year 2030 ($h = 16$)	Year 2050 ($h = 36$)	Year 2100 ($h = 86$)
World	2.02	5.18	13.11
China	0.78	1.99	5.02
European Union	1.45	3.71	9.37
India	2.62	6.70	16.92
Russia	2.00	5.13	12.94
United States	2.66	6.81	17.19

Notes: We consider persistent increases in temperatures based on the RCP 8.5 scenario but set $\sigma^1_{Ti} = \left(\mu^1_{Ti,j}/\mu^0_{Ti}\right)\sigma^0_{Ti}$. Numbers are PPP GDP weighted averages of $\Delta_{ih}\left(d_i\right)$, with $h = 16$, 36, and 86 (corresponding to the year 2030, 2050, and 2100, respectively) and $m = 30$.

Data availability

Mendeley data: http://dx.doi.org/10.17632/hytzz8wftw

Appendix A. Theory (A1), relation to literature (A2), temperature trends (A3), and individual country results (A4)

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2021.105624.

References

Agrawala, S., Carraro, M., Kingsmill, N., Lanzi, E., Mullan, M., Prudent-Richard, G., Private Sector Engagement in Adaptation to Climate Change: Approaches to Managing Climate Risks, OECD Environment Working Papers No 39.

Arguez, A., Durre, I., Applequist, S., Vose, R.S., Squires, M.F., Yin, X., Heim, R.R., Owen, T.W., 2012. Noaa's 1981-2010 U.S. climate normals: An overview. Bull. Am. Meteorol. Soc. 93 (11), 1687–1697.

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

Cashin, P., Mohaddes, K., Raissi, M., 2017. Fair weather or foul? The macroeconomic effects of El Niño. J. Int. Econ. 106, 37–54.

Chudik, A., Mohaddes, K., Pesaran, M.H., Raissi, M., 2013. Debt, Inflation and Growth: Robust Estimation of Long-Run Effects in Dynamic Panel Data Models. Federal Reserve Bank of Dallas, Globalization and Monetary Policy Institute Working Paper No. 162.

Chudik, A., Mohaddes, K., Pesaran, M.H., Raissi, M., 2016. Long-run effects in large heterogeneous panel data models with cross-sectionally correlated errors. In: Hill, R.C., Gonzalez-Rivera, G., Lee, T.-H. (Eds.), Advances in Econometrics (Volume 36): Essays in Honor of Aman Ullah. Emerald Publishing, pp. 85–135 (Chapter 4).

Chudik, A., Mohaddes, K., Pesaran, M.H., Raissi, M., 2017. Is there a debt-threshold effect on output growth? Rev. Econ. Stat. 99 (1), 135–150.

Chudik, A., Pesaran, M.H., Yang, J.-C., 2018. Half-panel jackknife fixed effects estimation of panels with weakly exogenous regressors. J. Appl. Econometrics 33 (6), 816–836.

CIESIN, 2016. Gridded Population of the World, Version 4 (GPWv4): Population Density. Columbia University, NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY.

Dell, M., Jones, B.F., Olken, B.A., 2009. Temperature and income: Reconciling new cross-sectional and panel estimates. Amer. Econ. Rev. 99 (2), 198–204.

Dell, M., Jones, B.F., Olken, B.A., 2012. Temperature shocks and economic growth: Evidence from the last half century. Am. Econ. J. Macroecon. 4 (3), 66–95.

Dell, M., Jones, B.F., Olken, B.A., 2014. What do we learn from the weather? The new climate-economy literature. J. Econ. Lit. 52 (3), 740–798.

Deryugina, T., Hsiang, S.M., Does the Environment Still Matter? Daily Temperature and Income in the United States, NBER Working Paper No. 20750.

Dhyne, E., Fuss, C., Pesaran, M.H., Sevestre, P., 2011. Lumpy price adjustments: A microeconometric analysis. J. Bus. Econom. Statist. 29 (4), 529–540.

Gallup, J.L., Sachs, J.D., Mellinger, A.D., 1999. Geography and economic development. Int. Reg. Sci. Rev. 22 (2), 179–232.

Heal, G., Park, J., 2016. Reflections - Temperature stress and the direct impact of climate change: A review of an emerging literature. Rev. Environ. Econ. Policy 10 (2), 347–362.

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

Hsiang, S.M., 2016. Climate econometrics. Annu. Rev. Resour. Econ. 8 (1).

International Monetary Fund, 2017. The effects of weather shocks on economic activity: How can low-income countries cope? In: World Economic Outlook. pp. 117–183 (Chapter 3).

IPCC, 2014. Climate Change 2014: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Volume 1. Cambridge University Press, Cambridge.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Jones, B.F., Olken, B.A., 2010. Climate shocks and exports. Amer. Econ. Rev. 100 (2), 454–459.

Kalkuhl, M., Wenz, L., 2020. The impact of climate conditions on economic production. evidence from a global panel of regions. J. Environ. Econ. Manag. 103, 102360.

Letta, M., Tol, R.S.J., 2019. Weather, climate and total factor productivity. Environ. Resour. Econ. 73, 283–305.

Matsuura, K., Willmott, C.J., 2015. Terrestrial air temperature and precipitation: Monthly and annual time series (1900 - 2014), v 4.01.

Mejia, S.A., Mrkaic, M., Novta, N., Pugacheva, E., Topalova, P., 2018. The Effects of Weather Shocks on Economic Activity: What are the Channels of Impact? International Monetary Fund, IMF Working Paper WP/18/144.

Mendelsohn, R., 2016. Measuring weather impacts using panel data.

Newell, R.G., Prest, B.C., Sexton, S.E., 2021. The GDP-temperature relationship: Implications for climate change damages. J. Environ. Econ. Manag. 108, 102445.

Nickell, S., 1981. Biases in dynamic models with fixed effects. Econometrica 49 (6), 1417–1426.

Nordhaus, W.D., 1992. The "DICE" Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming. Technical Report 1009, Cowles Foundation Discussion Paper No. 1009.

Nordhaus, W.D., 2006. Geography and macroeconomics: New data and new findings. Proc. Natl. Acad. Sci. USA 103 (10), 3510–3517.

Obama, B., 2017. The irreversible momentum of clean energy. Science.

Pesaran, M.H., 1997. The role of economic theory in modelling the long run. Econom. J. 107, 178–191.

Pesaran, M.H., Shin, Y., 1999. An autoregressive distributed lag modelling approach to cointegration analysis. In: Strom, S. (Ed.), Econometrics and Economic Theory in 20th Century: The Ragnar Frisch Centennial Symposium. Cambridge University Press, Cambridge, pp. 371–413 (Chapter 11).

Pesaran, M.H., Smith, R., 1995. Estimating long-run relationships from dynamic heterogeneous panels. J. Econometrics 68 (1), 79–113.

Sachs, J.D., Warner, A.M., 1997. Sources of slow growth in African economies. J. Afr. Econ. 6 (3), 335–376.

Schlenker, W., Auffhammer, M., 2018. The cost of a warming climate. Nature 557 (News & Views Forum), 498–499.

Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge.

Tol, R.S.J., 2009. The economic effects of climate change. J. Econ. Perspect. 23 (2), 29–51.

Tol, R.S.J., 2014. Correction and update: The economic effects of climate change. J. Econ. Perspect. 28 (2), 221–226.

Tol, R.S.J., 2017. Population and trends in the global mean temperature. Atmósfera 30 (2), 121–135.

Tol, R.S.J., 2018. The economic impacts of climate change. Rev. Environ. Econ. Policy 12 (1), 4–25.

Tol, R.S.J., The Economic Impact of Weather and Climate, CESifo Working Paper No. 8946.

Vose, R.S., Applequist, S., Squires, M., Durre, I., Menne, M.J., Williams, C.N., Fenimore, C., Gleason, K., Arndt, D., 2014. Improved historical temperature and precipitation time series for U.S. climate divisions. J. Appl. Meteorol. Climatol. 53 (5), 1232–1251.