The economic commitment of climate change

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Global projections of macroeconomic climate-change damages typically consider impacts from average annual and national temperatures over long-time horizons. Here, we utilize recent empirical findings from more than 1600 regions worldwide over the past 40 years to project sub-national damages from temperature and precipitation including daily variability and extremes. Using an empirical approach which provides a robust lower-bound on the persistence of impacts on economic growth, we find that the world economy is committed to an income reduction of 19% within the next 26 years due to historical carbon emissions and socioeconomic inertia (relative to a baseline without climate impacts, likely range of 11-29% accounting for physical climate and empirical uncertainty). These damages already outweigh the mitigation costs required to limit global warming to two degrees by sixfold over this near-term timeframe, and thereafter diverge strongly dependent on emission choices. Committed damages arise predominantly through changes in average temperature, but accounting for further climatic components raises estimates by approximately fifty percent and leads to stronger regional heterogeneity. Committed losses are projected for all regions except those at very high latitudes, where reductions in temperature variability bring benefits. The largest losses are committed at lower latitudes in regions with lower cumulative historical emissions and lower present-day income.

Projections of the macroeconomic damage caused by future climate change are crucial to informing public and policy debates regarding adaptation, mitigation and climate justice. On the one hand, adaptation against climate impacts must be justified and planned on the basis of an understanding of their future magnitude and spatial distribution[1]. This is also of importance in the context of climate justice[2], as well as to key societal actors including governments, central banks and private businesses which increasingly require the inclusion of climate risks in their macroeconomic forecasts to aid adaptive decision making[3,4]. On the other hand, climate mitigation policy such as the Paris Climate Agreement is often evaluated by balancing the costs of its implementation against the benefits of avoiding projected physical damages. This evaluation occurs both formally via cost-benefit analyses[5–8], as well as informally via public perception of mitigation and damage costs[9].

Projections of future damages meet challenges when informing these debates, in particular the human biases relating to uncertainty and remoteness which are raised by long-term perspectives[10]. Here we aim to overcome such challenges, by assessing the extent of economic damages from climate change to which the world is already committed by historical emissions and socioeconomic inertia (the range of future emission scenarios which are considered socioeconomically plausible[11]). Such a focus on the near-term limits the large uncertainties regarding diverging future emission trajectories, the resulting long-term climate response, and the validity of applying historically observed climate-economic relations over long timescales during which socio-technical conditions may change considerably. As such, this focus aims to simplify the communication and maximize the credibility of projected economic damages from future climate change.

In projecting the future economic damages from climate change, we make use of recent advances in climate econometrics which provide evidence for impacts on sub-national economic growth from numerous components of the distribution of daily temperature and precipitation[12–14]. Using fixed effects panel regression models to control for potential confounders, these studies exploit within-region variation in local temperature and precipitation in a panel of more than 1600 regions worldwide, comprising climate and income data over the past 40 years to identify the plausibly causal effects of changes in several climate variables on economic productivity[15,16]. Specifically, macroeconomic impacts have been identified from changing daily temperature variability, total annual precipitation, the annual number of wet days and extreme daily rainfall which occur in addition to those already identified from changing average temperature[12,17,18]. Moreover, regional heterogeneity in these effects based on the prevailing local climatic conditions has been found using interactions terms. The selection of these climate variables follows micro-level evidence for mechanisms related to the impacts of average temperatures on labor and agricultural productivity[17], of temperature variability on agricultural productivity and health[13], as well as of precipitation on agricultural, labor outcomes, and flood damages[14] (see Table S1 for an overview including more detailed references). Refs. [13,14] contain a more detailed motivation for the use of these particular climate variables and provide extensive empirical tests regarding the robustness and nature of their effects on economic output which are summarized in our methods section. By accounting for these additional climatic variables at the sub-national level, we aim for a more comprehensive description of climate impacts with greater detail across both time and space.

A robust lower bound on the persistence of climate impacts on growth

A key determinant and source of discrepancy in estimates of the magnitude of future climate damages is the extent to which the impact of a climate variable on economic growth rates persists. The two extreme cases in which these impacts persist indefinitely or only instantaneously are commonly referred to as growth or level effects[19,20] (see methods section "Empirical specification – fixed-effects distributed lag model" for definitions). Recent work shows that future damages from climate change depend strongly on whether growth or level effects are assumed[20]. Following refs. ([17,18]), we provide constraints on this persistence by using distributed lag models to test the significance of delayed effects separately for each climate variable. Importantly and in contrast to refs ([17,18]), we use climate variables in their first-differenced form following ref. [12], implying a dependence of the growth rate on a change in climate variables. This choice means that a baseline specification without any lags constitutes a model prior of purely level effects, in which a permanent change in the climate has only an instantaneous effect on the growth rate[12,19,21]. By including lags, one can then test whether any effects may persist further. This is in contrast to the specification used by refs. [17,18] in which climate variables are used without taking the first difference, implying a dependence of the growth rate on the level of climate variables. In this alternative case, the baseline specification without any lags constitutes a model prior of pure growth effects, in which a change in climate has an infinitely persistent effect on the growth rate. Consequently, including further lags in this alternative case tests whether the initial growth impact is recovered[18,19,21]. Both of these specifications suffer from the limiting possibility that if too few lags are included, one might falsely accept the model prior. The limitations of including a very large number of lags, including loss of data and increasing statistical uncertainty with an increasing number of parameters, means that such a possibility is likely. By choosing a specification in which the model prior is one of level effects, our approach is therefore conservative by design, avoiding assumptions of infinite persistence of climate impacts on growth and instead providing a lower-bound on this persistence based on what is observable empirically (see methods section “Empirical specification – fixed-effects distributed lag model” for further exposition of this framework). The conservative nature of such a choice is likely the reason that ref. [19] finds much greater consistency between the impacts projected by models which use the first difference of climate variables as opposed to their levels.

We begin our empirical analysis of the persistence of climate impacts on growth using ten lags of the first-differenced climate variables in fixed-effects distributed lag models. We detect significant effects on economic growth at time lags of up to approximately eight to ten years for the temperature terms, and up to approximately four years for the precipitation terms (Extended Data Figure 1, Table S2). Furthermore, evaluation by means of Information Criteria indicates that the inclusion of all five climate variables and the use of these numbers of lags provide a preferable trade-off between best-fitting the data and including additional terms which could cause overfitting, in comparison to model specifications excluding climate variables or including more or fewer lags (Supplementary Methods Section S1, Fig. S1 and Table S3). We therefore remove insignificant terms at later lags (Figs. S2-4, Tables S4-6). Further tests using Monte-Carlo simulations demonstrate that the empirical models are robust to autocorrelation in the lagged climate variables (Supplementary Methods Section S2, Figs. S5& S6), that Information Criteria provide an effective indicator for lag selection (Supplementary Methods Section S2, Fig. S7), that the results are robust to concerns of imperfect multi-collinearity between climate variables and that including several climate variables is actually necessary to isolate their separate effects (Supplementary Methods Section S3, Fig. S8). We provide a further robustness check using a restricted distributed lag model to limit oscillations in the lagged parameter estimates which may result from autocorrelation, finding that it provides similar estimates of cumulative marginal effects to the un-restricted model (Supplementary Methods Section S4, Figs. S9 and S10). Finally, to explicitly account for any outstanding uncertainty arising from the precise choice of the number of lags, we include empirical models with marginally different numbers of lags in the error sampling procedure of our projection of future damages. Based on the lag selection procedure (the significance of lagged terms in Extended Data Figure 1 and Table S2, as well as Information Criteria in Fig. S1), we sample from models with eight to ten lags for temperature and four for precipitation (models shown in Figs. S2-S4 and Tables S3-S5). In summary, this empirical approach to constrain the persistence of climate impacts on economic growth rates is conservative by design in avoiding assumptions of infinite persistence, but nevertheless provides a lower bound on the extent of impact persistence which is robust to the numerous tests outlined above.

Economic damages until mid-century are committed and diverge thereafter

We combine these empirical economic response functions (Figs. S2-S4 and Tables S3-5) with an ensemble of twenty-one climate models (see Table S7) from the Coupled Model Intercomparison Project phase-6 (CMIP-6)[22] to project the macroeconomic damages from these multiple components of physical climate change (see methods for further details). Bias-adjusted climate models which provide a highly accurate reproduction of observed climatological patterns with limited uncertainty (Table S8) are used to avoid introducing biases in the projections. Following a well-developed literature[12,17,19], these projections do not aim to provide a prediction of future economic growth. Instead, they are a projection of the exogenous impact of future climate conditions on the economy relative to the baselines specified by socioeconomic projections, based on the plausibly causal relationships inferred by the empirical models, and assuming ceteris paribus. Other exogenous factors relevant for the prediction of economic output are purposefully assumed constant.

A Monte-Carlo procedure which samples from climate model projections, empirical models with different numbers of lags, and model parameter estimates (obtained by 1000 block-bootstrap resamples of each of the regressions in Figs. S2-S4 and Tables S3-5) is used to estimate the combined uncertainty from these multiple sources. Given these uncertainty distributions, we find that projected global damages are statistically indistinguishable across the two most extreme emission scenarios until 2049 (at the 5% significance level, Fig. 1). As such, the climate damages occurring before this time constitute those to which the world is already committed due to the combination of past emissions and the range of future emission scenarios which are considered socioeconomically plausible[11]. These committed damages comprise a permanent income reduction of 19% on average globally (population weighted average) in comparison to a baseline without climate change impacts (with a likely range of 11-29%, following the likelihood classification adopted by the Intergovernmental Panel on Climate Change (IPCC), see caption of Fig. 1). Even though levels of income per capita generally still increase relative to those today, this constitutes a permanent income reduction for the majority of regions, including North America and Europe (each with median income reductions of approximately 11%) and with South Asia and Africa being the most strongly affected (each with median income reductions of approximately 22%; Fig. 1). Under a middle-of-the road scenario of future income development (SSP2), this corresponds to global annual damages in 2049 of 38 trillion in 2005 International Dollars (likely range of 19-59 trillion 2005 International Dollars). Compared to empirical specifications which assume pure growth or pure level effects, our preferred specification which provides a robust lower-bound on the extent of climate impact persistence produces damages between these two extreme assumptions (Extended Data Fig. 2).

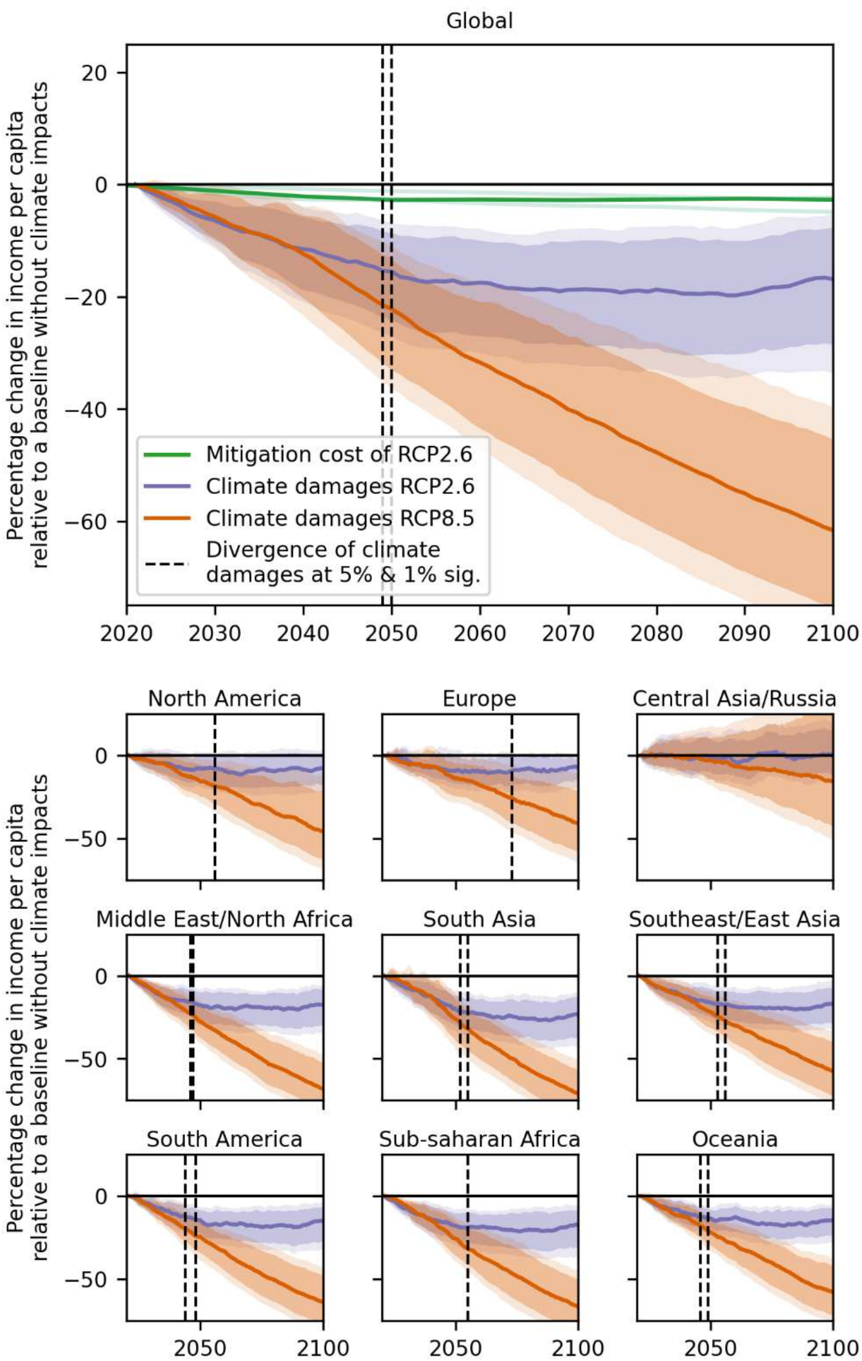

Figure 1. The commitment and divergence of economic climate damages vs mitigation costs. Estimates of the projected reduction in income per capita from changes in all climate variables based on empirical models of climate impacts on economic output with a robust lower-bound on their persistence (Extended Data Fig. 1) under a low-emission scenario compatible with the 2C warming target and a high-emission scenario (SSP2-RCP2.6 and SSP5-RCP8.5 respectively) are shown in purple and orange respectively. Shading represents

the 17% and 10% confidence intervals reflecting the *likely* and *very likely* ranges respectively (following the likelihood classification adopted by the Intergovernmental Panel on Climate Change), having estimated uncertainty from a Monte-Carlo procedure which samples the uncertainty from both the choice of physical climate models, empirical models with different numbers of lags, and bootstrapped estimates of the regression parameters shown in Figs. S2-S4. Vertical dashed lines show the time at which the climate damages of the two emission scenarios diverge at the 5% and 1% significance level based on the distribution of differences between emission scenarios arising from the uncertainty sampling discussed above. Note that uncertainty in the *difference* of the two scenarios is smaller than the combined uncertainty of the two respective scenarios because samples of the uncertainty (climate model and empirical model choice as well as model parameter bootstrap) are consistent across the two emission scenarios; hence the divergence of damages occurs while the uncertainty bounds of the two separate damage scenarios still overlap. Estimates of global mitigation costs from the three Integrated Assessment Models which provide results for the SSP2 baseline and SSP2-RCP2.6 scenario are shown in light green in the upper panel, with the median of these estimates shown in bold.

Committed damages outweigh the mitigation costs required to limit warming to 2C before mid-century

We compare the damages to which the world is committed over the next 26 years to estimates of the mitigation costs required to achieve the Paris Climate Agreement. Taking estimates of mitigation costs from the three Integrated Assessment Models (IAMs) in the IPCC AR6 database[23] which provide estimates under comparable scenarios (SSP2 baseline, and SSP2-RCP2.6), we find that the median committed climate damages outweigh the median mitigation costs in 2050 (six trillion in 2005 International dollars) approximately sixfold (note estimates of mitigation costs are only provided every 10 years by the IAMs and so a comparison in 2049 is not possible). These results emphasise that climate damages strongly outweigh mitigation costs already over the next 25 years, a perspective which may complement formal cost-benefit analyses which find that the net benefits of mitigation only emerge after 2050[7]. While these near-term damages constitute those to which the world is already committed, we note that damage estimates diverge strongly across emission scenarios after 2049, conveying the clear benefits of mitigation from a purely economic point of view which have been emphasised in previous studies[5,24]. In addition to the uncertainties assessed in Fig. 1, these conclusions are robust to structural choices such as the timescale with which changes in the moderating variables of the empirical models are estimated (Figs. S11 & S12), as well as the order in which one accounts for the inter-temporal and inter-national components of currency comparison (Fig. S13, see methods for further detail).

Accounting for additional climatic components raises net damages

Committed damages primarily arise through changes in average temperature (Fig. 2). This reflects the fact that projected changes in average temperature are larger than those in other climate variables when expressed as a function of their historical interannual variability (Fig. S14). Since the historical variability is that on which the empirical models are estimated, larger projected changes in comparison to this variability are likely to lead to larger future impacts in a purely statistical sense. From a mechanistic perspective, one may plausibly interpret this result as implying that future changes in average temperature are the most unprecedented from the perspective of the historical fluctuations to which the economy is accustomed, and therefore will cause the most damage. This insight may prove useful in terms of guiding adaptation measures to the sources of greatest damage.

Nevertheless, future damages based on empirical models which consider changes in annual average temperature only and exclude the other climate variables constitute income reductions of only 13% in 2049 (Fig. S16a, likely range 5-21%). This suggests that accounting for the other components of the distribution of temperature and precipitation raises net damages by nearly fifty percent. This increase arises through the additional damages which these climatic components cause, but also because their inclusion reveals a stronger negative economic response to average temperatures (Fig. S16b). The latter finding is consistent with our Monte-Carlo simulations which suggest that the magnitude of the effect of average temperature on economic growth is underestimated unless accounting for the impacts of other correlated climate variables (Fig. S8).

In terms of the relative contributions of the different climatic components to overall damages, we find that accounting for daily temperature variability causes the largest increase in overall damages relative to empirical frameworks which only consider changes in annual average temperature (4.9%-points, likely range 2.4-8.7%-points, equivalent to approximately 10 trillion International Dollars). Accounting for precipitation causes smaller increases in overall damages which are nevertheless equivalent to approximately 1.2 trillion International Dollars: 0.01%-points (-0.37-0.33%-points), 0.34%-points (0.07-0.90%-points) and 0.36%-points (0.13-0.65%-points) from total annual precipitation, the number of wet days and extreme daily precipitation respectively. Moreover, climate models appear to underestimate future changes in temperature variability[25] and extreme precipitation[26,27] in response to anthropogenic forcing as compared to that observed historically, suggesting that the true impacts from these variables may be larger.

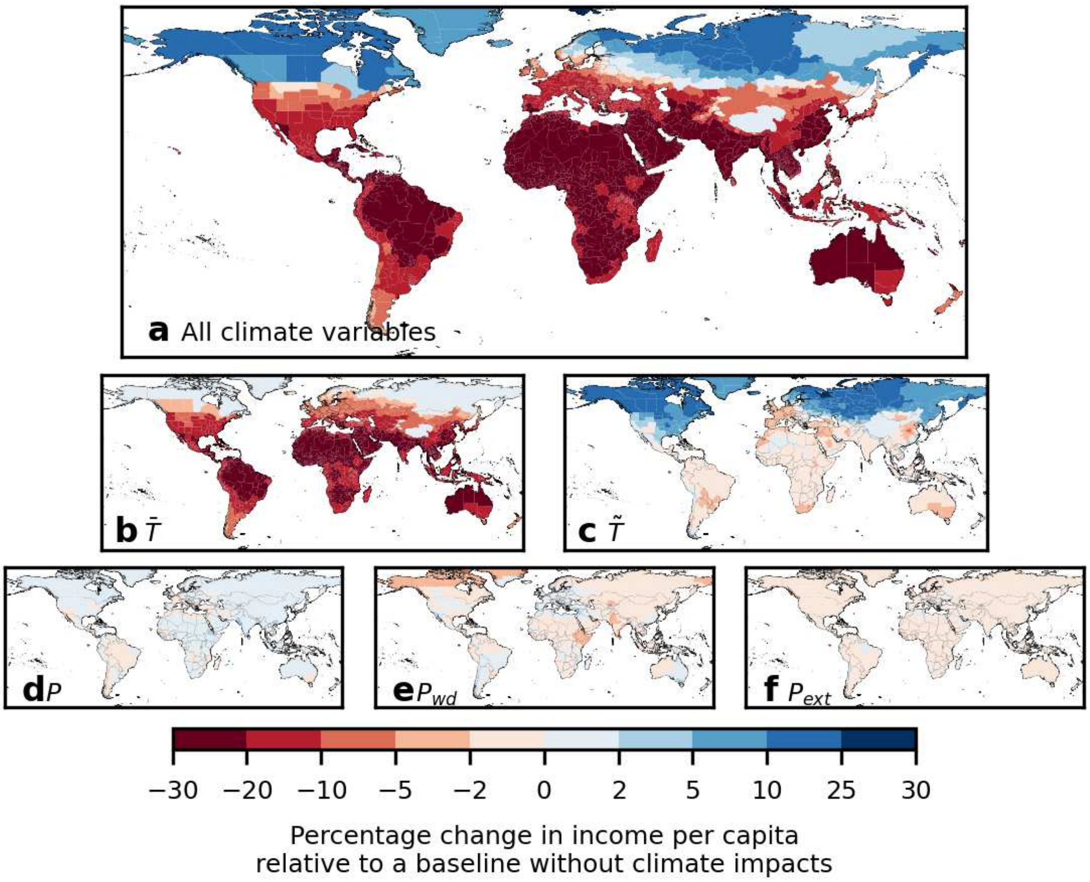

Figure 2. The committed economic damages of climate change by sub-national region and climatic component. Estimates of the median projected reduction in sub-national income per capita across emission scenarios (SSP2-RCP2.6 and SSP2-RCP8.5) as well as climate model, empirical model and model parameter uncertainty in the year at which climate damages diverge at the 5% level (2049, as identified in Fig. 1). Panel (a) shows the impacts arising from all climate variables, while panels (b-f) show the impacts arising separately from changes in annual mean temperature, daily temperature variability, total annual precipitation, the annual number of wet days (>1mm) and extreme daily rainfall respectively (see methods for further definitions).

Heterogeneity of committed economic climate damages

The spatial distribution of committed damages (Fig. 2a) reflects a complex interplay between the patterns of future change in multiple climatic components and those of historical economic vulnerability to changes in those variables. Damages due to increasing annual mean temperature (Fig. 2b) are negative almost everywhere globally, and larger at lower latitudes in regions where temperatures are already higher and economic vulnerability to temperature increases is greatest (see the response heterogeneity to mean temperature embodied in Extended Data Fig. 1a). This occurs despite the amplified warming projected at higher latitudes[28], suggesting that regional heterogeneity in economic vulnerability to temperature changes outweighs heterogeneity in the magnitude of future warming (Fig. S15a). Economic damages due to daily temperature variability (Fig. 2c) exhibit a strong latitudinal polarisation, primarily reflecting the physical response of daily variability to greenhouse forcing in which increases in variability across lower latitudes (and Europe) contrast decreases at high latitudes (Fig S15b) [25]. These two temperature terms are the predominant determinants of the pattern of overall damages (Fig. 2a), which exhibits a strong polarity with damages across most of the globe except at the highest northern latitudes. Future changes in total annual precipitation mainly bring economic benefits except in regions of drying such as the Mediterranean and central South America (Fig. 2d, Fig. S15c), but these benefits are opposed by changes in the number of wet days, which produce damages with a similar pattern of opposite sign (Fig. 2e, Fig. S15d). By contrast, changes in extreme daily rainfall produce damages in all regions, reflecting the intensification of daily rainfall extremes over global land areas[29,30] (Fig. 2f, Fig. S15e).

The spatial distribution of committed damages implies considerable injustice along two dimensions: culpability for the historical emissions which have caused climate change, and pre-existing levels of socio-economic welfare. Spearman's rank correlations indicate that committed damages are significantly larger in countries with smaller historical cumulative emissions, as well as in regions with lower current income per capita (Fig. 3). This implies that those countries which will suffer the most from the damages which are already committed are those which are least responsible for climate change, and which also have the least resources to adapt to it.

To further quantify this heterogeneity, we assess the difference in committed damages between the upper and lower quartiles of regions when ranked by present income levels and historical cumulative emissions (using a population weighting to both define the quartiles and estimate the group averages). On average, the quartile of countries with lower income are committed to an income loss which is 8.9 percentage-points (or 61%) greater than the upper quartile (Fig. S17), with a likely range of 3.8-14.7 percentage-points across the uncertainty sampling of our damage projections (following the likelihood classification adopted by the IPCC). Similarly, the quartile of countries with lower historical cumulative emissions are committed to an income loss which is 6.9 percentage-points (or 40%) greater than the upper quartile, with a likely range of 0.27-12 percentage-points. These patterns re-emphasise the prevalence of injustice in climate impacts[31–33] in the context of the damages to which the world is already committed by historical emissions and socio-economic inertia.

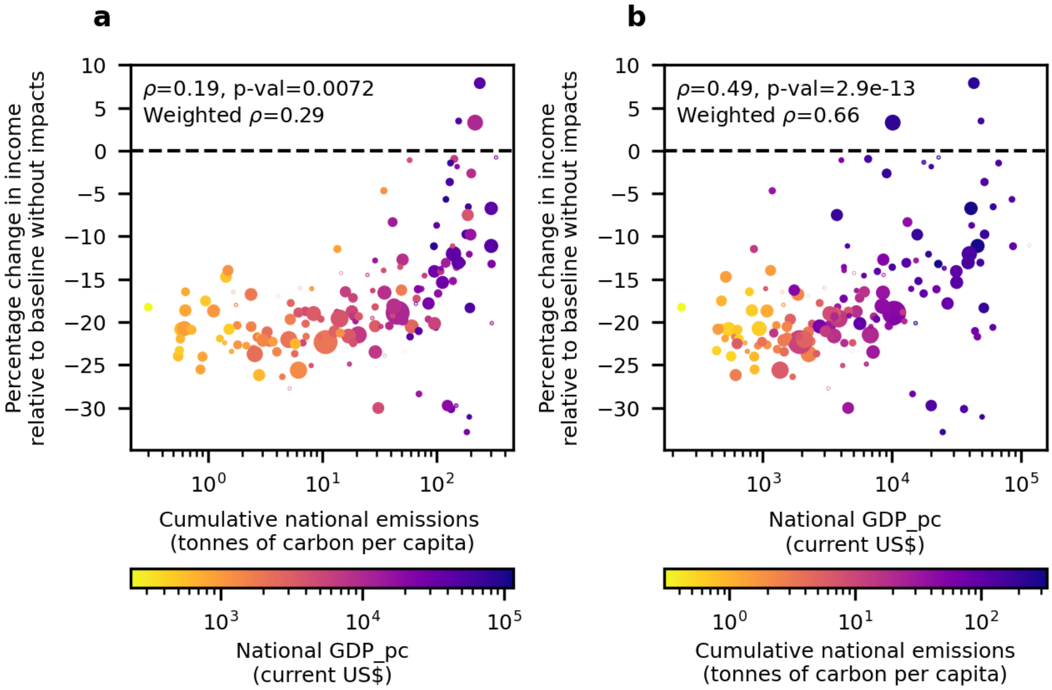

Figure 3. The injustice of committed climate damages by cumulative historical emissions and income. Estimates of the median projected change in national income per capita across emission scenarios (RCP2.6 and RCP8.5) as well as climate model, empirical model and model parameter uncertainty in the year at which climate damages diverge at the 5% level (2049, as identified in Fig. 1), are plotted against national cumulative emissions per capita in 2020 (from the Global Carbon Project) and coloured by national income per capita in 2020 (from the World Bank) in panel (a), and vice versa in panel (b). In each panel, the size of each scatter point is weighted by the national population in 2020 (from the World Bank). Inset figures indicate the Spearman's rank correlation, ρ, and p-values for a hypothesis test whose null hypothesis is of no correlation, as well as the Spearman's rank correlation weighted by national population.

Discussion

The magnitude of projected economic damages exceeds previous literature estimates[12,17], arising from a number of developments made upon previous approaches. Our estimates are larger than those of ref.[17] (see first row of Extended Data Table 1) primarily due to the facts that sub-national estimates typically show a steeper temperature response (see also refs. [12,34]) and that accounting for other climatic components raises damage estimates (Fig. S16). However, we note that our empirical approach using first-differenced climate variables is conservative compared to that of ref. [17] with regards to the persistence of climate impacts on growth (see introduction and methods section "Empirical specification – fixed-effects distributed lag model"), an important determinant of the magnitude of long-term damages[19,21]. Using a similar empirical specification to ref. [17] which assumes infinite persistence while maintaining the rest of our approach (sub-national data and additional climate variables), produces considerably larger damages (purple curve of Extended Data Fig. 2). Compared to studies which do take the first-difference of climate variables[12,35], our estimates are also larger (see second and third rows of Extended Data Table 1). The inclusion of additional climate variables (Fig. S16) and a sufficient number lags to more adequately capture the extent of impact persistence (Extended Data Fig. 1) are major sources of this difference, as is the use of specifications which capture non-linearities in the temperature response when compared to ref. [35]. In summary, our estimates develop upon previous studies by incorporating the latest data and empirical insights[13,14], as well as in providing a robust empirical lower-bound on the persistence of impacts on economic growth, which constitutes a middle ground between the extremes of the growth-vs-levels debate[19,21] (Extended Data Fig. 2).

Compared to the fraction of variance explained by the empirical models historically (<5%), the projection of reductions in income of 19% may appear large. This arises due to the fact that projected changes in climatic conditions are much larger than those which were experienced historically, particularly for changes in average temperature (Fig. S14). As such, any assessment of future climate change impacts necessarily requires an extrapolation outside of the range of the historical data on which the empirical impact models were evaluated. Nevertheless, these models constitute the most state-of-the-art methods for inference of plausibly causal climate impacts based on observed data. Moreover, we take explicit steps to limit out-of-sample extrapolation by capping the moderating variables of the interaction terms at the 95th percentile of the historical distribution (see methods). This avoids extrapolating the marginal effects outside of what was observed historically. Given the non-linear response of economic output to annual mean temperature (Extended Data. Fig.1, Table S2), this is a conservative choice which limits the magnitude of damages which we project.

Despite assessing multiple climatic components from which economic impacts have recently been identified[12–14], this assessment of aggregate climate damages should not be considered comprehensive. Important channels such as impacts from heatwaves[31], sea-level rise[36], tropical cyclones[37] and tipping points[38,39], as well as non-market damages such as those to ecosystems[40] and human health[41] are not considered in these estimates. Sea-level rise is unlikely to be feasibly incorporated into empirical assessments such as this since historical sea level variability is mostly insignificant. Non-market damages are inherently intractable within our estimates of impacts on aggregate monetary output and estimates of these impacts could arguably be considered as additional to those identified here. Recent empirical work suggests that accounting for these channels would likely raise estimates of these committed damages with larger damages continuing to arise in the global south[31,36–41].

We find that the economic damages due to climate change until 2049 are those to which the world economy is already committed, and that these greatly outweigh the costs required to mitigate emissions in line with the 2C target of the Paris Climate Agreement (Fig. 1). For simplicity and due to the availability of data, we compare damages to mitigation costs at the global level. Regional estimates of mitigation costs may shed further light on the national incentives for mitigation to which our results already hint, of relevance for international climate policy. While these damages are committed from a mitigation perspective, adaptation may provide an opportunity to reduce them. Moreover, the strong divergence of damages after mid-century reemphasises the clear benefits of mitigation from a purely economic perspective as emphasised in previous studies[5,6,8,24].

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Methods

Historical climate data

Historical daily 2-m temperature and precipitation totals (in mm) are obtained for the period 1979-2019 from the W5E5 database. W5E5 stems from ERA-5, a state-of-the-art reanalysis of historical observations, but has been bias-adjusted by applying version 2.0 of the WATCH Forcing Data to ERA-5 reanalysis data, and precipitation data from version 2.3 of the Global Precipitation Climatology Project to better reflect ground-based measurements[42–44]. We obtain this data on a 0.5-by-0.5-degree grid from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) database. Importantly, this historical data has been used to bias-adjust future climate projections from CMIP-6 (see the following section), ensuring consistency between the distribution of historical daily weather on which our empirical models were estimated, and the climate projections used to estimate future damages. These data are publicly available from the ISIMIP database. See refs. [13,14] for robustness tests of the empirical models to the choice of climate data reanalysis products.

Future climate data

Daily 2-m temperature and precipitation totals (in mm) are taken from 21 climate models participating in CMIP-6 under a high (RCP8.5) and a low (RCP2.6) greenhouse gas emission scenario from 2015-2100. The data have been bias-adjusted and statistically downscaled to a common half-degree grid to reflect the historical distribution of daily temperature and precipitation of the W5E5 dataset using the trend-preserving method developed by ISIMIP[43,45]. As such, the climate model data reproduces observed climatological patterns exceptionally well (Table S8). Gridded data are publicly available from the ISIMIP database.

Historical economic data

Historical economic data stem from the DOSE database of sub-national economic output[46]. We use a recent update to DOSE which provides data across 83 countries, 1660 sub-national regions with varying temporal coverage from 1960-2019. Sub-national units constitute the first administrative division below national, e.g., states for the USA and provinces for China. Data stem from measures of gross-regional product per capita (GRPpc) or income per-capita in local currencies, reflecting the values reported in national statistical agencies, yearbooks and, in some cases, academic literature. We follow previous literature [12–14,47] and assess real sub-national output per capita by first converting values from local currencies to US dollars to account for diverging national inflationary tendencies, and then account for US inflation using a US deflator. Alternatively, one might first account for national inflation and then convert between currencies. Fig. S13 demonstrates that our conclusions are consistent when accounting for price changes in the reversed order, although the magnitude of estimated damages varies. See the documentation of DOSE for further discussion of these choices. Conversions between currencies are conducted using exchange rates from the FRED database of the Federal Reserve Bank of St Louis[48] and the national deflators from the World Bank[49].

Future socioeconomic data

Baseline gridded GDP and population data for the period 2015-2100 are taken from the middle-of-the-road Shared Socioeconomic Pathway scenario SSP2[11]. Population data have been downscaled to a half-degree grid by ISIMIP following the methodologies of refs. [50,51], which we then aggregate to the sub-national level of our economic data using the spatial aggregation procedure described below. Since current methodologies for downscaling GDP of the SSPs use downscaled population to do so, per capita estimates of GDP with a realistic distribution at the sub-national level are not readily available for the SSPs. We therefore use national-level GDP per capita projections for all sub-national regions of a given country, assuming homogeneity within countries in terms of baseline GDP per-capita. Here, we use projections which have been updated to account for the impact of the Covid-19 pandemic on the trajectory of future income, while remaining consistent with the long-term development of the SSPs[52]. The choice of baseline SSP alters the magnitude of projected climate damages in monetary terms, but when assessed in terms of percentage change from the baseline, the choice of socioeconomic scenario is inconsequential. Gridded SSP population data and national level GDP per capita data are publicly available from the ISIMIP database. Sub-national estimates as used in this study are available in the code and data replication files.

Climate variables

Following recent literature[12–14] we calculate an array of climate variables for which significant impacts on macro-economic output have been identified empirically, supported by further evidence at the micro-level for plausible underlying mechanisms. Please see refs. [13,14] for an extensive motivation for the use of these particular climate variables and for detailed empirical tests regarding the nature and robustness of their effects on economic output. To summarize, these studies have found evidence for independent impacts on economic growth rates from annual average temperature, daily temperature variability, total annual precipitation, the annual number of wet days and extreme daily rainfall. Assessments of daily temperature variability were motivated by evidence of impacts on agricultural output and human health, as well as macroeconomic literature on the impacts of volatility on growth when manifest in different dimensions such as government spending, exchange rates and even output itself[13]. Assessments of precipitation impacts were motivated by evidence of impacts on agricultural productivity, metropolitan labor outcomes and conflict, as well as damages caused by flash flooding[14]. See Table S1 for detailed references to empirical studies of these physical mechanisms. Significant impacts of daily temperature variability, total annual precipitation, the number of wet days and extreme daily rainfall on macroeconomic output were identified robustly across different climate data-sets, spatial aggregation schemes, specifications of regional time-trends, and error-clustering approaches. They were also found to be robust to the consideration of temperature extremes[13,14]. Furthermore, these climate variables were identified as having independent effects on economic output[13,14], which we further elucidate here using Monte-Carlo simulations to demonstrate the robustness of the results to concerns of imperfect multi-collinearity between climate variables (Supplementary Methods Section S2), as well as by using Information Criteria (Table S3) to demonstrate that including several lagged climate variables provides a preferable trade-off between optimally describing the data and limiting the possibility of overfitting.

We calculate these variables from the distribution of daily, d, temperature, $T_{x,d}$, and precipitation, $P_{x,d}$, at the grid-cell, x, level for both the historical and future climate data. In addition to annual mean temperature, $\bar{T}_{x,y}$, and annual total precipitation, $P_{x,y}$, we calculate annual, y, measures of daily temperature variability, $\tilde{T}_{x,y}$:

$$\tilde{T}_{x,y} = \frac{1}{12}\sum_{m=1}^{12}\sqrt{\frac{1}{D_m}\sum_{d=1}^{D_m}(T_{x,d,m,y} - \bar{T}_{x,m})^2}, \quad (1)$$

the number of wet days, $Pwd_{x,y}$:

$$Pwd_{x,y} = \sum_{d=1}^{D_y} H\,(P_{x,d} - 1mm), \quad (2)$$

and extreme daily rainfall:

$$Pext_{x,y} = \sum_{d=1}^{D_y} H(P_{x,d} - P99.9_x)\,.\,P_{x,d}, \quad (3)$$

where $T_{x,d,m,y}$ is the grid-cell specific daily temperature in month m and year y, $\bar{T}_{x,m,y}$ is the year and grid-cell specific monthly, m, mean temperature, H the Heaviside step function, 1mm the threshold used to define wet days, and $P99.9_x$, the 99.9^{th} percentile of historical (1979-2019) daily precipitation at the grid-cell level. Units of the climate measures are degrees Celsius for annual mean temperature and daily temperature variability, millimeters for total annual precipitation and extreme daily precipitation, and simply the number of days for the annual number of wet days.

We additionally calculated weighted standard deviations of monthly rainfall totals as also used in ref. [14], but do not include them in our projections as we find that when accounting for delayed effects their effect becomes statistically indistinct and is better captured by changes in total annual rainfall.

Spatial aggregation

We aggregate grid-cell level historical and future climate measures, as well as grid-cell level future GDPpc and population, to the level of the first administrative unit below national level of the GADM database using an area-weighting algorithm which estimates the portion of each grid-cell falling within an administrative boundary. We use this as our base-line specification following previous findings that the effect of area or population weighting at the sub-national level is negligible[13,14].

Empirical model specification – fixed-effects distributed lag models

Following a wide-range of climate econometric literature[15,53], we use panel regression models with a selection of fixed-effects and time-trends to isolate plausibly exogenous variation with which to maximise confidence in a causal interpretation of the effects of climate on economic growth rates. The use of region fixed effects, μ_r, accounts for unobserved time-invariant differences between regions such as prevailing climatic norms and growth rates due to historical and geo-political factors. The use of yearly fixed effects, η_y, accounts for regionally invariant annual shocks to the global climate or economy such as the El-Nino Southern Oscillation or global recessions. In our base-line specification we also include region-specific linear time trends, $k_r y$, to exclude the possibility of spurious correlations due to common slow-moving trends in climate and growth.

The persistence of climate impacts on economic growth rates is a key determinant of the long-term magnitude of damages. Methods for inferring the extent of persistence in impacts on growth rates have typically used lagged climate variables to evaluate the presence of delayed effects or catch up dynamics[17,18]. For example, consider starting from a model in which a climate condition, $C_{r,y}$, (e.g. annual mean temperature) impacts the growth rate, $\Delta lgrp_{r,y}$ (the first difference of the logarithm of gross-regional product) of region r in year *y*:

$$\Delta lgrp_{r,y} = \mu_r + \eta_y + k_r y + \alpha C_{r,y} + \varepsilon_{r,y}, \quad (4)$$

which we refer to as a "pure growth-effects" model in the main text. Typically, additional lags are included,

$$\Delta lgrp_{r,y} = \mu_r + \eta_y + k_r y + \sum_{L=0}^{NL} \alpha_L C_{r,y-L} + \varepsilon_{r,y}, \quad (5)$$

and the cumulative effect of all lagged terms is evaluated to assess the extent to which climate impacts on growth rates persist. Following ref. [18], in the case that,

$$\sum_{L=0}^{NL} \alpha_L < 0 \text{ for } \alpha_0 < 0; \text{ or } \sum_{L=0}^{NL} \alpha_L > 0 \text{ for } \alpha_0 > 0 \quad (6)$$

the implication is that impacts on the growth rate persist up to NL years after the initial shock (possibly to a weaker or stronger extent), whereas if

$$\sum_{L=0}^{NL} \alpha_L = 0, \quad (7)$$

then the initial impact on the growth rate is recovered after NL years and the effect is only one on the level of output. However, we note that such approaches are limited by the fact that when including an insufficient number of lags to detect a recovery of the growth rates, one may find equation (6) to be satisfied and incorrectly assume that a change in climatic conditions impacts the growth rate indefinitely. In practice, given a limited record of historical data, including too few lags to confidently conclude in an infinitely persistent impact on the growth rate is likely, particularly not over the long-timescales over which future climate damages are often projected[17,24]. To avoid this issue, we instead begin our analysis with a model in which the level of output, $lgrp_{r,y}$, depends on the level of a climate variable, $C_{r,y}$:

$$lgrp_{r,y} = \mu_r + \eta_y + k_r y + \alpha C_{r,y} + \varepsilon_{r,y}. \quad (8)$$

Given the non-stationarity of the level of output, we follow the literature[19] and estimate such an equation in first-differenced form as,

$$\Delta lgrp_{r,y} = \mu_r + \eta_y + k_r y + \alpha \Delta C_{r,y} + \varepsilon_{r,y}. \quad (8)$$

which we refer to as a model of "pure level-effects" in the main manuscript. This model constitutes a baseline specification in which a permanent change in the climate variable produces an instantaneous impact on the growth rate, and a permanent effect only on the level of output. By including lagged variables in this specification,

$$\Delta lgrp_{r,y} = \mu_r + \eta_y + k_r y + \sum_{L=0}^{NL} \alpha_L \Delta C_{r,y-L} + \varepsilon_{r,y}, \quad (9)$$

we are able to test whether the impacts on the growth rate persist any further than instantaneously by evaluating whether $\alpha_{L>0}$ are statistically significantly different from zero. Even though this framework is also limited by the possibility of including too few lags, the choice of a baseline model specification in which impacts on the growth rate do not persist means that in the case of including too few lags, the framework reverts to the baseline specification of level-effects. As such, this framework is conservative with respect to the persistence of impacts and the magnitude of future damages. It naturally avoids assumptions of infinite persistence and we are able to interpret any persistence which we do identify with equation (9) as a lower-bound on the extent of climate impact persistence on growth rates. See the main text for further discussion of this specification choice, in particular regarding its conservative nature compared to previous literature estimates such as refs. [17,18].

We allow the response to climatic changes to vary across regions, using interactions of the climate variables with historical average (1979-2019) climatic conditions reflecting heterogenous effects identified in previous work [13,14]. Following this previous work, the moderating variables of these interaction terms constitute the historical average of either the variable itself or of the seasonal temperature difference, $\hat{T}_r$, or annual mean temperature, $\bar{T}_r$, in the case of daily temperature variability [13] and extreme daily rainfall, respectively [14].

The resulting regression equation with *N* and *M* lagged variables, respectively, reads:

$$\Delta lgrp_{r,y} = \mu_r + \eta_y + k_r y + \sum_{L=0}^{N}(\alpha_{1,L}\Delta\bar{T}_{r,y-L} + \alpha_{2,L}\Delta\bar{T}_{r,y-L}\cdot\bar{T}_r) + \sum_{L=0}^{N}(\alpha_{3,L}\Delta\tilde{T}_{r,y-L} + \alpha_{4,L}\Delta\tilde{T}_{r,y-L}\cdot\hat{T}_r) + \sum_{L=0}^{M}(\alpha_{5,L}\Delta P_{r,y-L} + \alpha_{6,L}\Delta P_{r,y-L}\cdot P_r) + \sum_{L=0}^{M}\left(\alpha_{7,L}\Delta Pwd_{r,y-L} + \alpha_{8,L}\,\Delta Pwd_{r,y-L}\cdot Pwd_r\right) + \sum_{L=0}^{M}(\alpha_{9,L}\Delta Pext_{r,y-L} + \alpha_{10,L}\Delta Pext_{r,y-L}\cdot\bar{T}_r) + \epsilon_{r,y} \qquad (10)$$

where $\Delta lgrp_{r,y}$ is the annual, regional GRPpc growth rate, measured as the first difference of the logarithm of real GRPpc, following previous work[12–14,17–19].

Estimates of the coefficients of interest $\alpha_{i,L}$ are shown in Extended Data Fig. 1 for N=M=10 lags and for our preferred choice of the number of lags in Figs. S2-S4. In Extended Data Fig. 1 errors are shown clustered at the regional level, but for the construction of damage projections we block-bootstrap the regressions by region 1000 times to provide a range of parameter estimates with which to sample the projection uncertainty (following refs. [17,31]).

Constructing projections of economic damage from future climate change

We construct projections of future climate damages by applying the coefficients estimated in equation (10) and shown in Tables S3-5 (when including only lags with significant effects in specifications which limit overfitting, see Supplementary Methods Section S1) to projections of future climate change from the CMIP-6 models. Year-on-year changes in each primary climate variable of interest are calculated to reflect the year-to-year variations used in the empirical models. 30-year moving averages of the moderating variables of the interaction terms are calculated to reflect the long-term average of climatic conditions which were used for the moderating variables in the empirical models. By using moving averages in the projections, we account for the changing vulnerability to climate shocks based on the evolving long-term conditions (Figs. S11 & S12 show that the results are robust to the precise choice of the window of this moving average). While these climate variables are not differenced, the fact that the bias-adjusted climate models reproduce observed climatological patterns across regions for these moderating variables very accurately (Table S8) with limited spread across models (<3%)

precludes the possibility that any considerable bias or uncertainty is introduced by this methodological choice. However, we impose caps on these moderating variables at the 95th percentile at which they were observed in the historical data, in order to prevent extrapolation of the marginal effects outside of the range in which the regressions were estimated. This is a conservative choice which limits the magnitude of our damage projections.

Time-series of primary climate variables and moderating climate variables are then combined with estimates of the empirical model parameters to evaluate equation (10), producing a time series of annual GRPpc growth rate reductions for a given emission scenario, climate model and set of empirical model parameters. The resulting time series of growth rate impacts reflect those occurring due to future climate change. By contrast, a future scenario with no-climate change would be one in which climate variables do not change (other than with random year-to-year fluctuations), and hence the time-averaged evaluation of equation (10) would be zero. Our approach therefore implicitly compares the future climate change scenario to this no-climate change baseline scenario.

The time-series of growth rate impacts due to future climate change in region *r* and year *y*, $\delta_{r,y}$, are then added to the future baseline growth rates, $\pi_{r,y}$, (in log-diff form) obtained from the SSP2 scenario to yield trajectories of damaged GRPpc growth rates, $\rho_{r,y}$. These trajectories are aggregated across time to estimate the future trajectory of GRPpc with future climate impacts:

$$GRPpc_{r,Y} = GRPpc_{r,2020} \sum_{y=2020}^{Y} \rho_{r,y} = GRPpc_{r,2020} \sum_{y=2020}^{Y} (1 + \pi_{r,y} + \delta_{r,y}) \qquad (11)$$

where $GRPpc_{r,y=2020}$ is the initial log-level of GRPpc. We begin damage estimates in 2020 to reflect the damages occurring since the end of the period for which we estimate the empirical models (1979-2019) and to match the timing of mitigation cost estimates from most IAMs (see below).

For each emission scenario, this procedure is repeated 1000 times while randomly sampling from the selection of climate models, the selection of empirical models with different numbers of lags (shown in Figs. S2-S4 and Table S4-S6), and bootstrapped estimates of the regression parameters. The result is an ensemble of future GRPpc trajectories which reflect uncertainty from both physical climate change and the structural and sampling uncertainty of the empirical models.

Estimates of mitigation costs

We obtain IPCC estimates of the aggregate costs of emission mitigation from the AR6 Scenario Explorer and Database hosted by IIASA[23]. Specifically, we search the AR6 Scenarios Database World v1.1 for Integrated Assessment Models (IAMs) which provided estimates of global GDP and population under both an SSP2 baseline and SSP2-RCP2.6 scenario in order to maintain consistency with the socio-economic and emission scenarios of the climate damage projections. We find five IAMs which provide data for these scenarios, namely MESSAGE-GLOBIOM 1.0, REMIND-MAgPIE 1.5, AIM/GCE 2.0, GCAM 4.2, and WITCH-GLOBIOM 3.1. Of these five, we use results only from the first three which passed the IPCC vetting procedure for reproducing historical emission and climate trajectories. We then estimate global mitigation costs as the percentage difference in global per capita GDP between the SSP2 baseline and the SSP2-RCP2.6 emission scenario. In the case of one of these IAMs, estimates of mitigation costs begin in 2020 while in the case of two others mitigation costs begin in 2010. The mitigation cost estimates prior to 2020 in these two IAMs are mostly negligible, and our choice to begin comparison to damage estimates in 2020 is conservative with respect to the relative weight of climate damages compared to mitigation costs for these two IAMs.

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Author contributions

All authors contributed to the design of the analysis. MK conducted the analysis and produced the figures. All authors contributed to the interpretation and presentation of the results. MK and LW wrote the manuscript.

Competing interest declaration

We have no competing interests to declare.

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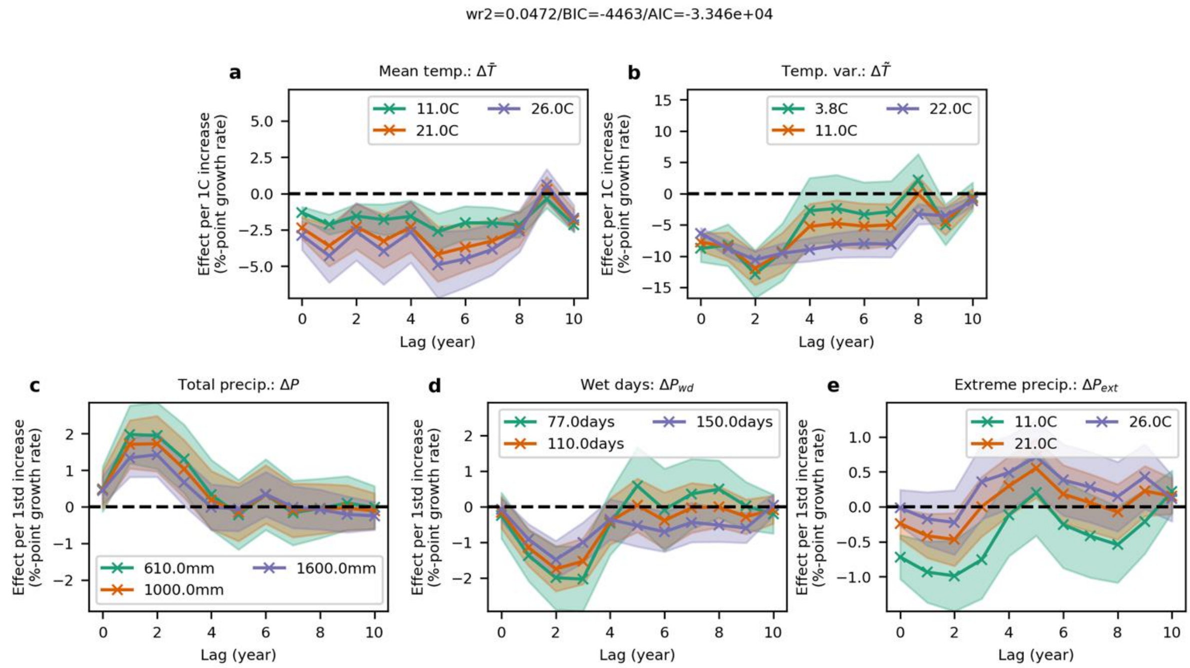
Data availability

Data on economic production and ERA-5 climate data are both publicly available at http://doi.org/10.5281/zenodo.4681306, and https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5 respectively. Data on mitigation costs are publicly available at https://data.ene.iiasa.ac.at/ar6/#/downloads. All secondary data will be made available at a public repository upon publication.

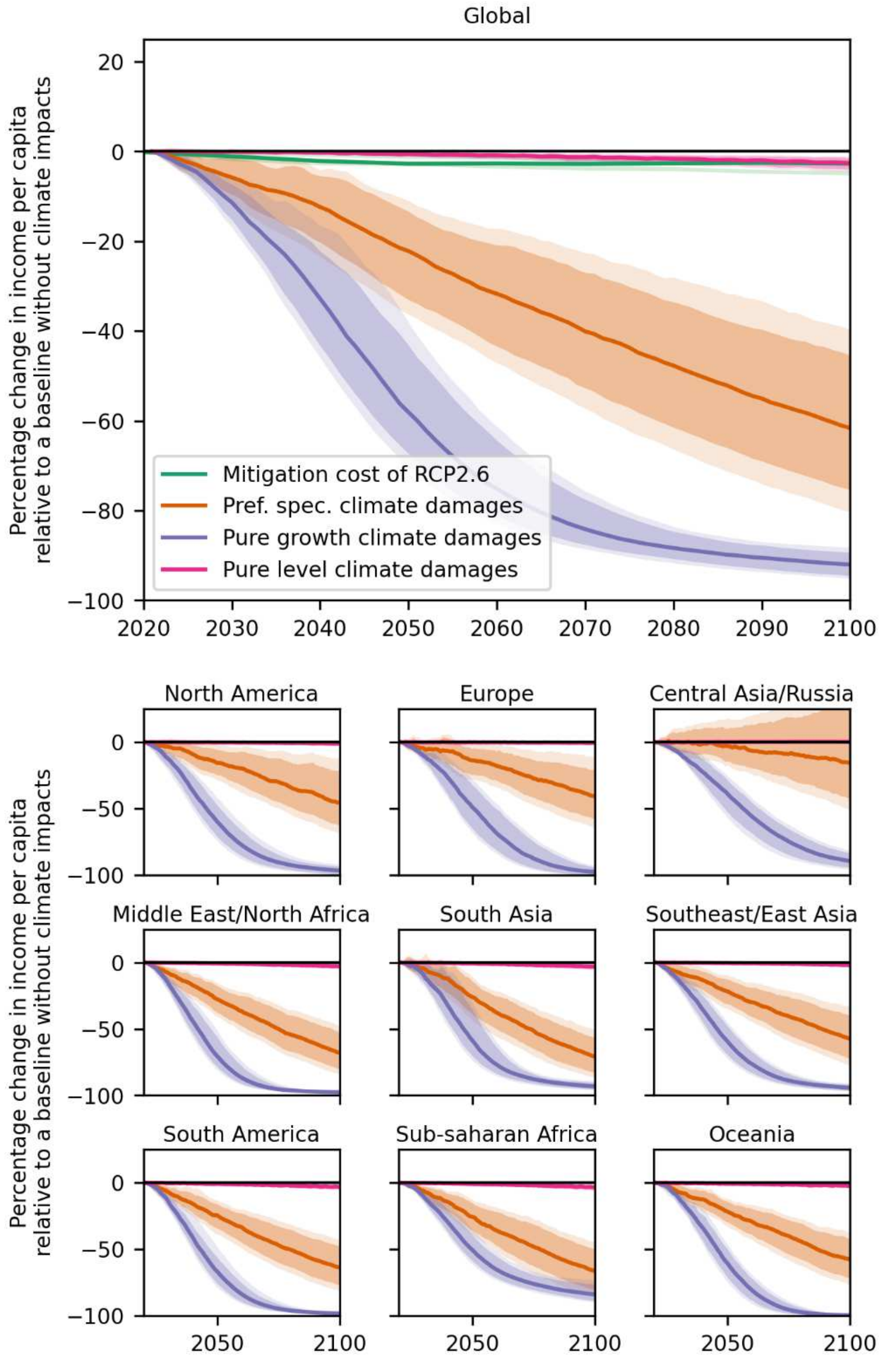
Code availability

Code used for the analysis will be made available at a public repository upon publication.

Extended Data Figures



Extended Data Figure 1. Constraining the persistence of historical climate impacts on economic growth rates. The results of a panel fixed effects distributed lag model for the effects of annual mean temperature (a), daily temperature variability (b), total annual precipitation (c), the number of wet days (d) and extreme daily precipitation (e) on sub-national economic growth rates. Point estimates show the effects of a one degree Celsius or one standard deviation increase (for temperature and precipitation variables respectively) at the lower quartile, median and upper quartile of the relevant moderating variable (green, orange, purple, respectively) at different lagged periods after the initial shock (note that these are not cumulative effects). Climate variables are used in their first-differenced form (see main text for discussion), and the moderating climate variables are the annual mean temperature, seasonal temperature difference, total annual precipitation, number of wet days, and annual mean temperature respectively in panels (a-e) (see methods for further discussion). Error bars show the 95% confidence intervals having clustered standard errors by region. The within-region R-squared, Bayesian and Akaike Information criteria for the model are shown at the top of the figure. This figure shows results with ten lags for each variable to demonstrate the observed levels of persistence, but our preferred specifications remove later lags based on the significance of terms shown above and the Information Criteria shown in Fig. S5. The resulting models without later lags are shown in Figs. S8-S10.



Extended Data Figure 2. Damages in our preferred specification which provides a robust lower-bound on the persistence of climate impacts on economic growth vs damages in specifications of pure growth or pure level effects. Estimates of future damages as shown in Fig. 1 of the main manuscript, but under the emission scenario RCP8.5 for three separate empirical specifications: in orange our preferred specification which provides an empirical lower-bound on the persistence of climate impacts on economic growth rates while avoiding assumptions of infinite persistence (see main text for further discussion); in purple a specification of “pure growth effects” in which the first difference of climate variables is not taken and no lagged climate variables are included (the baseline specification of ref [17]); and in pink a specification of “pure level effects” in which the first difference of climate variables is taken but no lagged terms are included.

Study	Empirical resolution	Number of climate variables considered	Baseline specification of growth or level effect	Number of lags in primary specification	Damages by 2100 under RCP8.5
Burke (2015)[17]	National	One	Growth	None	~25%
Kahn (2019)[35]	National	One	Level	Four	7.2%
Kalkuhl & Wenz (2020)[12]	Sub-national	One	Level	One	14.2%
This study	Sub-national	Five	Level	Eight-ten/four	61.6%

Extended Data Table 1. A comparison of the magnitude of estimated economic damage from future climate change across recent panel-based empirical studies. All studies use fixed effects panel regressions. The first four columns describe differences in the underlying data and empirical specification. The third column shows the nature of the baseline specification without lags with regards to growth or level effects (see main text for further discussion). The last column compares projections of future economic damage under RCP-8.5 by 2100 as reported by the respective study.

Supplementary Files

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- KotzLevermannWenzNatureSIrevised3.pdf