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Rising temperatures, melting incomes: Country-specific macroeconomic effects of climate scenarios

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Abstract

Quantifying the macroeconomic impact of climate change has been a focal point in academic and policy discussions since the early 1990s. The estimates of (global) GDP losses at future warming levels vary widely due to differing methodologies, complicating the formulation of effective climate policies. This study aims to bridge the gap between these varying estimates by quantifying *country-specific* annual per-capita GDP losses from global warming using the most recent climate scenarios of the Intergovernmental Panel on Climate Change (IPCC) under different mitigation, adaptation, and climate variability assumptions. Motivated by the need to inform policy decisions, we hypothesize that without substantial mitigation and adaptation efforts, global GDP per capita could decline by up to 24 percent under high-emissions climate scenarios by 2100. To test this hypothesis, we conduct a series of counterfactual exercises, investigating the cumulative income effects of annual temperature increases by the end of the century. Our findings reveal significant disparities in income losses across the 174 countries in our sample, highlighting that the impacts of climate change are not uniform but depend on the projected paths of temperatures and their variability.

1. Introduction

Climate change—marked by rising average temperatures and sea levels, shifting precipitation patterns, and more frequent and intense extreme weather events—poses a critical challenge to the global economy. While the physical manifestations of climate change are visibly alarming, its macroeconomic implications are equally significant but difficult to quantify—Most models are unable to account for tipping points, non-market damages (e.g., mortality, conflicts, food insecurity), and spillovers. Inference about damages up to 2100 based on past data is inherently difficult. Current literature has established that climate change can lead to significant GDP per capita losses; however, estimates of these impacts vary widely—from negligible to catastrophic—due to differing methodologies and assumptions [1]. This paper aims to bridge the gap between these varying estimates by providing plausible *country-specific* annual per-capita GDP losses from global warming based on the methodology in [2], but using a wider and more up-to-date set of climate scenarios under different mitigation (i.e., reducing greenhouse gas emissions), adaptation (i.e., adjusting to climate change impacts), and climate variability (i.e., fluctuations in weather patterns) assumptions. A key objective of the paper is to consider the uncertainty of warming predictions of climate models by providing a range of GDP per capita impacts within an empirical approach that deals with many of the econometric pitfalls of earlier studies. We also compare our income loss estimates with those from select papers in the literature, utilizing a common baseline scenario to rule out implausibly small and excessively large estimates. We, therefore, contribute to a more nuanced understanding of the macroeconomic impacts of climate change.

While understanding the economic impact of rising temperatures is crucial for climate policy design, the most used estimates in the literature differ by orders of magnitude. For a worst-case global warming scenario, [3] estimate a 60% loss in global GDP per capita by 2100, while [4] conducts a meta-study of existing literature and reports a negligible income loss. This wide range of estimates arises from disagreements about whether a temperature increase will affect GDP levels or GDP growth rates (see, for instance, [5–9] and Fig 1A) and from different model specifications (including how extreme weather events, climate variability and adaptation are considered). Most papers that relate temperature to GDP levels yield income loss estimates that are relatively small. More recent studies, that relate temperature to GDP growth (possibly nonlinearly), show that a shift to a higher (non-decreasing) temperature reduces per capita output growth significantly (with compounding level effects) compared to a "no further warming" baseline. For example, the Network for Greening the Financial Sector (NGFS) measures the global GDP impact of climate change relative to a baseline scenario "in which climate change does not occur". [6] argue that "if future adaptation mimics past adaptation, unmitigated warming is expected to reshape the global economy by reducing average global incomes roughly 23% by 2100 and widening global income inequality, relative to scenarios without climate change". However, according to [4,10,11], the hypothesis that a one-off rise in temperature affects the growth rate of the economy permanently is inconsistent with growth theory. To arrive at a more nuanced quantification of the GDP impacts of climate change, we follow [2] in distinguishing between a one-off shift to permanently higher temperatures and persistent above-norms temperature increases (i.e., climate vs. climate change); modelling adaptation implicitly (by varying adaptation

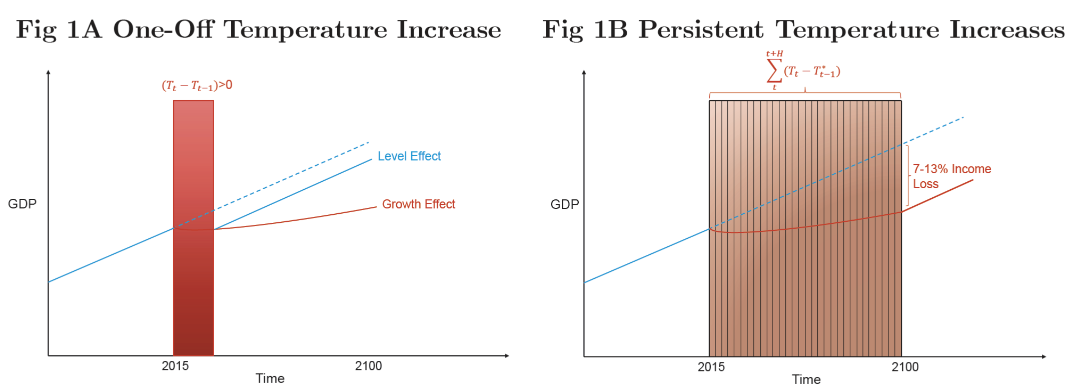

Fig 1. GDP impact of increases in temperature: Level vs. growth effects. Notes: Fig 1B shows the results in [2] under RCP8.5 with and without climate variability.

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speeds from one decade to a century) and climate variability explicitly (i.e., by accounting for the natural fluctuations of temperature around its rising trend)—Understanding interannual and interdecadal natural climate variability is crucial for GDP impact assessments, not least because climate change significantly alters the frequency, intensity, and patterns of climate variability. Interannual climate variability is observed as changes in climate patterns from one year to the next. A well-known example is the El Niño Southern Oscillation (ENSO), which includes both El Niño and La Niña events (see, for instance, [12] and [13] for details). Interdecadal climate variability refers to fluctuations in climate that occur over periods of several decades. Examples include the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO)—and conducting a range of counterfactual exercises relative to a baseline under which temperature in each country increases according to its historical trend of 1960–2014.

Specifically, [2] establish a relationship between deviations in temperature (weather) from 30-year moving averages (climate) and GDP per capita across countries. Note that regressing GDP per capita growth on temperature levels leads to biased impact estimates because GDP growth is stationary while temperature is positively trended due to global warming. Relatedly, [2] demonstrate that a sustained increase in above-norm temperature—indicative of climate change—correlates with decreased long-term economic growth. This suggests that while temporary temperature fluctuations may result in short-term economic impacts, climate change can alter the long-term averages and variability of weather, thereby affecting an economy's growth potential over time. The impact on GDP per capita accumulates as temperatures continue to rise and adaptation measures are implemented gradually; however, these effects may stabilize if temperatures eventually level off [2] calculate annual income losses resulting from climate change by analyzing weather anomalies over time for 174 countries under different climate scenarios. They project that if temperatures increase persistently by 0.04° C per year under a high-emissions scenario (RCP 8.5), real GDP per capita worldwide could decline by 7–13% by 2100, compared to a baseline where temperatures follow their trends from 1960-2014 (Fig 1B). In contrast, adhering to the Paris Agreement's goal of capping the temperature increase to 0.01° C annually would reduce this loss to about 1%. While adapting to climate change may reduce these negative long-term growth effects, it is highly unlikely to completely eliminate them. See also [14] who provided evidence for the damage that climate change causes in the United States using within-country data on Gross State Product (GSP) GSP per capita, labour productivity and employment as well as output growth in ten economic sectors (such as agriculture, construction, manufacturing, services, retail and wholesale trade). They show that while certain sectors in the U.S. economy might have adapted to higher temperatures, economic activity in the U.S. overall and at the sectoral level continues to be sensitive to deviations of temperature and precipitation from their historical norms.

Given that the planet has already warmed by 1.2°C compared to pre-industrial averages, its impact on GDP per capita (alongside past adaptation) is already reflected in historical growth observations. To highlight the size of this observed damage, we estimate a weighted-average global income loss of 2 percent (USD 1.6 trillion) from above-norm temperature increases over 1960-2014. However, global warming is projected to accelerate under various IPCC climate scenarios, and hence its impact on the economy will be more detrimental than in the past, unless countries close the mitigation ambition and policy implementation gaps that are needed to abide by the Paris agreement temperature goals. We use the latest IPCC climate scenarios in our counterfactual exercises to better reflect uncertainties of climate change, technological pathways, and policies. We investigate the cumulative income effects of continuous above-norm temperature increases (by assuming that GDP per capita in each country is affected by temperature only when it deviates from its historical norm, serving as country-specific but time-varying thresholds or climates) over 2015–2100 relative to a baseline under which temperature in each country increases according to its trend of 1960–2014. We also report the associated income losses relative to a scenario without climate change and with extremely-slow adaptation.

Prior research projects the GDP impact of temperature increases for some future year, typically 2100, assuming a "no further warming" counterfactual (e.g., [3,6,7]). Since there are no pathways to a scenario in which baseline temperatures remain constant, we compare the per capita GDP impact of temperature increases under different climate scenarios to a baseline under which temperature in each country rises according to its historical trend of 1960–2014. We find that the global income effects of persistent increases in average temperatures by 0.04°C per year, assuming very limited mitigation and adaptation action, ranges from -10% to -11% by the end of this century. Furthermore, climate variability amplifies the projected income losses, with estimates surging to 12–14% globally with significant variations across countries. The upper bound of these losses allow for temperature increases to affect the variability of temperature shocks commensurately. Accounting for transition risks (in addition to physical risks) would lead to larger losses (especially for advanced economies, see, for instance, [15] and [16]). While adaptation presents a viable pathway to reducing the detrimental long-term growth effects of climate change, it falls short of completely eliminating these impacts. We, therefore, underscore the pressing need for climate change mitigation policies to slowing global warming. Abiding by the Paris Agreement goals, thereby limiting the temperature increase to 0.01 degrees Celsius per year, generates a positive income gain of about 0.25 percent globally.

To have better comparability to the literature, we also conduct an exercise in which adaptation is assumed to be extremely slow (i.e., we use 100-year historical norms) and income losses from temperature increases based on the 1960–2014 trends are compared to a "no further warming" scenario. Overall, our analysis results in per capita income losses of 20 to 24 percent under the high-emissions climate scenarios by 2100, with significant variations across countries. Our income loss estimates encompass findings from several studies in the literature; however, they are considerably smaller than damages reported by [3] and [8]. Establishing a reliable range for GDP impact assessments is essential for incorporating climate-related risks into macro-fiscal frameworks and for effectively informing and guiding climate action initiatives.

The rest of the paper is organized as follows. Sect 2 briefly describes the IPCC climate scenarios. Sect 3 discusses the methodology used for the counterfactual analysis. Sect 4 estimates the cumulative income effects of annual increases in temperatures under different climate scenarios. Finally, Sect 5 offers some concluding remarks.

2. Climate scenarios

Climate scenarios describe how the future might unfold under different levels of radiative forcing (the warming effect caused by greenhouse gases) and socio-economic pathways. Representative Concentration Pathways (RCPs) are scenarios of future greenhouse gas concentrations that describe the level of radiative forcing by 2100. Four independent radiative forcing pathways or RCPs were created by modelling groups to produce distinct and discernible climate change outcomes – RCP2.6, RCP4.5, RCP6.0 and RCP8.5 – each named after the approximate radiative forcing in 2100.

Shared Socio-economic Pathways (SSPs) describe potential future pathways of societal development, focusing on factors like population and education, urbanization, and economic development. The SSPs provide a framework for understanding how different socioeconomic conditions could influence greenhouse gas emissions and climate change. Five SSPs have been developed by the scientific community to span a range of outcomes that describe the challenges of climate change mitigation and adaptation.

SSPs are meant to be used in combination with RCPs in a scenario matrix to explore the impact of climate change mitigation on future global warming. SSPs without RCPs lack a specific quantitative translation to temperature, making comparisons across SSP scenarios difficult. RCPs without explicit SSPs assume an unspecified socio-economic context (energy, land-use, and emission pathways), limiting their ability to fully portray the nuances of future societal dynamics impacting emissions.

Within the RCP-SSP scenario matrix (Fig 2), this paper focuses on SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. The choice of climate scenarios is informed by the baseline global temperature pathways under current policies as well as (un)mitigated pathways. The first Global Stocktake (IPCC 2023) estimates that global temperature increase will be in the range of 2.1-2.8°C by 2100 with implementation of the latest nationally determined contributions. However, current policies are not consistent with these commitments, which means that the world is set to experience a temperature increase at the upper bound of the above range. This is largely consistent with SSP2-4.5 and close to the 1960-2014 trend temperature increase baseline. An aspirational global warming scenario consistent with Paris Agreement is also considered (SSP1-2.6). Moreover, two pessimistic scenarios reflecting policy reversals (SSP3-7.0), or continued expansion of fossil fuels (SSP5-8.5) are used to highlight the risks of

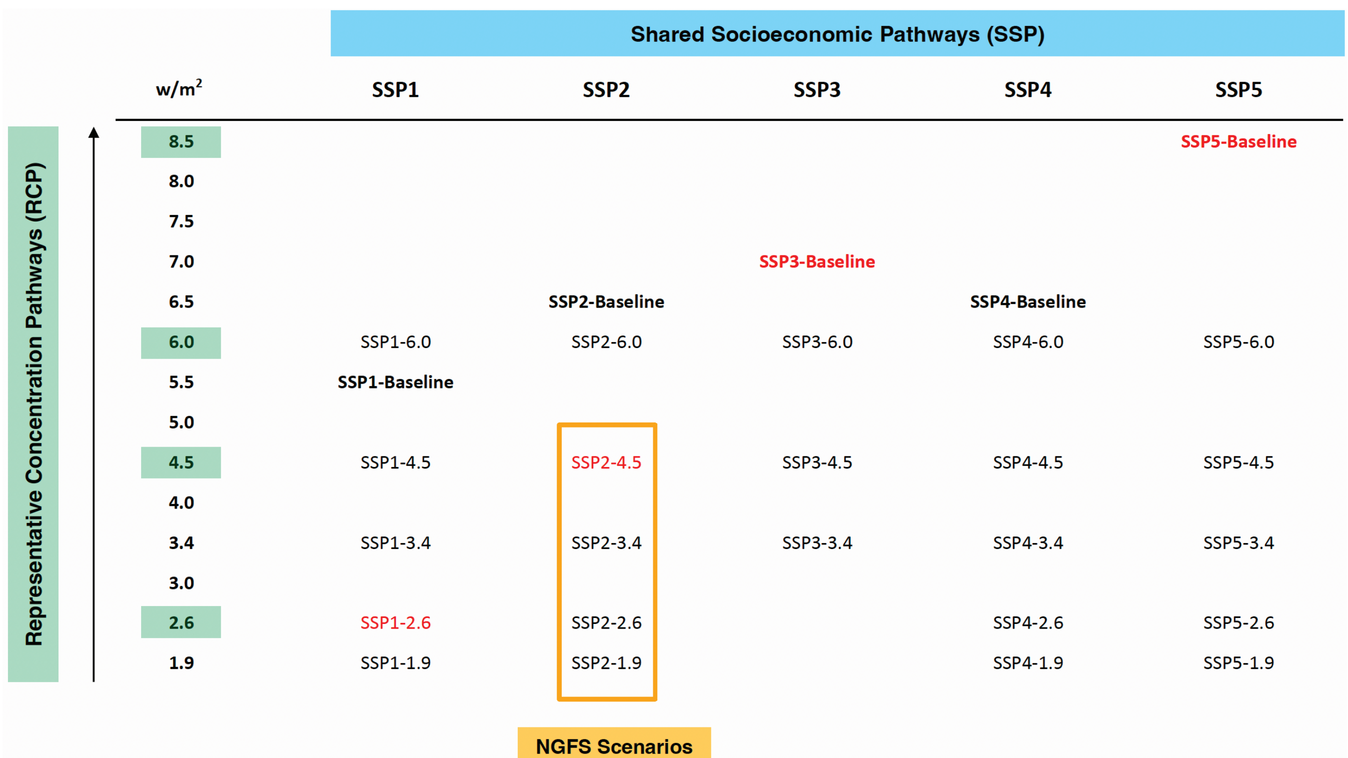

Fig 2. How are RCPs, SSPs, and NFGS scenarios related? Sources: The authors, [17], and [18].

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faster temperature increases. The 90th percentile of the ensemble of climate models for SSP3-7.0— that is, SSP3-7.0 (90th percentile)— is used to highlight a "hotter" world as SSP5-8.5 is deemed unrealistic.

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 over the period 2015–2100 using the Half-Panel Jackknife Fixed Effects (HPJ-FE) estimates of the following Autoregressive Distributed Lag (ARDL) model:

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

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, $x_{it}(m) = |T_{it} - T^{*}_{it-1}(m)|$ measures the absolute value of temperature relative to its historical norms, 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. Climate norms are typically computed using 30-year moving averages (see, for instance, [19] and [20]), but to check the robustness of our results and model adaptation, we also consider historical norms computed using moving averages with $m = 10, 20, 40, 50$, and 100. $m = 30$ also corresponds to the official World Meteorological Organization definition of climate. $\varphi(L) = 1 - \sum_{\ell=1}^{4}\varphi_\ell L^l$, $\beta(L) = \sum_{\ell=0}^{4}\beta_\ell L^l$, and L is the lag operator.

Pre-multiplying both sides of the above equation by the inverse of $\varphi(L)$ yields

$$\Delta y_{it} = \tilde{a}_i + \psi(L)\Delta x_{it} + \vartheta(L)\varepsilon_{it}, \tag{1}$$

where $\tilde{a}_i = \varphi(1)^{-1}a_i$, $\vartheta(L) = \vartheta_0 + \vartheta_1 L + \vartheta_2 L^2 + \ldots$ and $\psi(L) = \varphi(L)^{-1}\beta(L) = \psi_0 + \psi_1 L + \psi_2 L^2 + \ldots$ We are suppressing the dependence of x_{it} on m to simplify the exposition.

The counterfactual effects of climate change can be derived by comparing the output trajectory of country i over the period $T+1$ to $T+h$ under the baseline 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 $\mathbf{x}^0_{i,T+1,T+h} = \{x^0_{i,T+1}, x^0_{i,T+2}, \ldots, x^0_{i,T+h}\}$, and $\mathbf{x}^1_{i,T+1,T+h} = \{x^1_{i,T+1}, x^1_{i,T+2}, \ldots, x^1_{i,T+h}\}$, the counterfactual output change can be written as

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

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 (1) from $t = T+1$ to $T+h$ and taking conditional expectations under the two scenarios we have

$$\xi_{i,T+h} = \sum_{j=1}^{h}\psi_{h-j}\left(x^1_{i,T+j} - x^0_{i,T+j}\right), \tag{2}$$

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 under various SSP scenarios, and compare them with a baseline scenario under which temperature in each country increases according to its historical trend of 1960–2014. 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. Future temperature changes over the counterfactual horizon, T+j, $j = 1, 2, ...$ can be represented by

$$T_{i,T+j} = a_{Ti} + b_{Ti,j}\left(T + j\right) + \nu_{Ti,T+j}, \text{ for } j = 1, 2, ..., \tag{3}$$

where we allow for the trend change in the temperature to vary over time. 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

$$T_{i,T+j} - T^*_{i,T+j-1}(m) = \left(\frac{m+1}{2}\right) b_{Ti,j} + \left(\nu_{Ti,T+j} - \bar{\nu}_{Ti,T+j-1,m}\right),\ j = 1, 2, ..., h, \tag{4}$$

where $\bar{\nu}_{Ti,T+j-1,m} = m^{-1}\sum_{s=1}^{m} \nu_{Ti,T+j-s}$. The realised values of $\left|T_{i,T+j} - T^*_{i,T+j-1}(m)\right|$ depend on the probability distribution of weather shocks, $\nu_{Ti,T+j}$, as well as the trend change in temperature, given by $b_{Ti,j}$. As a first order approximation, and in order to obtain analytic expressions, we assume that temperature shocks, $\nu_{Ti,T+j}$, over $j = 1, 2, ...$, 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 [21], we have

$$\mathbb{E}\left|T_{i,T+j} - T^*_{i,T+j-1}(m)\right| = \mu_{Ti,j}\left[\Phi\left(\frac{\mu_{Ti,j}}{\omega_{Ti}}\right) - \Phi\left(\frac{-\mu_{Ti,j}}{\omega_{Ti}}\right)\right] + 2\omega_{Ti}\phi\left(\frac{\mu_{Ti,j}}{\omega_{Ti}}\right) = g_{Ti}(m, b_{Ti,j}, \sigma_{Ti}) \tag{5}$$

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

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

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.

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 $j = 1, 2, ..., H$, as compared to the historical trend rise in temperature (namely b^0_{Ti}):

$$b^1_{Ti,j} = T_{i,T+j} - T_{i,T+j-1} = b^0_{Ti} + jd_i, \text{ for all } j = 1, 2..., H, \tag{6}$$

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 hypothesised value of b^1_{Ti}, and note that

$$b^1_{Ti} = H^{-1}\sum_{j=1}^{H} b^1_{Ti,j} = H^{-1}\sum_{j=1}^{H}\left(T_{i,T+j} - T_{i,T+j-1}\right) = \frac{T_{i,T+H} - T_{i,T}}{H}, \tag{7}$$

where $T_{i,T+H}$ denotes the level of temperature at the end of the counterfactual period. Averaging (6) over j we have

$$d_i = \frac{2\left(b^1_{Ti} - b^0_{Ti}\right)}{H+1}. \tag{8}$$

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 $T_{i,2099}$, where $i = 1, 2, ..., N$, we consider five sets of values based on IPCC's projections under SSP scenarios (see Fig 2). 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 (6), does not affect the volatility of temperature shocks, and set $\sigma^1_{Ti,j}$ 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. Moreover, accounting for international spillover effects of climate change, individual countries' long-term growth effects could be larger. With these considerations in mind, and using (2), the mean counterfactual impact of the temperature change on output is given by

$$\begin{aligned}\Delta_{ih}(d_i) &= \mathbb{E}\left(y^1_{i,T+h} \,|\mathcal{F}_{i,T}\right) - \mathbb{E}\left(y^0_{i,T+h} \,|\mathcal{F}_{i,T}\right) \\ &= \sum_{j=1}^{h} \psi_{h-j}\left[g_{Ti}(m, b^0_{Ti} + jd_i, \sigma^0_{Ti}) - g_{Ti}(m, b^0_{Ti}, \sigma^0_{Ti})\right], \end{aligned} \tag{9}$$

where we base the estimates of b^0_{Ti} and σ^0_{Ti} on the pre-counterfactual period 1960-2014, and use

$$g^1_{Ti}(m, b^1_{Ti,j}, \sigma^0_{Ti}) = \mu^1_{Ti,j}\left[\Phi\left(\frac{\mu^1_{Ti,j}}{\omega^0_{Ti}}\right) - \Phi\left(\frac{-\mu^1_{Ti,j}}{\omega^0_{Ti}}\right)\right] + 2\omega^0_{Ti}\phi\left(\frac{\mu^1_{Ti,j}}{\omega^0_{Ti}}\right), \tag{10}$$

$$g^0_{Ti}(m, b^0_{Ti}, \sigma^0_{Ti}) = \mu^0_{Ti}\left[\Phi\left(\frac{\mu^0_{Ti}}{\omega^0_{Ti}}\right) - \Phi\left(\frac{-\mu^0_{Ti}}{\omega^0_{Ti}}\right)\right] + 2\omega^0_{Ti}\phi\left(\frac{\mu^0_{Ti}}{\omega^0_{Ti}}\right), \tag{11}$$

$$\mu^1_{Ti,j} = \left(\frac{m+1}{2}\right)\left(b^1_{Ti,j}\right), \; \mu^0_{Ti} = \left(\frac{m+1}{2}\right) b^0_{Ti}, \tag{12}$$

and $\omega^0_{Ti} = \sigma^0_{Ti}\left(1 + \frac{1}{m}\right)^{1/2}$. To obtain $\{\hat{\psi}_j\}$, we use the HPJ-FE estimates of $\{\beta_\ell\}^4_{l=0}$ and $\{\varphi_l\}^4_{l=1}$ 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 1. Fig 3 plots the estimates of ψ_j for $j = 0, 1, 2, \dots, 20$, 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.

To study the role of climate volatility in determining GDP per capita losses, instead of setting $\sigma^1_{Ti,j} = \sigma^0_{Ti}$, we allow temperature increases to affect the variability of temperature shocks commensurately. That is, we keep the coefficient of variation unchanged, and therefore set $\sigma^1_{Ti,j} = \left(\mu^1_{Ti,j}/\mu^0_{Ti}\right)\sigma^0_{Ti}$.

We compare the per capita GDP impact of temperature increases under various SSP scenarios 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 studies, we also perform a counterfactual exercise where temperature increases under the historical trend of 1960–2014 are compared to a baseline scenario no further warming and assuming that adaptation is extremely slow (i.e., historical norms are computed using moving averages with $m = 100$ in counterfactuals from 2015 onwards).

Table 1. Effects of climate change on per capita real GDP growth, 1960–2014

$\widehat{\beta}_0$	-0.0038*	$\widehat{\varphi}_1$	0.2643***	No. of Countries (N)	174
	(0.0021)		(0.0500)	max T	50
$\widehat{\beta}_1$	-0.0056*	$\widehat{\varphi}_2$	0.0785***	avg$T$	38.36
	(0.0029)		(0.0266)	min T	2
$\widehat{\beta}_2$	-0.0084***	$\widehat{\varphi}_3$	0.0547**	No. of Obs. $(N \times T)$	6,674
	(0.0031)		(0.0216)		
$\widehat{\beta}_3$	-0.0090***	$\widehat{\varphi}_4$	-0.0016		
	(0.0026)		(0.0327)		
$\widehat{\beta}_4$	-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, $x_{it}(m) = |T_{it} - T_{i,t-1}^{*}(m)|$, 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 HPJ-FE procedure and the standard errors are based on the estimator proposed in Proposition 4 of [22]. Asterisks indicate statistical significance at 1% (***), 5% (**), and 10% (*) levels.

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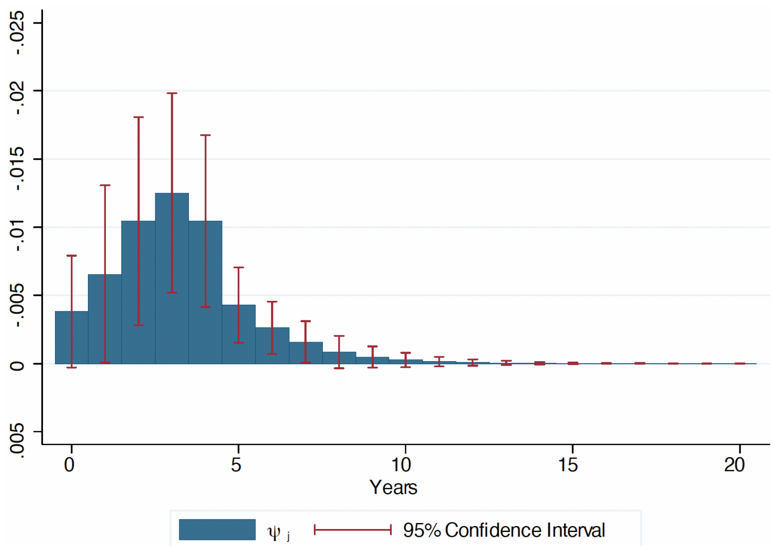

Fig 3. $\{\psi_j\}$ **for** $j = 0, 1, 2, \ldots, 20$**.** Source: [2].

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4. GDP losses from global warming

We report the real GDP per capita losses (gains) from trend temperature changes under various SSP-RCP scenarios for the year 2100 compared to: (i) a baseline under which temperature in each country increases according to its historical trend of 1960–2014 (Fig 4, yellow bar); and (ii) a commonly adopted baseline in the literature without climate change and with extremely-slow adaptation. Since the benchmark for measuring temperature anomalies is a moving average temperature (e.g., calculated over the thirty years preceding each observation), the critical factor in determining income losses is not the absolute level of temperature but rather changes in its trend. If the temperature trend stays constant, economic growth remains unaffected despite increases in temperature. Conversely, if the trend accelerates, growth declines further (the red bars in Fig 4). A deceleration in the trend leads to faster economic growth (the green bar in Fig 4), and if temperatures stabilize, growth returns to its

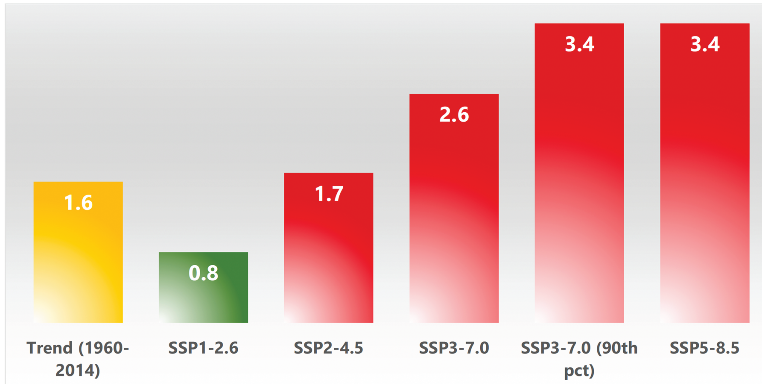

Fig 4. Additional global temperature increase under different scenarios (2014 to 2100). Source: Authors calculations based on IPCC AR6 Physical Science Report. Notes: Reports temperature increases relative to the 2014 average global surface temperature. At the time of the Paris Agreement's adoption in 2015, global temperatures were estimated to be 0.98°C above pre-industrial levels, with the agreement aiming to limit warming to well below 2°C, and pursue efforts to limit it to 1.5°C.

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baseline rate. We make all of the 174 *country-specific* estimates of annual income losses available to download from here. Fig 5 shows that income losses under various SSP-RCP scenarios vary significantly across countries depending on the *country-specific* projected paths of

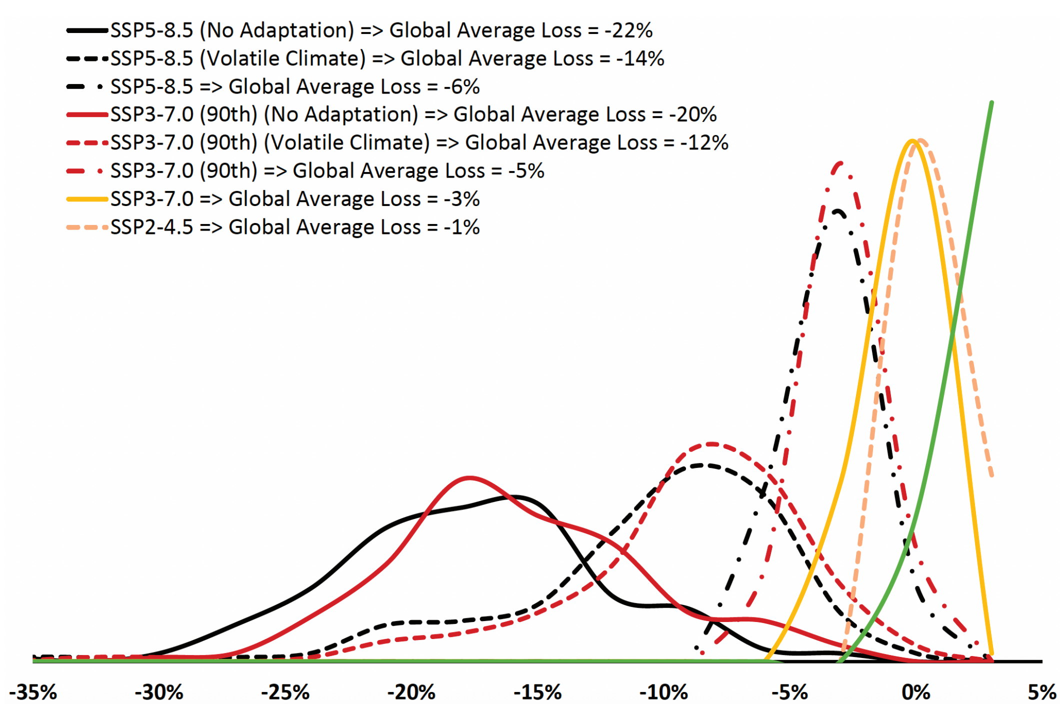

Fig 5. Frequency distribution of income losses across 174 countries by 2100. Notes: We consider income losses from increases in temperatures under various IPCC climate scenarios relative to a baseline in which temperatures increase according to their 1960-2014 trends. Numbers are PPP GDP weighted averages of $\Delta_{ih}(d_i)$, see Eq (9), with $h = 86$ (corresponding to the year 2100). Under the "No Adaptation" assumption, historical norms are formed over 100 years (i.e., $m = 100$). We keep $\sigma^1_{Ti,j} = \left(\mu^1_{Ti,j}/\mu^0_{Ti}\right)\sigma^0_{Ti}$ under the "Volatile Climate" assumption.

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temperatures, climate variability, and adaptation efforts; however, losses (gains) follow the logic above.

Averaging the losses across countries, using PPP-GDP weights, we report that the global income effects of trend temperature increases relative to baseline (i) ranges from 5.4% under SSP3-7.0 (90th) to 11% under SSP5-8.5 with slower adaptation (Fig 6)—SSP3-7.0 is a high-emissions scenario under which global warming accelerates and temperature increases by 3.6°C in 2100, with respect to its pre-industrial average level. To provide a faster-warming scenario, we also utilize the 90th percentile of the SSP3-7.0 climate ensemble. Global temperature with this high-emission, fast-warming scenario increases by approximately 4.4°C. This warming level is similar to the ensemble median warming level under SSP5-8.5. Climate variability amplifies the projected economic losses, with estimates under SSP3-7.0 (90th) (Volatile Climate) and SSP5-8.5 (Volatile Climate) surging to 12–14% globally with a considerable variation in income losses across countries (Fig 5). However, while adaptation—encompassed within the "Faster Adaptation" scenarios in Figs 5 and 6—present a viable pathway to reducing the detrimental long-term growth effects of trend temperature increases, they fall short of completely eliminating these adverse impacts. This limitation suggests that adaptation, although beneficial, cannot serve as a standalone solution but rather as a critical component of a broader, more comprehensive approach to addressing the impacts of climate change. We, therefore, underscore the pressing need for climate change mitigation policies to slow global warming. Abiding by the Paris Agreement goals, thereby limiting the temperature increase to 0.01 degrees Celsius per year, generates an income benefit of 0.25 percent globally.

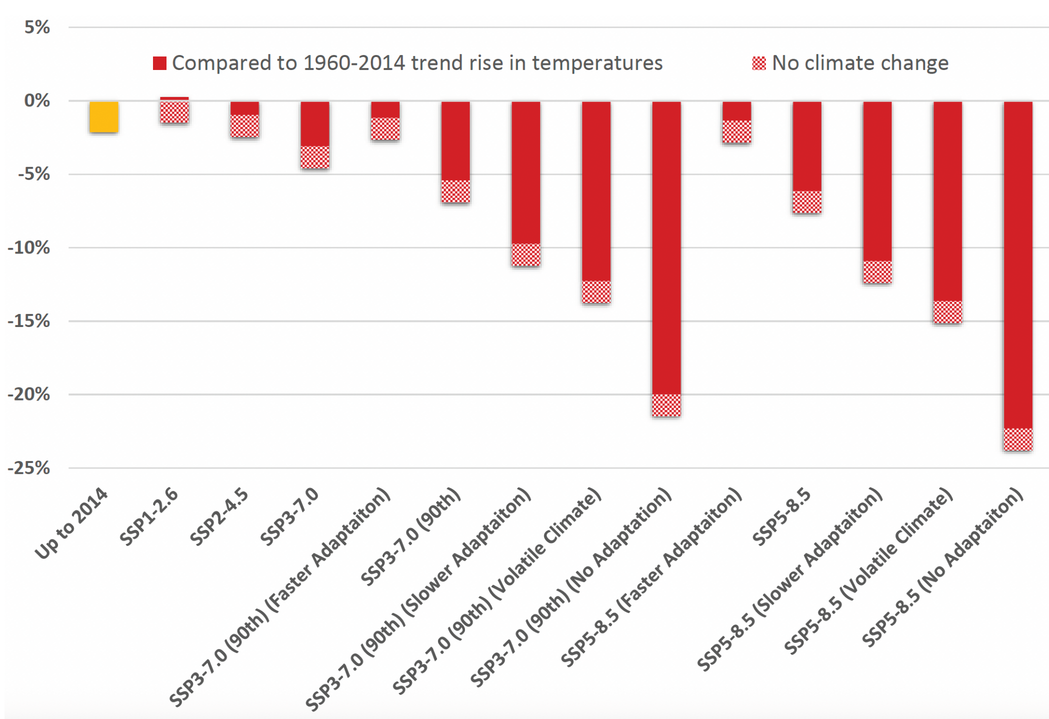

Fig 6. Global income losses from rising temperatures by 2100. Notes: We consider persistent increases in temperatures based on various climate scenarios in Fig 4. Solid-color bars are PPP GDP weighted averages of $\Delta_{ih}\ (d_i)$, see Eq (9), with $h = 86$ (corresponding to the year 2100). Pattern-fill bars show global income losses from a continuation of 1960-2014 trend temperature increases compared to a baseline scenario without climate change. For "Faster Adaptation", $m = 10$. For "Slower Adaptation", $m = 50$. For "No Adaptation", $m = 100$. For "Volatile Climate", $\sigma^1_{Ti,j} = \left(\mu^1_{Ti,j}/\mu^0_{Ti}\right)\sigma^0_{Ti}$.

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This is because under SSP1-2.6, emissions decline at a rapid pace; the warming trend slows down; and global mean temperature stabilizes around 2°C (a level that is 0.6°C lower than what would result if temperatures were continuing to increase according to their historical trend of 1960–2014). Under SSP2-4.5, emissions would grow in line with their observed historical trends and current policies, and the global mean temperature would increase by 2.7°C with respect to its pre-industrial average level (this is very close to baseline (i) in Fig 6). Considering the additional income losses from temperature warming under the 1960–2014 trends relative to a baseline without climate change and assuming extremely-slow adaptation efforts brings the total losses under SSP5-8.5 scenario to 24 percent. This is the worst-case scenario in our counterfactuals.

To put our results into perspective, Fig 7 compares our income loss estimates (shaded area) with those from select papers in the literature. While our counterfactual estimates are conservative (given the caveats mentioned in the introduction), they are non-negligible especially when the reference point of comparison is harmonized across studies. However, our loss estimates are significantly lower than [3] and [8]. The underlying reasons are explained in [23]. While almost all countries are likely to experience a fall in GDP per capita in the absence of climate change policies, the size of income effects varies considerably across countries and regions.

The differential impact of average temperature increases across countries further emphasize the complexity of loss estimates. Countries situated in hotter climates and those classified as low-income likely face disproportionately higher losses, ranging from 30-60% above the global average. This disparity not only highlights the exacerbated vulnerability of these

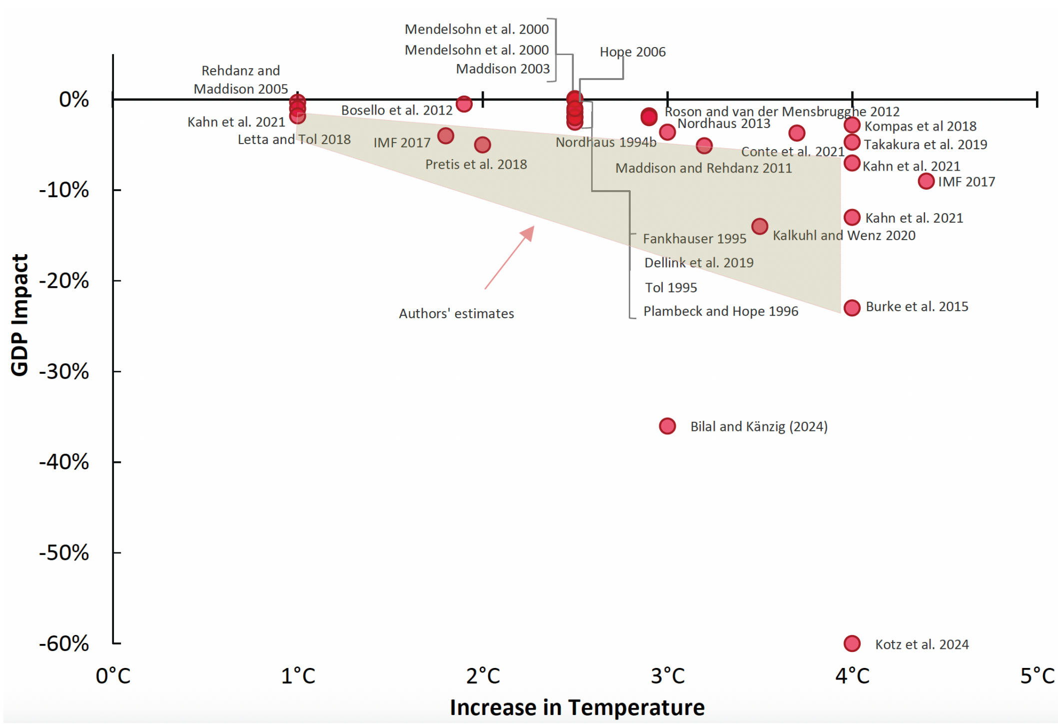

Fig 7. GDP impact of increases in temperature. Sources: [2,4], and authors' estimates (shown as the shaded area in the chart). Notes: Projected GDP impact is for some future year, typically 2100. The shaded area represents the GDP per capita losses from our counterfactual exercise in Sect 3 with the upper bound based on $m = 30$ and the lower bound based on $m = 100$.

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countries but also stresses the need for tailored climate strategies that address their specific challenges. Conversely, countries in colder climates are not spared from the adverse effects of climate change. The faster rate of temperature increases in these areas introduces unique challenges, despite [2]'s finding that the marginal effect of average temperature increases in cold countries is 40 percent lower than that of the global average.

5. Concluding remarks

We estimated *country-specific* annual per-capita GDP losses from global warming using the most-recent climate scenarios of the IPCC under different mitigation, adaptation, and climate variability assumptions. We also showed that without significant mitigation and adaptation efforts, global GDP per capita could decline by up to 24 percent under the high-emissions climate scenarios by 2100, with these income losses varying greatly across the 174 countries in our sample, depending on the projected paths of temperature increases and their variability. Our findings emphasize the importance of mitigating climate change and implementing adaptation measures to minimize these negative effects. However, even with adaptation policies, the long-term growth effects of climate change are likely to persist, particularly in countries with hotter climates and lower incomes. Future research could focus on incorporating these estimated physical climate risks into macro-fiscal frameworks and for effectively informing and guiding country-specific climate action.

Supporting information

Country-specific annual per-capita GDP losses from global warming under different climate scenarios are reported in S1 Table using databases S1 Data and S2 Data. All STATA do and ado files needed to replicate the empirical findings in our paper are publicly available and can be accessed at: https://data.mendeley.com/datasets/hytzz8wftw/1.

S1 Data. Database. This file serves as the main database for the analysis.
(DTA)

S2 Data. Trend temperature change. This file contains the 'di' values for different climate scenarios, used to estimate the GDP per capita impacts.
(DTA)

S1 Table. Country-specific income loss estimates.
(XLSX)

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