LETTER

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Large potential reduction in economic damages under UN mitigation targets

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International climate change agreements typically specify global warming thresholds as policy targets[1], but the relative economic benefits of achieving these temperature targets remain poorly understood[2,3]. Uncertainties include the spatial pattern of temperature change, how global and regional economic output will respond to these changes in temperature, and the willingness of societies to trade present for future consumption. Here we combine historical evidence[4] with national-level climate[5] and socioeconomic[6] projections to quantify the economic damages associated with the United Nations (UN) targets of 1.5 °C and 2 °C global warming, and those associated with current UN national-level mitigation commitments (which together approach 3 °C warming[7]). We find that by the end of this century, there is a more than 75% chance that limiting warming to 1.5 °C would reduce economic damages relative to 2 °C, and a more than 60% chance that the accumulated global benefits will exceed US$20 trillion under a 3% discount rate (2010 US dollars). We also estimate that 71% of countries—representing 90% of the global population—have a more than 75% chance of experiencing reduced economic damages at 1.5 °C, with poorer countries benefiting most. Our results could understate the benefits of limiting warming to 1.5 °C if unprecedented extreme outcomes, such as large-scale sea level rise[8], occur for warming of 2 °C but not for warming of 1.5 °C. Inclusion of other unquantified sources of uncertainty, such as uncertainty in secular growth rates beyond that contained in existing socioeconomic scenarios, could also result in less precise impact estimates. We find considerably greater reductions in global economic output beyond 2 °C. Relative to a world that did not warm beyond 2000–2010 levels, we project 15%–25% reductions in per capita output by 2100 for the 2.5–3 °C of global warming implied by current national commitments[7], and reductions of more than 30% for 4 °C warming. Our results therefore suggest that achieving the 1.5 °C target is likely to reduce aggregate damages and lessen global inequality, and that failing to meet the 2 °C target is likely to increase economic damages substantially.

Anticipating the potential impacts of climate change is central to planning appropriate policy responses, including how to allocate resources among mitigation and adaptation options. By committing the international community to holding global warming to "well below 2 °C above pre-industrial levels" and pursuing a 1.5 °C target[1], the UN Paris Agreement increased the need for quantitative analysis of uncertainties in the costs and benefits of achieving highly resolved warming targets. In particular, because mitigation costs are thought to rise rapidly for more stringent targets[9], understanding the value of avoided impacts (what we term 'benefits') is central to evaluating the 1.5 °C target. Quantification of these potential benefits and their uncertainties is needed at the aggregate global level to guide coordinated global policy, as well as at a more local level to understand the distributional impacts of global policy choices[10]. Further, because the current national commitments imply warming[7] of 2.5–3 °C, quantifying the impact of exceeding the 1.5 °C and 2 °C targets is also critical to understanding the implications of policy choices.

Here we estimate the global and country-specific economic impacts of limiting warming to 1.5 °C relative to 2 °C, as well as the global impacts of projected warming under current mitigation commitments, separate from any mitigation costs incurred in achieving those targets. We measure potential global and country-level damages using gross domestic product (GDP), the total value of goods and services produced in a country in a given year. GDP is clearly an incomplete summary of the benefits of mitigation, and it cannot easily diagnose many sector-specific impacts (for example, in crop agriculture versus manufacturing). However, it does capture how sector-specific impacts interact and aggregate—a traditional challenge for sector-specific empirical work and model-based approaches to aggregation[11]. GDP also remains highly relevant to policy discussions, and the level and uncertainty in GDP impacts associated with the UN temperature targets has not been formally quantified.

We construct a probabilistic framework (Fig. 1) that incorporates uncertainty in (1) the historical relationship between temperature variability and economic growth, (2) the spatial pattern of future mean annual temperature change associated with a given level of aggregate emissions, (3) the future rate and pattern of economic development absent climate change, and (4) how future damages should be discounted.

To estimate the historical relationship between temperature and GDP, we use annual measurements of average temperature and growth in GDP per capita from 165 countries over the years 1960–2010. Following Burke et al.[4], we use a fixed-effects estimator that isolates the effect of temperature fluctuations from other time-invariant and time-varying factors that might be correlated with both temperature and economic output, and we estimate nonlinear response functions that allow the marginal effect of warming to differ as a function of countries' average temperatures. To quantify uncertainty in this historical relationship, we employ multiple bootstrapping approaches, estimating a separate response function for each re-sample (see Methods).

All estimated response functions relating GDP growth to temperature display a similar concave shape (Fig. 1a), suggesting that additional warming accelerates growth in cooler regions and slows growth in warmer regions. These findings are consistent with a large body of work demonstrating nonlinear responses of economic outcomes to changes in temperature[12–17]. However, there is uncertainty in the temperature at which additional warming begins to generate damages rather than benefits (the 'temperature optimum'), with a median estimate of 13.1 °C but a 5%–95% range of 9.7–16.8 °C. Because much of today's GDP is produced in areas just beyond the median estimated optimal temperature (density plot, bottom of Fig. 1a), uncertainty in this optimum leads to substantial overall uncertainty in both the magnitude and sign of the impact of additional warming.

We project impacts under different levels of future warming by combining these historical response functions with the Intergovernmental Panel on Climate Change (IPCC) projections of future climate[18]. The climate model experiments used by the IPCC involve dozens of general circulation models (GCMs) run under four forcing pathways (called

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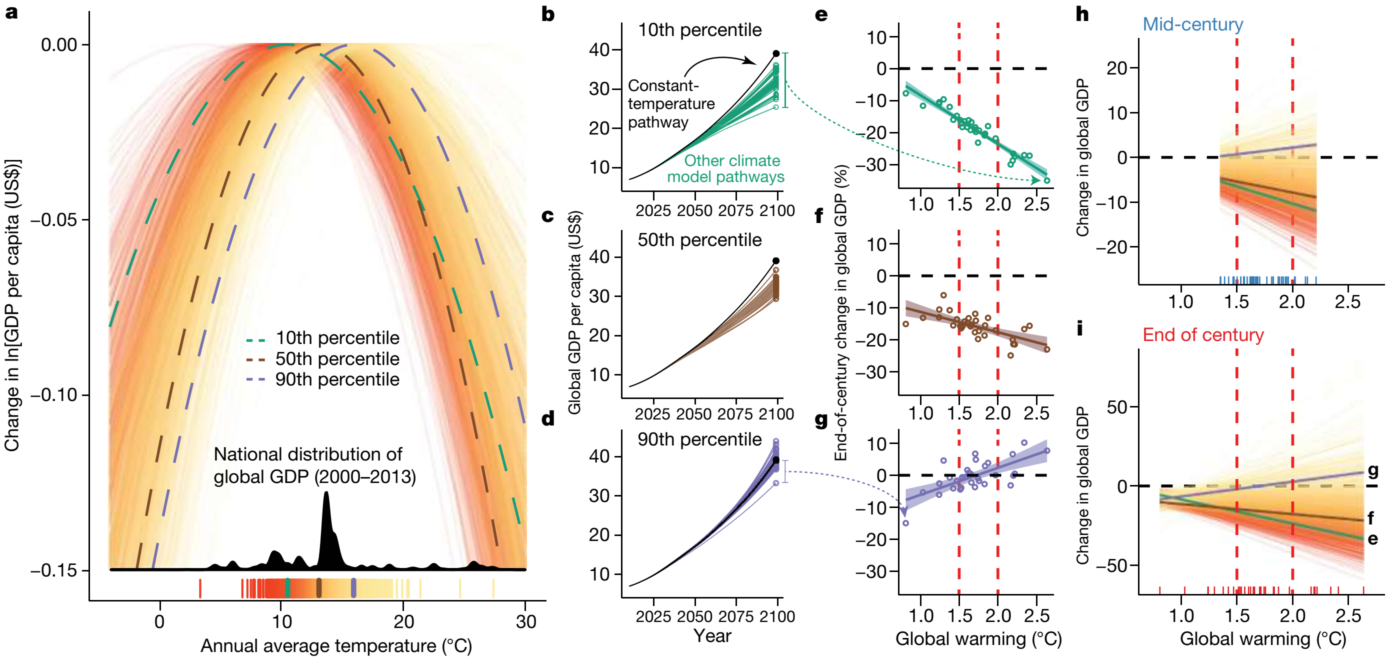

Fig. 1 | Deriving impact projections. a, Historical response of per capita GDP growth rates to temperature. Each curve is the response function estimated from one of 1,000 bootstraps of a historical regression with colour corresponding to the temperature at which it optimizes (redder colours for cooler optima). The green, brown and purple dashed curves highlight bootstraps at the 10th, 50th and 90th percentiles of optimizing temperatures, respectively. The rug plot at the bottom shows the distribution of optimizing temperatures across bootstraps using the same colour scheme. The density plot in black shows the GDP-weighted distribution of baseline average national temperatures. **b**–**d**, Projected future economic pathways under different historical response functions. Black lines represent the pathway of global GDP per capita, assuming no future warming. Coloured lines are pathways corresponding to the response functions at the 10th, 50th and 90th percentiles highlighted in **a**, under warming projections from 32 GCMs consistent with RCP2.6. Points represent values projected for 2099. **e**–**g**, Projected climate impact on global GDP per capita by 2099 for the same response functions, equivalent to the percentage difference between the black points and coloured points in **b**–**d**. The warming on the *x* axes is the global warming projected for 2099 by GCMs running RCP2.6, relative to a pre-industrial benchmark. Red vertical dashed lines mark 1.5 °C and 2.0 °C warming. Linear ordinary least-squares models are fitted for each of the response functions, with the slope estimating the per-degree impact of global warming on global GDP per capita. Shaded areas represent the 95% confidence interval of the ordinary least-squares fit. **i**, The linear fits from **e**–**g**, but for all bootstrapped response functions instead of just the three highlighted in **b**–**g**. The colours correspond to the optimizing temperatures of the response functions, as in **a**. The rug plot at the bottom marks global warming for the end of the century (2099) projected by the 32 GCMs consistent with RCP2.6, equivalent to the *x*-axis values of points in **e**–**g**. **h**, Equivalent to **i** but for mid-century (2049) projections based on 42 GCMs consistent with RCP4.5.

representative concentration pathways, or RCPs). Each GCM realization contains a temperature trajectory for each country and, in aggregate, for the globe. Because temperature affects both the level and the growth rate of economic output[4,11], and because growth effects compound over time, the projected differential impacts of 1.5 °C versus 2 °C are a function of the time horizon. We calculate differential impacts under the two targets using temperature changes for the mid-century (2046–2065) and end-of-century (2081–2100) periods used by the IPCC, focusing on output from those RCPs whose ensemble range spans 1.5 °C and 2 °C for a given time period (Methods). We use projections from the relevant shared socioeconomic pathways (SSPs) to define the secular evolution of population and economic development[6,19], (Fig. 1b–d, Extended Data Fig. 2).

Economic impacts are calculated relative to a constant-temperature counterfactual and are then aggregated globally (weighting by population), resulting in a unique estimate of global impact for each bootstrap–GCM–SSP–year combination. We present two measures of these relative impacts: the percentage difference in annual GDP at the end of the chosen projection period and the discounted present value of absolute GDP differences accumulated over that span. For the second measure we employ a range of discounting schemes, including fixed rates of 2.5%–5% per annum (where a 5% discount rate assumes that society values a given amount of consumption in one year roughly 5% less than it values it today) and time-varying rates that depend on the levels of and uncertainty in realized growth (Methods).

We estimate the benefits of 1.5 °C versus 2 °C by fitting a linear least-squares regression relating either measure of relative economic impact to the global warming projected by each GCM that archives the RCP (Fig. 1e–g). We repeat this procedure for every bootstrapped response function to arrive at a distribution of estimated impacts for the chosen combination of GCM, SSP and projection period. See Methods for a full derivation.

Most response functions generate more negative global impacts at 2 °C than at 1.5 °C (Fig. 1h–i, Extended Data Fig. 2). Cooler estimated historical optima (red colours) generate steeper negative responses to additional warming, implying greater benefits from more stringent mitigation. We estimate that limiting warming to 1.5 °C instead of 2 °C by mid-century would lead to an increase in global GDP of 1.5%–2.0% (median estimate; Fig. 2a) and US$7.7–11.1 trillion in discounted avoided damages under a 3% fixed annual discount rate. Meeting these targets at the end of the century is estimated to lead to median gains in global GDP per capita of 3.4% and discounted avoided damages of US$36.4 trillion.

We use the distributions of bootstrapped estimated impacts to quantify the probability that more stringent mitigation yields benefits of different magnitudes (Extended Data Table 1). We estimate that achieving the 1.5 °C target at mid-century (2046–2065) would lead to a 68%–76% chance of overall cumulative net benefit relative to 2 °C under a fixed 3% discount rate. Under the same discount rate, we estimate a 43%–53% chance of discounted cumulative benefits exceeding US$10 trillion and a 4%–8% chance of exceeding $30 trillion, which is about 40% of current global GDP. For the end of the century (2081–2100), we estimate a >75% chance of net gain in per capita global GDP, an approximately 38% chance that benefits exceed US$50 trillion, and

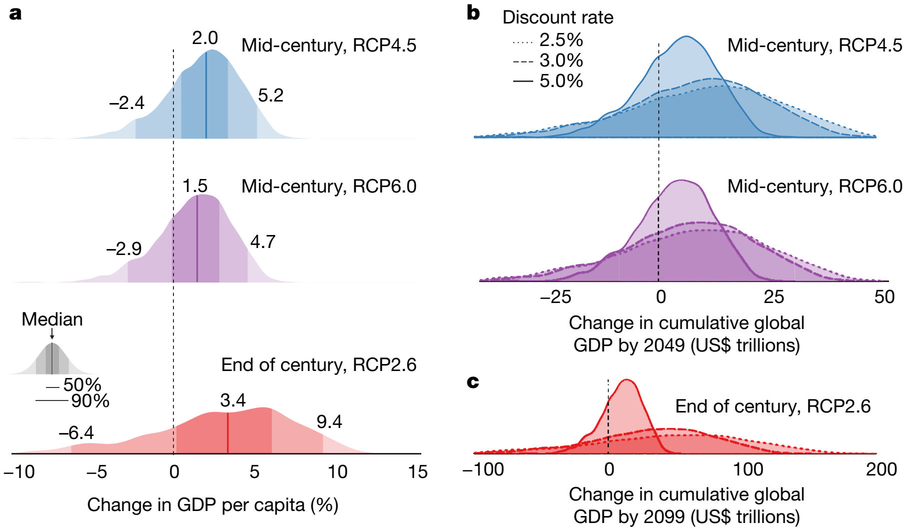

Fig. 2 | Global impact of limiting global warming to 1.5 °C relative to 2 °C. a, Probability distribution of the percentage change in global GDP per capita for 1.5 °C versus 2 °C by mid-century and by the end of the century, as derived from the slopes of the linear fits across response functions illustrated in Fig. 1h–i. Positive values indicate reduced damages at 1.5 °C of global warming as compared to 2 °C. Values above distribution report percentage changes at the 10th, 50th and 90th percentiles of distribution. **b**, Probability distribution of the change in cumulative global GDP by mid-century, assuming discount rates of 2.5% (dotted line), 3% (dashed line) and 5% (filled line). **c**, The equivalent for the end of the century.

an approximately 5% chance that benefits exceed US$100 trillion (3% discount rate; Extended Data Table 2).

While end-of-century estimates of the magnitude of absolute impacts are sensitive to choices about discounting (Extended Data Fig. 3, Extended Data Table 1), estimates of the probability of positive benefits are much less so (Extended Data Tables 2 and 3). Results are also relatively insensitive to alternative bootstrap resampling approaches, to different SSPs, and to alternative assumptions about the time path of future warming for a given RCP (Extended Data Figs. 4, 5). Inclusion of additional lags of temperature in the historical regression—a common

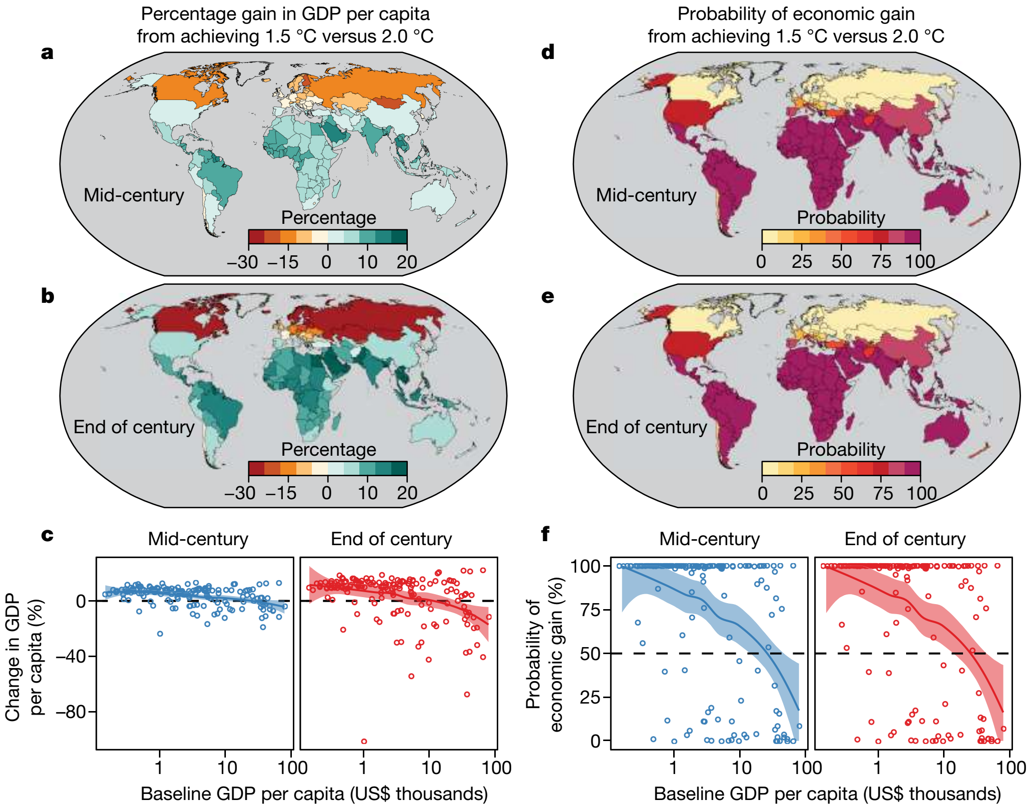

Fig. 3 | Country-level impact of limiting global warming to 1.5 °C relative to 2 °C. a, **b**, Median estimates of impacts on change in GDP per capita under 1.5 °C versus 2 °C, for mid-century and the end of the century. Positive values indicate reduced damages at 1.5 °C of global warming as compared to 2 °C. **c**, Median estimated impacts as a function of each country's baseline GDP per capita, with each country weighted equally. Lines represent local polynomial regression fits to the data with the corresponding 95% confidence intervals shaded in grey. **d**–**f**, As in **a**–**c**, but for the probability of per capita GDP gain, calculated as the percentage of bootstrap response functions projecting a net gain in a country's GDP per capita under 1.5 °C of global warming as compared to 2 °C.

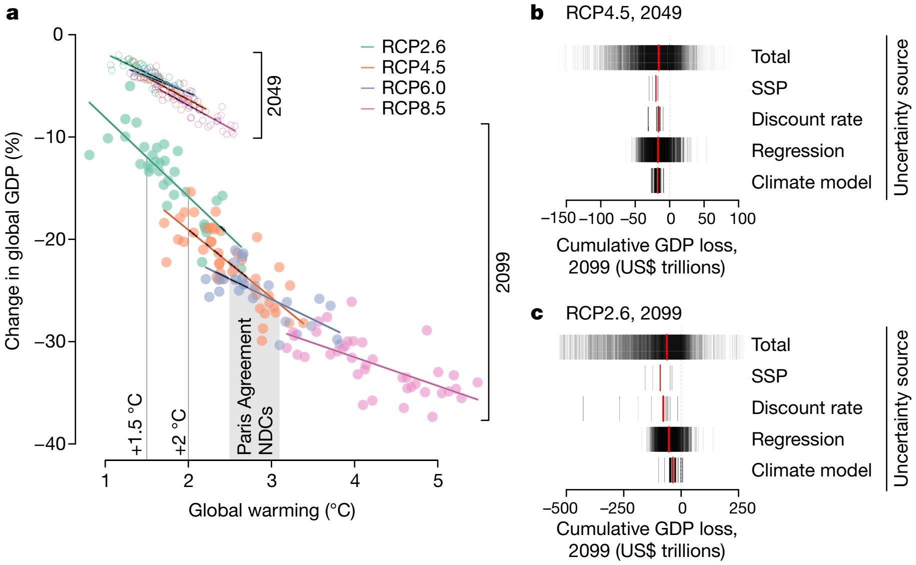

Fig. 4 | The impact of global warming on global GDP per capita, relative to a world without warming, for different forcing levels. a, Projected percentage change in global GDP for different climate models under different RCP forcing scenarios, relative to a no-warming baseline (median bootstrap, SSP1). Colours denote different RCPs. Unfilled points show mid-century projections, filled points show end-of-century projections. Vertical lines show the UN temperature targets as well as the range of estimates of end-of-century warming under current Paris commitments[7]. Warming is relative to pre-industrial levels. **b**, **c**, Sources of uncertainty in estimates of global warming on cumulative global GDP loss for a given forcing level. Total uncertainty in the impact of warming on global GDP under a given forcing scenario is a combination of uncertainty in how economies respond to warming ('historical regression uncertainty'), uncertainty across climate models in the amount and pattern of warming for a given level of forcing ('climate model uncertainty'), uncertainty in baseline future growth rates across baseline socioeconomic scenarios ('SSP uncertainty'), and plausible alternatives for how to specify the discount rate ('discount rate uncertainty'). Values show cumulative global GDP losses in trillions of US$ for mid-century under RCP4.5 (**b**) and the end of the century under RCP2.6 (**c**), either with all factors allowed to vary ('total uncertainty') or with the listed factor allowed to vary and all others fixed at their median (see Methods). Each vertical line is a point estimate; for example, with 32 climate models running RCP2.6 there are 32 estimates shown for 'climate model uncertainty' in **c**. Red lines are the median estimate across each uncertainty distribution.

approach to capturing persistent growth effects[11]—amplifies the effect of temperature on growth rates and results in larger estimates of benefits under 1.5 °C (Extended Data Fig. 4). Other potential sources of uncertainty, such as uncertainty in the secular rate of growth beyond the scenarios prescribed by the SSPs, were not quantified and could increase overall impact uncertainty.

At the country level, both the magnitude and the uncertainty of potential benefits are highly non-uniform. We find that 71% of countries—encompassing about 90% of projected global population—exhibit a >75% chance of experiencing positive economic benefits at 1.5 °C relative to 2 °C (Fig. 3), and 59% of countries exhibit a >99% chance. These countries include the three largest economies (the USA has a 76% chance of positive benefits; China 85%; Japan 81%) (Fig. 3, maps). They also include a large fraction of the world's poorest countries, with the likelihood of economic gains rising rapidly at lower levels of GDP per capita (Fig. 3c, f). Many of the countries that exhibit a high probability of economic benefits from 1.5 °C are concentrated in the tropics and sub-tropics, where both current and future temperatures are warmer than the economic optimum[4]. As a result, even small reductions in future warming in these countries can generate substantial increases in per capita GDP, with many countries in the tropics exhibiting per capita GDP 10%–20% higher at 1.5 °C than 2 °C by the end of the century (Fig. 3a, b, d, e). The opposite is true for a smaller number of high-latitude countries, where 1.5 °C is estimated to slow growth and generate a high probability of negative impacts relative to 2 °C. Achieving the 1.5 °C target will thus have unequal consequences, with today's poorest countries benefiting the most.

Despite the Paris Agreement's focus on the 1.5 °C and 2 °C targets, its actual Nationally Determined Contributions (NDCs) are instead consistent with 2.5–3 °C of global warming[7]. We estimate that this level of warming could lead to a reduction in global GDP as high as 10% by mid-century and 15%–25% by the end of the century (median estimates across SSPs; Fig. 4 and Extended Data Fig. 6), relative to a world that did not warm beyond 2000–2010 levels. In addition, failing to meet the NDC commitments is likely to lead to reductions in global GDP that exceed 25% by the end of the century. Uncertainty in these estimates is driven much more by uncertainty in economic parameters—namely, the economic response to warming and the discount rate—than by uncertainty in the pattern and magnitude of temperature change reflected in the climate model ensemble (Fig. 4b and c), highlighting the importance of better constraining these economic parameters[20].

Because our future impact estimates are based on observed historical economic responses to temperature variability, our projections will misstate impacts if the relationship between future annual temperatures and climatic extremes differs from what has occurred historically, or if future societies respond differently from societies in the recent past—although there is growing evidence that economic development might not fundamentally alter these economy–environment linkages[4,15–17]. We also cannot account for historically unprecedented changes, such as large-scale loss of land ice and associated sea level rise, which are more likely to occur[8,21] at 2 °C than 1.5 °C and are expected to exacerbate impacts[22,23].

To support policy decisions, our estimates of avoided damages need to be compared against the costs of meeting the UN targets. To our knowledge, no comparable estimates of global abatement costs through to the end of the century currently exist. However, a recent estimate[24] suggests that achieving emissions levels in 2030 that are consistent with the 1.5 °C target will lead to approximately US$300 billion in additional (non-discounted) abatement costs relative to emissions consistent with 2 °C. This estimate of abatement costs is >30 times smaller than our median estimate of (discounted) mid-century avoided damages.

Not accounting for abatement costs, our results suggest that 1.5 °C global warming is "likely"[25] to result in substantial economic benefits relative to 2 °C, with foregone damages probably in the tens of trillions of dollars and 59% of countries "virtually certain"[25] to benefit. Given that most of these countries feature large populations or high poverty rates or both, our results suggest that achieving more stringent mitigation targets will probably generate a net global benefit, with particularly large benefits for the poorest populations.

Online content

Any Methods, including any statements of data availability and Nature Research reporting summaries, along with any additional references and Source Data files, are available in the online version of the paper at https://doi.org/10.1038/s41586-018-0071-9.

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Competing interests The authors declare no competing interests.

Additional information
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METHODS

Deriving the historical response function. To understand the historical relationship between temperature and economic output, we assemble annual data on country-level GDP per capita from the World Bank's World Development Indicators, using data on 165 countries over the period 1960 to 2010. Growth is computed as the first difference of the natural logarithm of the annual purchasing power parity-adjusted per capita GDP series in each country. These data are then merged with temperature and precipitation data from the University of Delaware[26].The gridded monthly temperature and precipitation data are aggregated temporally to the annual level and spatially to the country level. We then follow ref. [4] and estimate a panel fixed effects model:

$$\Delta\log(y_{it}) = \beta_1 T_{it} + \beta_2 T_{it}^2 + \lambda_1 P_{it} + \lambda_2 P_{it}^2 + \mu_i + \upsilon_t + \theta_{1i}t + \theta_{2i}t^2 + \varepsilon_{it} \tag{1}$$

where y_{it} is per capita GDP in country i in year t, T and P are the average temperature and precipitation in year t, μ_i are country-fixed effects (dummies) that control for time-invariant differences between countries, υ_t are year-fixed effects that account for common global shocks in a given year, and $\theta_{1i}t + \theta_{2i}t^2$ are country-specific linear and quadratic time trends, which allow temperature and growth to evolve flexibly at the country level.

Equation (1) is estimated simultaneously on our global sample of country-years ($N = 6,584$). Point estimates for β_1 and β_2 are statistically significant in this regression ($\beta_1 = 0.0127$, standard error 0.0032, $P < 0.001$; $\beta_2 = -0.0005$, standard error 0.0001, $P < 0.001$).

Equation (1) assumes that there is a single response function (described by β_1 and β_2) that specifies the overall global relationship between income growth and changes in temperature, but that individual countries can respond differently to warming as a function of their average temperature (which can be seen by differentiating equation (1) with respect to temperature). Past work has shown that average temperature—rather than other correlated factors such as average income—is the main source of heterogeneity in how countries' income growth responds to changes in temperature and that estimates of β_1 and β_2 are highly robust to alternative specifications of the fixed effects and time controls[4].

An additional concern is that countries trade with one another and that unobserved temperature shocks across a trading network might lead to biased coefficient estimates in equation (1). However, if temperature shocks are uncorrelated across trading partners, then estimates of β_1 and β_2 still represent unbiased estimates of own-country temperature shocks on output; if shocks are correlated across trading partners, then β_1 and β_2 represent reduced-form estimates of the net effect in a given country of correlated shocks across that country's trading network. The main concern for our analysis is if the future pattern of temperature change should not correspond to the spatial pattern of historical shocks; however, we are unaware of any relevant research in climate science.

To quantify uncertainty in estimates of β_1 and β_2, we implement multiple bootstrapping strategies: (1) Sampling by country. From our list of 165 countries, draw (with replacement) a 165-element list of countries—which will omit some countries and contain duplicates of others—and retain all years of data for the selected countries; this is repeated 1,000 times, drawing a new country sample each time, re-estimating equation (1), and retaining estimates of β_1 and β_2. This approach allows for arbitrary correlation in residuals within countries over time. (2) Sampling by year. This allows for potential cross-sectional correlation in residuals in a given year, and is also repeated 1,000 times. (3) Sampling by five-year block. We divide the data into 10 five-year blocks (that is, 1961–65, 1966–70, and so on through 2010), and sample with replacement from these 10 blocks. This allows for both temporal and cross-sectional dependence in residuals, for example, as caused by global recessions that last multiple years.

Our main results use strategy (1) (sampling by country), but we show that our results are robust, regardless of the strategy used. In what follows, the bootstrapped response functions $h^j(T_{it}) = \hat{\beta}_1^{\,j} T_{it} + \hat{\beta}_2^{\,j} T_{it}^2$ are indexed with j, where $j \in (1, 2, \ldots, 1{,}000)$.

For each $h^j(T_{it})$, we define the 'temperature optimum' as the maximum of the quadratic function, that is, $\frac{-\beta_1^j}{2 \times \beta_2^j}$ (this is always a maximum because all estimates yield $\beta_1^{\,j} > 0$ and $\beta_2^{\,j} < 0$).

To ensure that equation (1) is capturing growth effects and not just level effects, we re-estimate equation (1) with additional lags of temperature (and their squares)[4,11]. This is important because countries' economic output could 'catch up' in the year following a temperature shock; this catch-up behaviour would not be captured in a model containing only contemporaneous temperature variables, but would be captured in a model that includes lags of temperature and where overall temperature effects are computed by summing contemporaneous and lagged coefficients[11]. We thus estimate equation (1) with up to five lags l of temperature, that is,:

$$h^j(T_{it}) = \sum_{l=0}^{5} \{\hat{\beta}_{1,l}^{\,j} T_{it-l} + \hat{\beta}_{2,l}^{\,j} T_{it-l}^2\} \tag{2}$$

and re-estimate all calculations below with results from these distributed lag models. Our main results with this sensitivity test are shown in Extended Data Fig. 4.

Climate model simulations. To follow the IPCC protocols, we analyse the exact climate model realizations and time periods used by the IPCC in its most recent assessment report[5]. These climate model realizations were generated by the World Climate Research Program under Phase Five of the Climate Model Intercomparison Project (CMIP5)[18]. For the historical baseline experiment, the CMIP5 protocol ran each climate model from the mid-1800s to 2005, using the historical climate forcings. For the future scenarios, the CMIP5 protocol used the RCPs, which assume different levels of climate forcing going forward in the 21st century. In total, there are four: RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

Following the IPCC protocols, we use the same historical baseline period (1986–2005) and RCP future periods (2046–2065 and 2081–2100) as did the IPCC. In our bias correction method (see below), there are three RCPs whose global warming ranges are most consistent with the 1.5 °C and 2 °C targets in these IPCC scenario time periods: RCP4.5 and RCP6.0 during the 2046–2065 period, and RCP2.6 during the 2081–2100 period. (RCP2.6 is the only RCP scenario in which some models project global warming of less than 1.5 °C for the end of the century; for mid-century, none of the RCP2.6 model runs project warming above 2 °C, and so we do not utilize RCP2.6 for mid-century). We therefore calculate the distribution of GDP outcomes in response to the global warming levels projected during the 2046–2065 period of RCP4.5 and RCP6.0, and during the 2081–2100 period of RCP2.6. In addition, to compare the probability of economic impacts for the UN targets with the probability of those for higher levels of greenhouse gas emissions, we also calculate the distribution of GDP outcomes for the 2046–2065 and 2081–2100 periods of RCP8.5.

Uncertainty in the temperature-driven GDP impacts of a given level of greenhouse gas emissions arises from both uncertainty in the level of global warming associated with that level of emissions and uncertainty in the spatial pattern of temperature at that level of global warming. The IPCC climate analysis protocols span these uncertainty dimensions by analysing one realization of each climate model in each RCP scenario[5]. To follow the IPCC protocols, we analyse the same realizations as the IPCC.

However, it should be noted that the CMIP5 ensemble does not span the full range of each uncertainty dimension in a fully uniform framework. Rather, although the experimental conditions for the ensemble were coordinated between the modelling centres, both the models and the implementation of the simulation conditions vary across the ensemble. For example, the ensemble includes simulations from all national modelling centres that chose to participate, but not every modelling centre archived a simulation in each scenario. As a result, the IPCC selection of one realization of each model in each RCP yields different numbers of realizations—and model combinations—in each RCP (42 realizations in RCP4.5, 32 in RCP2.6, 25 in RCP6.0 and 39 in RCP8.5). Likewise, although each modelling centre conformed to a basic set of coordinated experimental conditions, the exact implementation of those conditions varied between the centres. This combination of coordinated but incomplete experimental uniformity has led the CMIP5 ensemble to be known as 'an ensemble of opportunity'. As in the IPCC, we leverage the CMIP5 ensemble of opportunity to estimate an approximate probability distribution; it should be emphasized that this approach is not identical to sampling across a probabilistic ensemble[27].

Because we use GDP data through 2010 and attempt to quantify economic impacts from that year forward, we must also project global and country-level temperature changes forward from the year 2010. To do so, and to control for individual climate model biases in average temperatures, we first calculate the difference between model-projected annual average future temperatures (in 2046–2065 or 2081–2100) and model-simulated annual average temperatures in the baseline 1986–2005 period. We then add those model-projected differences to the actual historical temperature observations.

For each climate model m corresponding to a chosen RCP scenario s at a given time period, we first calculate two quantities: (1). The magnitude of global temperature change ΔT^{sm}, which is the difference in annual average global surface temperature between a 1986–2005 baseline period and a future period (either 2046–2065 or 2081–2100). Gridded temperature projections relative to this baseline period are produced at 2.5° resolution. These are aggregated to a scalar 'global warming' projection by taking an average over all grid cells, with each cell g weighted by the cosine of the latitude of each cell g's centrepoint L (given the convergence of lines of latitude towards the poles):

$$\Delta T^{sm} = \frac{\sum_g \{\cos(\overline{L_g}) \times (T_{g,\mathrm{end}}^{sm} - T_{g,\mathrm{base}}^{sm})\}}{\sum_g \cos(\overline{L_g})} \tag{3}$$

(2). The magnitude of each country i's temperature change ΔT_i^{sm}, analogously computed by taking the average projected temperature change of all cells g but weighted by their share of country *i*'s population P_{ig} rather than by their relative surface area. Gridded population distribution data[28] is provided at 30-arc-sec resolution and is aggregated to 2.5° resolution to match the temperature projection data. Thus, country-level temperature change projections are described by the equation:

$$\Delta T_i^{sm} = \frac{\sum_g \{P_{ig} \times (T_{g,\text{end}}^{sm} - T_{g,\text{base}}^{sm})\}}{\sum_g P_{ig}} \tag{4}$$

To express the future global-scale temperature values relative to pre-industrial values, as in the UN temperature targets, we add these model-projected differences between the future and the baseline to the global-scale warming that occurred between the pre-industrial period and the end of the period of GDP and temperature observations (which extends to 2010). According to the IPCC, the "globally averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C, over the period 1880–2012," and the "total increase between the average of the 1850–1900 period and the 2003–2012 period is 0.78 [0.72 to 0.85] °C"[29]. We therefore assume that 0.8 °C of warming took place between the pre-industrial period and the end of our observational period. Thus for the global averages ΔT^{sm}, "global warming relative to pre-industrial" is equal to $\Delta T^{sm} + 0.8$ for all *s* and *m*.

To generate annual country-specific time series of projected future changes in temperature for input into the simulations below, we assume that temperatures increase linearly between the base period and the end period, and then add the linearized projected change in temperature to the observed average baseline temperature, thus 'bias-correcting' future national temperature time series. Thus for a given climate model–RCP realization, if the observed average historical temperature during the base period is $\overline{T_{i0}} = \frac{\sum_{t=1986}^{2005} T_{it}}{2005 - 1986}$, then the projected temperature in each future year is:

$$\Delta T_{it}^{sm} = \overline{T_{i0}} + \frac{t - t_{\text{base}}}{t_{\text{end}} - t_{\text{base}}} \times \Delta T_i^{sm} \tag{5}$$

where $t_{\text{base}} = 2010$ is the initial year of our simulation and t_{end} is either 2049 or 2099. (As before, small *t* indexes time and capital *T* refers to temperature). The assumed linear temperature increase appears to be consistent with RCP 4.5 or 6.0 through mid-century; it is perhaps less consistent with RCP2.6 through the end of the century, as RCP2.6 warms though mid-century and then stabilizes through to the end of the century. To understand whether our assumed linear warming path distorts our findings for RCP2.6, we conduct an additional experiment in which we assume all warming under RCP2.6 occurs by 2049, and then temperatures stabilize at this new level between 2050 and 2099 (Extended Data Fig. 5). This scenario has the same projected global warming by the end of the century as our baseline RCP2.6 scenario, but all warming is assumed to happen in the first half of the 21st century. As shown in Extended Data Fig. 5, we find that the scenario with rapid initial warming worsens the overall impacts of climate change and increases the cumulative benefits of limiting warming to 1.5 °C versus 2 °C.

Defining counterfactual growth scenarios. To project growth in GDP absent climate change, we use projections from the SSPs, a framework developed to describe conditions associated with various degrees of climate forcing by the end of the century. In all, there are five SSP narratives, each making different assumptions about mitigation and adaptation challenges, demographic trends, and developments in the energy industry[19]. We exploit the time series of projected country-level economic growth and population from 2010 to 2095 associated with the SSP1 narrative, because this appears to be the SSP most consistent with the forcing levels required to achieve 1.5 °C warming in 2049 or 2099[6] (although, as pointed out by ref. [6], with high enough carbon pricing all SSPs could potentially be consistent with 1.5 °C warming by mid-century, and three SSPs could be consistent with 1.5 °C warming by the end of the century). SSP1 is described as an optimistic future with 'low' challenges to adaptation and mitigation. SSP1 is characterized by many developing countries contributing an increasingly large share of global GDP by the end of the century (Extended Data Fig. 1a and b), with a larger share of total global GDP projected to be produced in countries with warmer average temperatures by the end of the century absent climate change (Extended Data Fig. 1c). In addition to using SSP1, we also test the robustness of our results to alternative choices from the other four SSPs (Fig. 4 and Extended Data Fig. 6).

Projecting economic impacts of 1.5 °C versus 2 °C. *Step (1). Assemble input data.* Required input data are the parameters of each response function $h^j(T_{it})$ estimated from each of the *j* bootstraps of equation (1); projections of country-year average temperature T_{it}^{sm} for each GCM *m* for a given RCP scenario *s* through to 2049 or 2099; projections of baseline country-year per capita growth rates λ_{it}^{κ} and populations ω_{it}^{κ} through 2099, for each country *i* and year *t*, from a given SSP scenario κ.

Step (2). Calculate country-specific growth trajectories for each bootstrap–RCP–GCM–SSP combination. Projections are initialized using average temperature and GDP per capita between 2000–2010 as the baseline for each of the countries in our analysis. For a given historical bootstrap run *j* and GCM–RCP–SSP projection $sm\kappa$, GDP per capita *y* in each future year $t+1$ in country *i* is projected by the equation:

$$y_{it+1}^{jsm\kappa} = y_{it}^{jsm\kappa} \times (1 + \lambda_{it+1}^{\kappa} + \varphi_{it+1}^{\kappa}) \tag{6}$$

where λ_{it+1}^{κ} is the level of economic growth projected by the data corresponding to the particular SSP series and $\varphi^{jsm} = h^j(T_{it+1}^{sm}) - h^j(T_{i0})$is the additional estimated change in the growth rate due to the projected temperature increase above baseline for bootstrap run *j* and GCM projection *ms*. We also run a counterfactual no-warming scenario where temperatures are fixed at baseline levels, that is, $T_{it+1} = T_{i0}$ and $\phi_{it} = 0$ for all *i* and *t*):

$$y_{it+1}^{0,\kappa} = y_{it}^{0,\kappa} \times (1 + \lambda_{it+1}^{\kappa}) \tag{7}$$

With 165 countries, 1,000 bootstrap estimates of the temperature response function $h(\cdot)$, 100 total temperature time series (corresponding to 42, 25 and 32 climate models for mid-century RCP4.5, mid-century RCP6.0, and end-of-century RCP2.6, respectively, plus the constant-temperature series), five SSPs, and five bootstrap resampling schemes, we analysed more than 400 million distinct country-level economic pathways.

Step (3). Calculate global GDP trajectories for each bootstrap–RCP–GCM–SSP combination. For each GCM–bootstrap–SSP combination in a given period *t*, global GDP per capita is calculated as the average GDP per capita across countries, weighted by share of world population:

$$y_t^{jsm\kappa} = \sum_i \frac{\omega_{it}^{\kappa}}{\omega_t^{\kappa}} \times y_{it}^{jsm\kappa} \tag{8}$$

where $\frac{\omega_{it}^{\kappa}}{\omega_t^{\kappa}}$ is country *i*'s projected share of global population in year *t* for a given SSP. We similarly produce a time series of total global GDP by replacing $\frac{\omega_{it}^{\kappa}}{\omega_t^{\kappa}}$ with ω_{it}^{κ}, the country *i*'s projected population in that year. This is also calculated for the no-warming scenario, yielding counterfactual global GDP time series $y_t^{0,\kappa}$ and $Y_t^{0,\kappa}$, where Y_t denotes GDP.

Step (4). Calculate projected percentage changes in GDP or global GDP relative to the no-warming counterfactual for each bootstrap–RCP–GCM–SSP combination. For each bootstrap–RCP–GCM–SSP combination, we calculate the warming-induced percentage change in GDP relative to the counterfactual no-warming scenario in each country as:

$$\Psi_{it}^{jsm\kappa} = \frac{y_{it}^{jsm\kappa}}{y_{it}^{0,\kappa}} - 1 \tag{9}$$

This is calculated for $t = 2049$ for RCP4.5 and RCP6.0, and $t = 2099$ for RCP2.6. The percentage impact on global GDP per capita, $\Psi_t^{jsm\kappa}$, is calculated similarly for these endpoint years.

Step (5). Calculate projected discounted absolute changes in GDP or global GDP relative to the no-warming counterfactual for each bootstrap–RCP–GCM–SSP combination. The cumulative absolute dollar impact of warming is calculated for each country by taking the annual difference between the unique bootstrap–RCP–GCM–SSP projected GDP time series and the counterfactual no-warming time series, and discounting these differences back to present:

$$\Theta_i^{jsm\kappa} = \sum_t \frac{Y_{it}^{jsm\kappa} - Y_{it}^{0,\kappa}}{(1 + r_t)^{t - t_0}} \tag{10}$$

where $Y_{it}^{jsm\kappa} = y_{it}^{jsm\kappa} \times \omega_{it}^{\kappa}$ and r_t is the social discount rate that could vary with *t*. The global absolute impact is calculated by summing country-level impacts: $\Theta^{jsm\kappa} = \sum_i \Theta_i^{jsm\kappa}$.

Given the long-running and unresolved debate over how *r* should be specified, we calculate $\Theta_i^{jsm\kappa}$ under a range of approaches to specifying *r*. Specifically, we implement a variety of approaches discussed and implemented by previous authors, including implementations of the Ramsey equation with and without uncertainty and under alternate parameter choices for time preference and the marginal utility of consumption[30–34], calibrations to historical market interest rates in the USA[35,36], and constant discount rates[37] ranging from 2.5%–5%. Choices about the discount rate clearly have large implications for the estimation of damages. For instance, US$1,000 of damages in 50 years is worth US$228 today under a 3% annual discount rate, but only US$87 under a 5% annual rate.

As described by multiple authors[33,34,38], choices about *r* can be approached from the perspective of a social planner wishing to maximize the welfare of society. The central intuitions in this approach are that extra income or consumption is worth more to poor people than it is to rich people, and that with rising incomes a dollar of additional income is worth less in the future than it is today. Under standard assumptions about the functional form of the 'utility function' that relates changes in consumption to changes in utility, this approach yields the Ramsey formula, which specifies the annual discount rate on consumption as:

$$r = \rho + \eta g \tag{11}$$

where ρ is the pure or social rate of time preference (the rate at which society discounts the utility of future generations), η is the elasticity of marginal utility of consumption (or how fast the utility of consumption declines as consumption increases), and g is the growth rate in consumption. If there is uncertainty about the growth rate in consumption, a third term is added to the Ramsey equation which induces a precautionary savings effect[34]:

$$r = \rho + \eta g - 0.5\eta^2\sigma_g^2 \tag{12}$$

where σ_g^2 is the variance in the growth rate. Uncertainty in future consumption growth enters negatively as the social planner, facing the possibility of slow future growth, wishes to transfer more resources to the future.

Using equations (11) and (12) and parameter choices about ρ and η from three benchmark studies[30–32] (Stern $\rho = 0.1, \eta = 1$; Nordhaus $\rho = 1$, $\eta = 2$; and Weitzman $\rho = 2$, $\eta = 2$; see Extended Data Fig. 1), we implement six versions of the Ramsey approach—three without uncertainty in future growth and three with uncertainty. For each bootstrap–RCP–GCM–SSP run, we define the growth rate g_t as the population-weighted average growth rate of GDP per capita:

$$g_t^{jsm\kappa} = \sum_i \frac{\omega_{it}^{\kappa}}{\omega_t^{\kappa}}(1 + \lambda_{it}^{\kappa} + \varphi_{it}^{jsm}) \tag{13}$$

with parameters defined as in equations (6) and (8) above. Average values across GCMs are shown in Extended Data Fig. 1a. Uncertainty in the growth rate for each future year is calculated as $\sigma_{gt}^2 = \text{var}(g_t^{jsm\kappa})$, that is, the variance in projected growth rates in a given year across all bootstrap–RCP–GCM–SSP estimates. This probably represents a substantial lower bound on the true uncertainty in the growth rate, as it accounts only for uncertainty induced by additional warming and not for uncertainty in the underlying secular rate of growth (for which the SSPs do not provide uncertainty estimates).

Parameter choices and estimates of future growth rates are then used in either equation (11) or (12) to calculate year-specific discount rates r_t. The resulting estimates of Ramsey-based discount rates are shown in Extended Data Fig. 1b. All versions estimate higher interest rates in earlier periods, which is primarily a result of higher estimated baseline (SSP) growth rates in the earlier half of the century. Discount rates by end of century using the Ramsey approach range from 1.2% (Stern) to 4.2% (Weitzman), with the inclusion of the uncertainty term lowering discount rates only slightly.

Given that future baseline growth rates in developing and developed countries could be different, and given that the marginal effect of warming will probably differ between developing and developed countries given their different baseline temperatures, we also run scenarios where discount rates are allowed to differ between rich and poor countries (defined as being below or above the median level of GDP per capita at baseline). Specifically, using SSP1 data we produce separate population-weighted growth series for poor and rich countries (as shown in Extended Data Fig. 1c), and plug these growth projections into the Ramsey equation for each of the three benchmark choices of ρ and η to produce the six time series of discount rates that appear in Extended Data Fig. 1d. These income-specific discount rates, which are higher for poor countries than for rich countries given differences in baseline growth rates, are then applied to the relevant country groupings in the calculations below. As shown in Extended Data Fig. 3, allowing for income-specific discount rates results in higher median estimates of the global benefit of restricting warming to 1.5 °C. This is because global benefits are driven largely by impacts in the largest economies, including the USA and China, and allowing for income-specific discount rates lowers the rates for rich countries relative to the pooled scheme (for example, compare Extended Data Fig. 1b against Extended Data Fig. 1d), which translates to larger cumulative benefits in large economies projected to be harmed by warming (which again includes both the USA and China).

Beyond the Ramsey framework, another approach to specifying the discount rate uses the observed evolution of market interest rates over long periods combined with models of interest rate behaviour to project interest rates. We extract estimates from two of these exercises[35,36], both of which assume an initial interest rate of 4% and then project interest rates to fall by almost half by end of century (Groom and Newell-Pizer; Extended Data Fig. 1b). Unlike for the Ramsey discount rates, we assume these market discount rates are the same across bootstrap–RCP–GCM–SSP combinations, and just vary over time as shown in the plot.

For each bootstrap–RCP–GCM–SSP combination, each of these fourteen discount rates (six Ramsey with global average income, three Ramsey with rich/poor differences, two market-based, and fixed rates of 2.5%, 3% and 5%) are calculated for each and used in equation (10) to calculate the present value (in 2010) of the damages from warming.

Step (6). Calculate percentage or absolute damages at 1.5 °C versus 2 °C. To calculate relative damages at 1.5 °C versus 2 °C for a given bootstrap–RCP–SSP combination, we take estimates of percentage impacts $\Psi_{it}^{jsm\kappa}$ or discounted absolute impacts $\Theta_i^{jsm\kappa}$ across GCMs and fit a linear least-squares regression that relates estimated damages to the amount of global warming projected by the climate model by the end of the projection period (ΔT^{sm}). So for absolute damages in a given country, this regression is:

$$\Theta_i^{jsm\kappa} = \beta_i^{js\kappa}\Delta T^{sm} + \varepsilon_i \tag{14}$$

This relation is shown to be well approximated at the global level by a linear model (Fig. 1e–g). The slope of the linear fit $\beta_i^{js\kappa}$ is that bootstrap's estimate of the per-degree-Celsius impact of global temperature change on GDP per capita in country *i*. Halving this value thus gives us the impact of a half-degree change in global temperature for a given bootstrap, which, given linearity, is the estimated impact of limiting global warming to 1.5 °C relative to 2.0 °C in that country. Equation (14) is then re-estimated for each country and for each bootstrap, generating 1,000 estimates of impacts in each country for each RCP and SSP combination. We also estimate equation (14) at the global level to generate comparable results on percentage and absolute damages to global GDP. Global results are shown in Figs. 1 and 2, and country-level results are shown in Fig. 3a and b.

Step (7). Calculate probability of economic benefits of limiting warming to 1.5 °C versus 2 °C. Finally, we calculate the probability of economic gain under the 1.5 °C versus 2 °C scenarios—that is, the probability that damages from 1.5 °C of global warming will be smaller than damages from 2 °C of global warming—as the fraction of estimates of $\beta^{js\kappa}$ across 1,000 bootstrap runs that are negative. This is calculated for the world as a whole, as well as separately for each country (Fig. 3c and d).

Quantifying impacts of global warming beyond 2 °C. Recent estimates suggest that countries' current mitigation commitments (NDCs) are unlikely to limit global warming to 2 °C and are instead more likely to be consistent with warming in a 2.5–3 °C range[7]. To evaluate the impact of warming under these alternative warming outcomes, as well as for warming that exceeds 3 °C, we recalculate estimates of $\Psi_t^{jsm\kappa}$ and $\Theta^{jsm\kappa}$ across all RCPs *s* and for all SSPs κ. This provides estimates of the global impact of various warming scenarios relative to a no-warming counterfactual.

As shown in Fig. 4 and Extended Data Fig. 6, impacts are larger at higher levels of warming, with estimates suggesting that if current NDCs are achieved, global GDP could be 15%–25% lower by the end of the century as compared to a world that did not warm. Impacts for warming beyond 3 °C are even larger, but decline less steeply at the highest levels of warming (consistent with ref. [4]). This is because for hot countries that are substantially harmed by high levels of warming, GDP levels are bounded below by zero, whereas for cold countries that are substantially benefited by future warming, GDP levels can grow unbounded.

Quantifying sources of uncertainty in overall impacts of global warming. Our impact estimates (for example, on discounted global world product $\Theta^{jsm\kappa}$ from equation (10) above) are derived by combining historical regression results, future climate change projections from climate models, assumptions on baseline future growth rates from SSPs, and discount rates. Each of these has associated uncertainty, which we propagate throughout the analysis. In particular, total uncertainty in the impact of warming on global GDP under a given forcing scenario is a combination of uncertainty in how economies respond to warming (what we term 'historical regression uncertainty'), uncertainty across climate models in the amount and pattern of warming for a given level of forcing ('climate model uncertainty'), uncertainty in baseline future growth rates across SSPs ('SSP uncertainty'), and plausible alternatives for how to specify the discount rate ('discount rate uncertainty'). To quantify the relative contribution of each to overall impact uncertainty under a given level of forcing (RCP), we hold three out of four variables fixed and allow the fourth to vary. Variables are fixed as follows: historical regression uncertainty is fixed at the regression point estimate, discount rates are fixed at 3%, the SSP is fixed at the SSP providing the median impact estimate (typically SSP3), and the climate model projection is fixed at the model giving the median global warming projection for either mid-century or the end of the century.

Results for discounted cumulative global GDP loss due to warming are shown in Fig. 4b–d. For both 2049 (RCP4.5) and 2099 (RCP2.6), historical regression uncertainty—that is, uncertainty in how economies have responded to warming in the recent past—is the dominant source of uncertainty in overall impact projections for a given forcing level, followed by uncertainty due to alternative possible specifications of the discount rate. For instance, holding all other sources of uncertainty fixed for the end of the century, historical regression uncertainty alone leads to a 95% confidence interval of impact estimates of −US$122 trillion to

US$32 trillion, discount rate uncertainty to a 95% confidence interval of −US$375 trillion to −US$25 trillion, and climate model uncertainty to a 95% confidence interval of −US$78 trillion to US$4 trillion. Thus the overall uncertainty in impacts induced by uncertainty in economic parameters is around 2–4 times higher than that resulting from climate model uncertainty.

There are multiple caveats to this analysis, including that historical uncertainty would be larger if regression models with additional lags were also included, and that discount rate uncertainty could be understated if our 14 alternative discounting approaches do not span the range of 'plausible' discount rates.

While further constraining the range of plausible discount rates is perhaps challenging, not least owing to ethical considerations central to the choice of social-welfare-based discount rates[33], reducing uncertainty around how economies will respond to warming could be more tractable. Promising avenues could include detailed empirically based bottom-up assessments of climate impacts at the country level[23], leveraging existing sub-national or firm (company)-level data to estimate impacts[15,17], or using new fine-scale remote-sensing-based estimates of economic output to greatly increase the temporal and spatial specificity of outcome measurements[39,40].

Data availability. All data and code that support the findings of this study are available at https://purl.stanford.edu/vn535jm8926.

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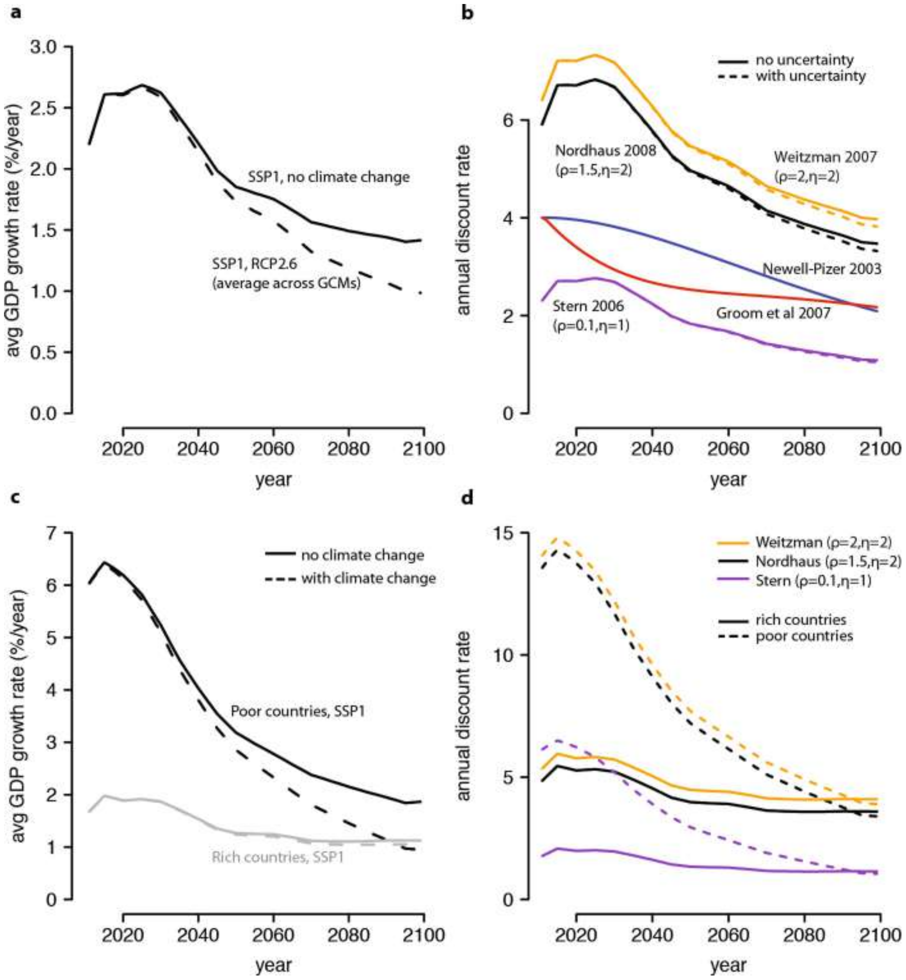
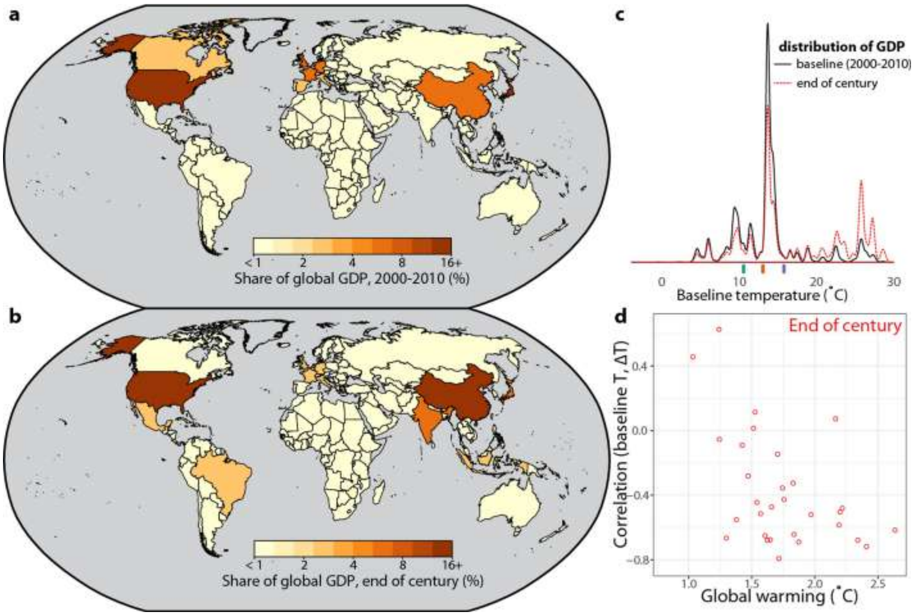
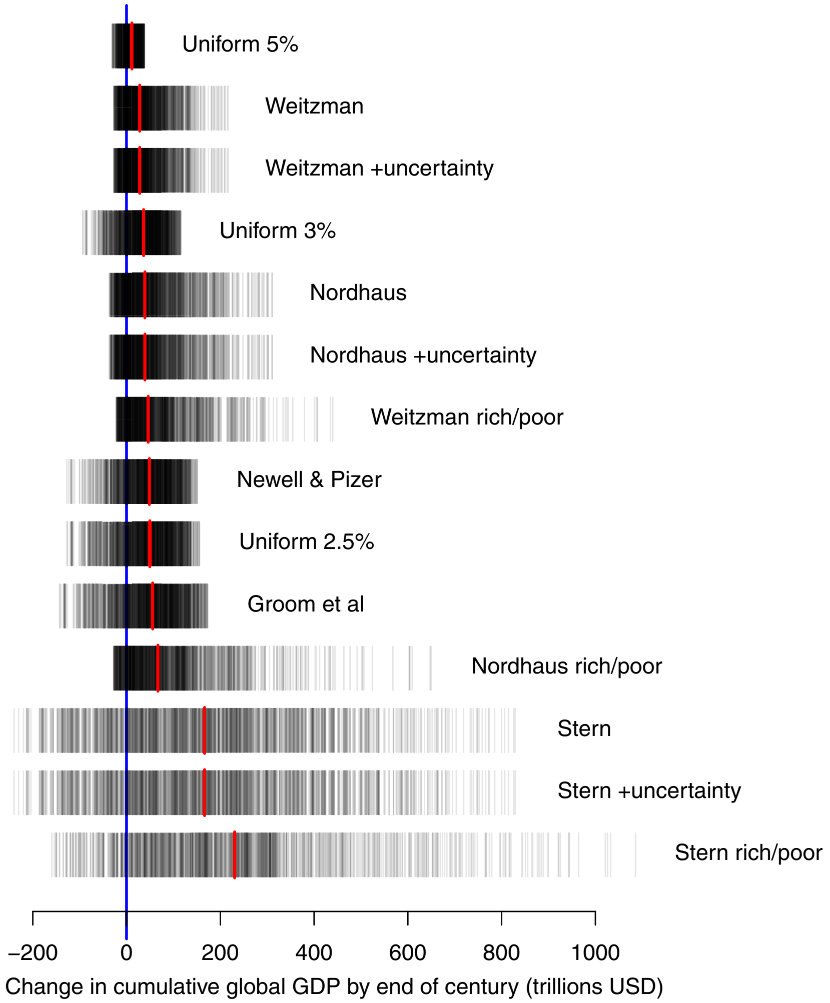


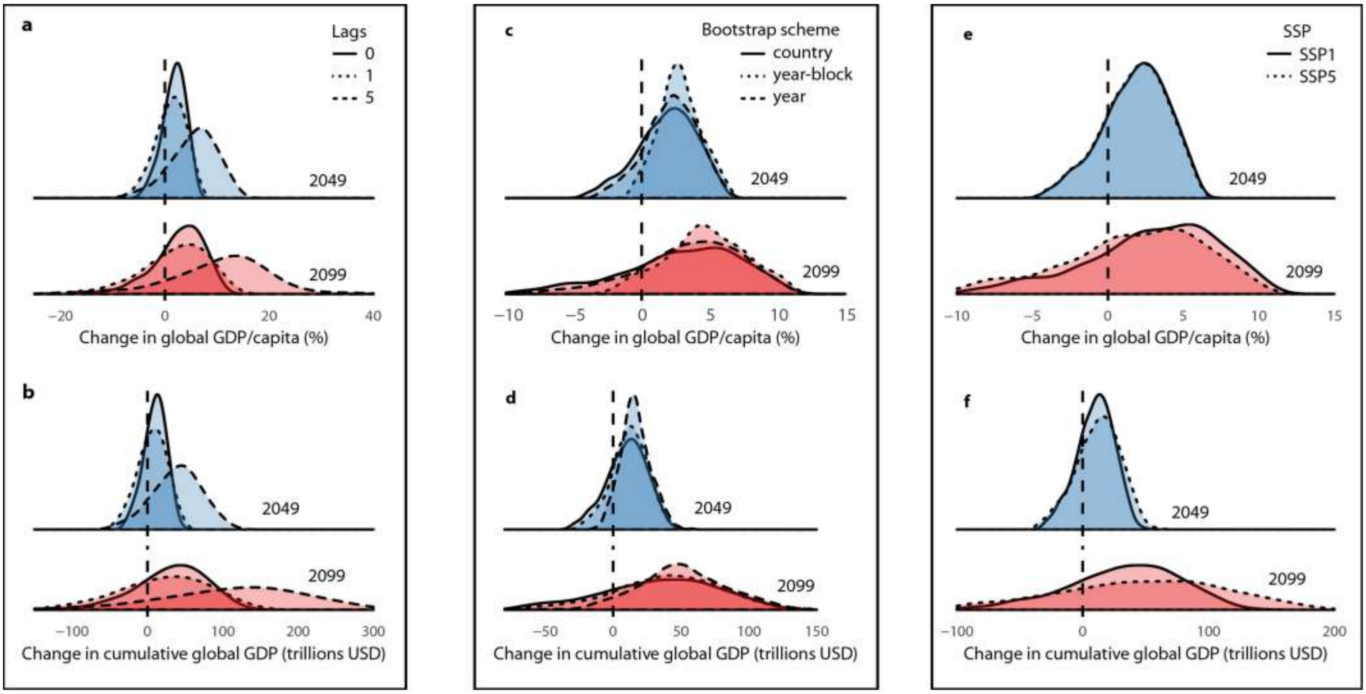
Extended Data Fig. 1 | Discount rate scenarios used in calculation of cumulative discounted impacts of future warming. a, Projected global average annual growth rates under SSP1 with and without climate change; estimates are averaged across bootstraps and climate models. Projected growth rates with climate change are used to define future consumption growth in Ramsey-based discount rates. **b**, Evolution of discount rates under different schemes through 2099. Ramsey-based schemes are Stern[30], Weitzman[31] and Nordhaus[32], with corresponding assumptions about the pure rate of time discount ρ and the elasticity of marginal utility of consumption η shown in parentheses. Dashed lines are versions of these Ramsey-based discounting schemes that account for growth-rate uncertainty. Non-Ramsey schemes are Newell and Pizer[35] and Groom[36]. **c**, Projected average annual growth rates separately for rich and poor countries under SSP1, with and without climate change. **d**, Corresponding Ramsey-based discount rates calculated separately for rich and poor countries, using income-specific growth rates from **c**.



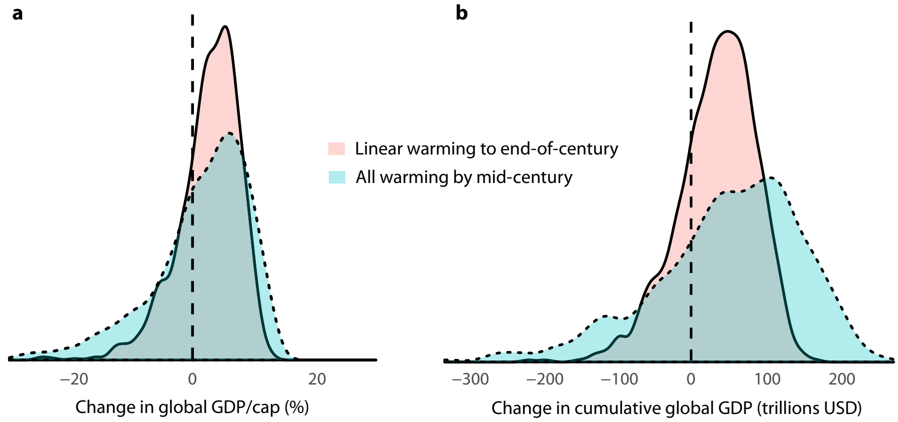
Extended Data Fig. 2 | Global GDP impacts can be negative at +1 °C but positive at +2 °C for some high-temperature-optimum bootstrap runs. **a**, **b**, Country share of global GDP at baseline (**a**) and by the end of the century (**b**) under SSP1, assuming no climate change. **c**, Distribution of global GDP by temperature, under baseline (black) and the end of the century SSP1 without climate change (red dashed); absent climate change, a substantial portion of global GDP is projected to be produced in countries with hotter average temperatures. **d**, Climate-model-predicted average global warming under RCP2.6 by the end of the century (*x* axis) versus the correlation between country-level baseline average temperature and country-level predicted warming in each model. In models that warm less at the global scale, countries that are currently warm tend to exhibit relatively larger warming, while in models that warm more at the global scale, countries that are currently cool tend to exhibit relatively larger warming. Future impacts on global GDP are a sum of country-specific impacts, which are a function of where each country is on the temperature response function (Fig. 1a) and the projected amount of future warming in that country; a given percentage impact in a country with a large GDP has a larger effect on global GDP than the same percentage impact in a country with small GDP. For high-temperature-optimum response functions (for example, Fig. 1g), impacts can be negative at +1 °C but positive at +2 °C because (i) absent climate change, a much larger proportion of total global GDP is projected by SSP1 to be produced in countries that are currently warmer than the optimum, and (ii) climate models with lower overall global warming projections under RCP2.6 tend to have higher relative warming in countries that are currently warm. This generates negative impacts at about 1 °C, where impacts are dominated by negative effects in warm countries (largely in the developing world), but positive impacts at about 2 °C, where high-latitude countries instead warm disproportionately and experience benefits that outweigh the damages in tropical countries.



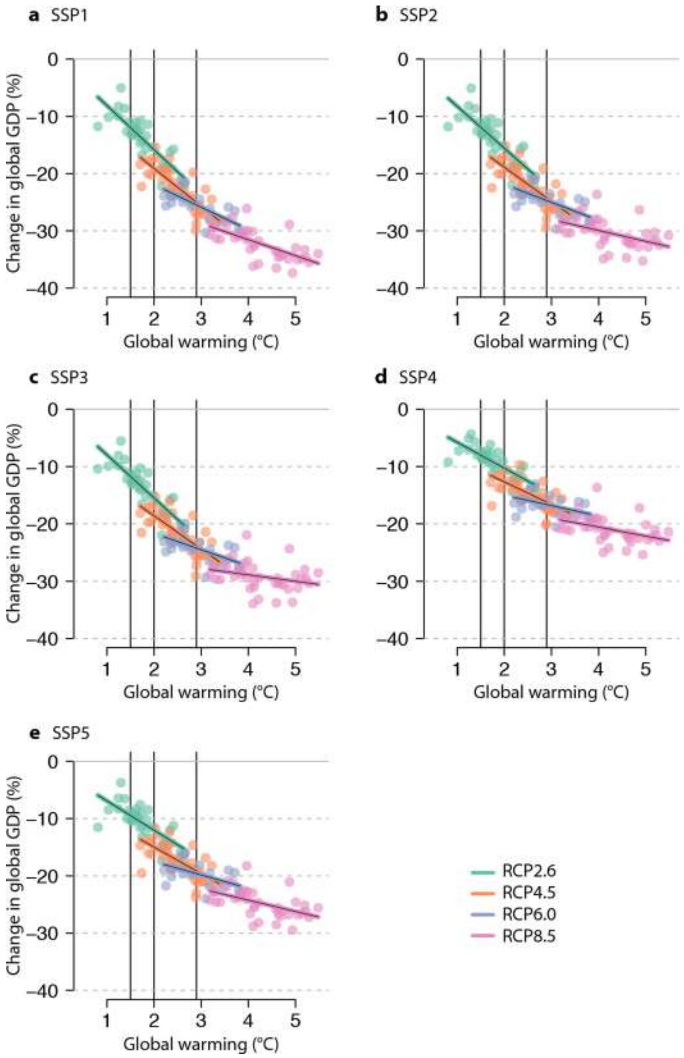
Extended Data Fig. 3 | Change in cumulative global GDP under 1.5 °C versus 2 °C global warming by the end of the century under different discounting schemes. Positive values indicate benefits (reduced losses) at 1.5 °C versus 2 °C. Each vertical line corresponds to a bootstrap estimate of benefits under each discounting scheme[30–32,35,36]. Red lines indicate median across bootstraps for each discounting scheme. Uniform schemes correspond to those in Extended Data Table 1; other schemes are described in Methods.



Extended Data Fig. 4 | Robustness of results to alternative specifications. Change in global GDP per capita in 2049 and 2099 based on regression models that include 0, 1 or 5 lags (**a** and **b**); bootstrap schemes that sample by country, five-year block or single year (**c** and **d**); or alternative SSPs (**e** and **f**). Top panels show percentage changes in global GDP per capita under 1.5 °C versus 2 °C; the bottom panels show change in cumulative global GDP in US$ trillions under a 3% discount rate.



Extended Data Fig. 5 | Robustness under alternative warming paths. Benefit—in terms of per capita GDP (**a**) and cumulative GDP (**b**)—of 1.5 °C versus 2 °C by end of century under the baseline assumption that overall projected warming occurs linearly between the baseline year and 2099 (pink), versus projected benefit assuming that all projected warming occurs by 2049 and temperatures remain constant thereafter (blue). Both scenarios have the same projected global warming by the end of the century. For the same level of overall warming by the end of the century, scenarios with rapid initial warming worsen the overall impacts of climate change and increase the cumulative benefits of limiting warming to 1.5 °C versus 2 °C.



Extended Data Fig. 6 | Projected change in global GDP (%) under global warming by the end of the century, for each SSP. Panels **a**–**e** show the change in GDP for different climate models under different RCP forcing scenarios, relative to a no-warming baseline (median bootstrap) for SSPs 1–5, respectively. Results are as in Fig. 4a, but for each SSP. Each dot represents an RCP-climate model projected change in global GDP under a given SSP; colours represent the four RCPs. Lines are least-squares fits to the points corresponding to the different RCPs with matching colour scheme. The three vertical black lines denote the 1.5 °C target, the 2 °C target and the median-estimated warming expected under current Paris commitments (2.9 °C)[7]. Warming is relative to pre-industrial levels.

Extended Data Table 1 | Change in cumulative global GDP (in US$ trillions) under 1.5 °C versus 2 °C global warming by the end of the century under different discounting schemes

discount scheme	1%	5%	10%	25%	50%	75%	90%	95%	99%
Uniform 5%	-31	-18	-11	0	11	21	29	33	40
Weitzman	-29	-17	-12	4	28	65	112	144	217
Weitzman +uncertainty	-29	-17	-12	4	28	65	112	144	217
Uniform 3%	-95	-54	-32	3	36	65	88	101	119
Nordhaus	-39	-23	-16	5	39	91	160	206	312
Nordhaus +uncertainty	-39	-23	-16	5	39	91	160	206	313
Weitzman rich/poor	-22	-14	-6	11	46	96	176	244	442
Newell & Pizer	-130	-72	-43	5	49	86	115	132	156
Uniform 2.5%	-129	-73	-43	5	50	87	118	136	161
Groom et al	-145	-81	-48	5	56	98	132	151	179
Nordhaus rich/poor	-28	-17	-7	17	67	140	257	360	657
Stern	-240	-136	-88	24	166	336	515	618	840
Stern +uncertainty	-240	-136	-88	24	166	336	515	619	841
Stern rich/poor	-171	-99	-38	71	231	414	623	740	1091

Values show estimated impacts at different quantiles of the estimated impact distribution for each discounting scheme (uniform schemes[37], Weitzman[31], Nordhaus[32], Newell and Pizer[35], Groom[36] and Stern[30]), and correspond to estimates shown in Extended Data Fig. 3. Positive values indicate benefits (reduced losses) at 1.5 °C versus 2 °C.

Extended Data Table 2 | Probability that limiting global warming to 1.5 °C will generate benefits relative to 2 °C warming

%Δglobal GDP/capita by mid-century		
benefit threshold	RCP4.5	RCP6.0
0%	0.80	0.73
1.25%	0.63	0.53
2.50%	0.42	0.31
3.75%	0.21	0.13
5.00%	0.07	0.03

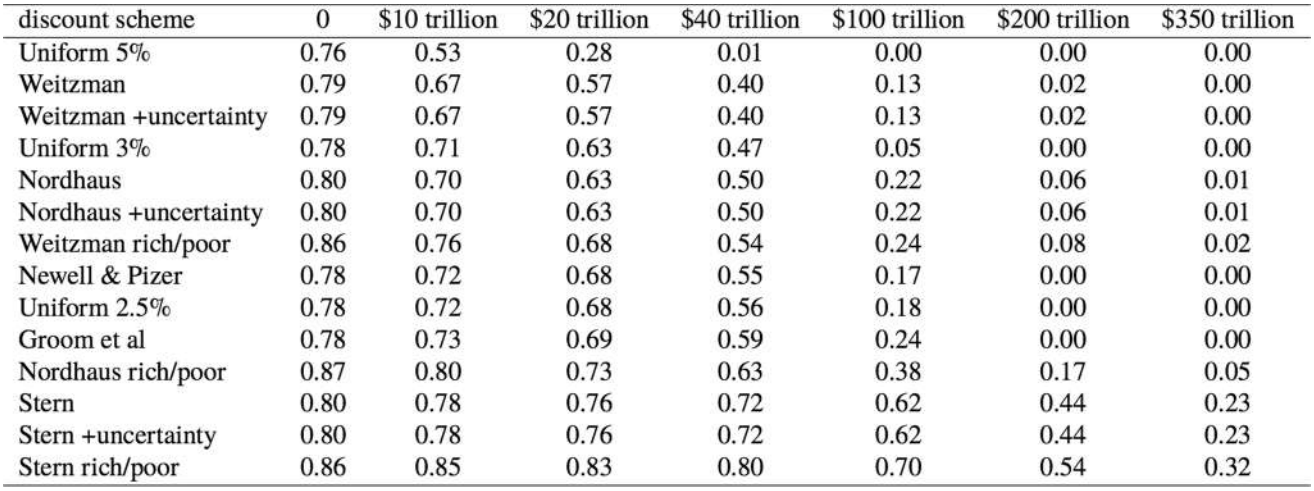
Cumulative Δglobal GDP by mid-century						
	RCP4.5			RCP6.0		
benefit threshold	2.5%	3.0%	5.0%	2.5%	3.0%	5.0%
0	0.76	0.76	0.75	0.69	0.68	0.68
$10 trillion	0.56	0.53	0.32	0.47	0.43	0.23
$20 trillion	0.33	0.27	0.03	0.24	0.18	0.01
$30 trillion	0.14	0.08	0.00	0.08	0.04	0.00
$40 trillion	0.04	0.01	0.00	0.01	0.00	0.00

%Δglobal GDP/capita by end-of-century	
benefit threshold	RCP2.6
0%	0.76
2%	0.62
4%	0.45
6%	0.27
8%	0.12
10%	0.03

Cumulative Δglobal GDP by end-of-century			
	RCP2.6		
benefit threshold	2.5%	3.0%	5.0%
0	0.78	0.78	0.76
$10 trillion	0.72	0.71	0.53
$20 trillion	0.68	0.63	0.28
$50 trillion	0.50	0.38	0.00
$100 trillion	0.18	0.05	0.00
$150 trillion	0.02	0.00	0.00

Left panels show benefits in terms of percentage change in global GDP per capita by mid-century and the end of the century. For instance, by mid-century under RCP4.5 there is a 42% probability of benefits exceeding 2.5% of global GDP per cap. Right panels show benefits in terms of cumulative change in global GDP by mid-century and the end of the century, under three different discount rates for each relevant RCP. For instance, by the end of the century, there is a 50% probability of benefits exceeding US$50 trillion using a discount rate of 2.5%.

Extended Data Table 3 | Probability that limiting global warming to 1.5 °C will generate different levels of benefits relative to 2.0 °C warming, under different discounting schemes



discount scheme	0	$10 trillion	$20 trillion	$40 trillion	$100 trillion	$200 trillion	$350 trillion
Uniform 5%	0.76	0.53	0.28	0.01	0.00	0.00	0.00
Weitzman	0.79	0.67	0.57	0.40	0.13	0.02	0.00
Weitzman +uncertainty	0.79	0.67	0.57	0.40	0.13	0.02	0.00
Uniform 3%	0.78	0.71	0.63	0.47	0.05	0.00	0.00
Nordhaus	0.80	0.70	0.63	0.50	0.22	0.06	0.01
Nordhaus +uncertainty	0.80	0.70	0.63	0.50	0.22	0.06	0.01
Weitzman rich/poor	0.86	0.76	0.68	0.54	0.24	0.08	0.02
Newell & Pizer	0.78	0.72	0.68	0.55	0.17	0.00	0.00
Uniform 2.5%	0.78	0.72	0.68	0.56	0.18	0.00	0.00
Groom et al	0.78	0.73	0.69	0.59	0.24	0.00	0.00
Nordhaus rich/poor	0.87	0.80	0.73	0.63	0.38	0.17	0.05
Stern	0.80	0.78	0.76	0.72	0.62	0.44	0.23
Stern +uncertainty	0.80	0.78	0.76	0.72	0.62	0.44	0.23
Stern rich/poor	0.86	0.85	0.83	0.80	0.70	0.54	0.32

Benefits are in terms of cumulative change in global GDP by the end of the century (RCP2.6). Discounting schemes are: uniform schemes[37], Weitzman[31], Nordhaus[32], Newell and Pizer[35], Groom[36] and Stern[30]).