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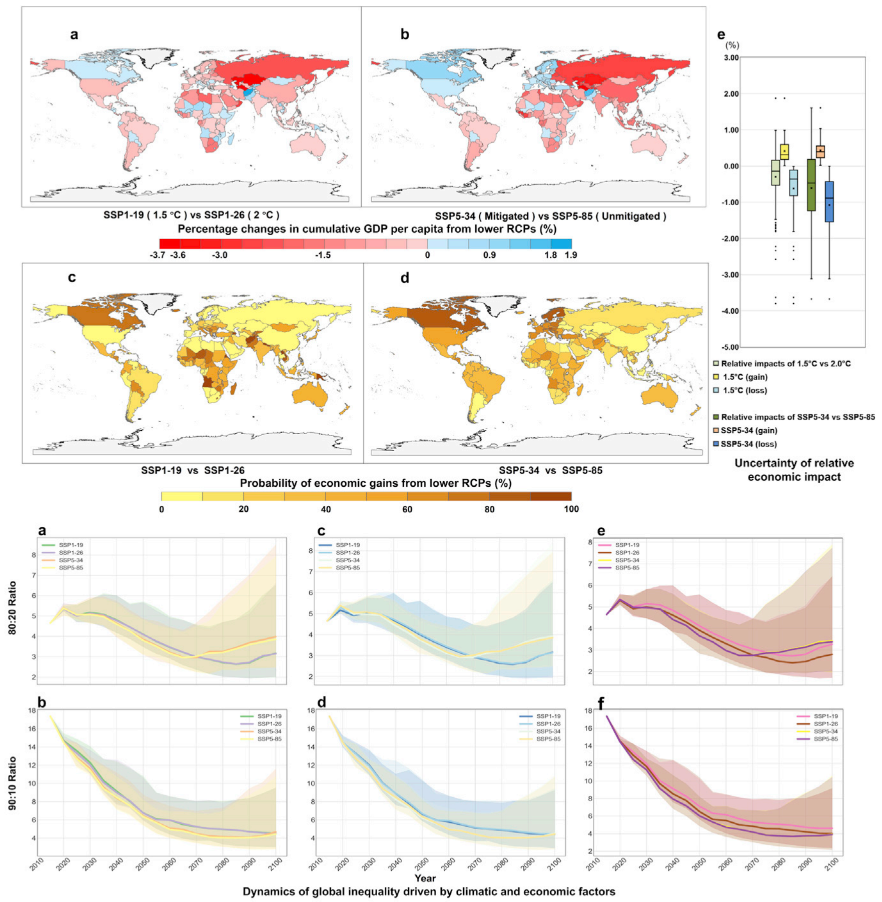

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Highlights

Benefits of avoiding climate damage may outweigh cost impacts later in the century

Pursuing 1.5°C goal could improve global inequality compared to 2°C in the long run

Vulnerable countries such as Laos could benefit from 1.5°C even earlier

Rapid economic growth leads to inequalities decrease but start to rise after 2065

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Mitigating climate change to alleviate economic inequality under the Paris Agreement

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SUMMARY

Understanding the implications of global climate governance is critical for achieving sustainable economic development, given that the economic impacts of climate change and policies are disproportionately distributed across regions. We estimate the updated damage functions and construct an uncertainty analysis framework to assess whether stringent climate policies entail economic benefits in terms of growth and inequality. The findings show that although climate policies slow the pace of economic growth, the benefits of avoided damage may overweight policy costs in the long run. Moreover, pursuing the 1.5°C goal slows economic catch-up of poor countries in the short to medium term relative to 2°C, but improves global inequality in the long run. This situation may, however, change when moving to a fast-growing and fossil-fueled world, in which inequalities gradually decline but start to rise after 2065. This study highlights the importance of synergizing the stringent 1.5°C goal with economic inequality alleviation.

INTRODUCTION

Mitigating global warming is of great importance to sustainable development of natural ecosystems and socio-economic systems. As the world's most complex environmental problem resulting in the largest externality,[1] climate change has a broad and profound impacts, leading to more frequent extreme weather events and increasing potential health risks.[2–4] Between 1998 and 2017, the direct economic loss caused by natural disasters in the world exceeded 2.9 trillion US dollars, among which the loss caused by climate-related disasters accounted for 77%.[5] Notably, many developing countries, especially the poor, are located in tropical areas,[6,7] such as countries in Africa and Southeast Asia, which are more exposed to extreme weather events like drought and flood.[8] Further, global warming proves to increase the risk of cross-species transmission of viruses,[9] and leads to emergence of zoonotic diseases and serious threats to human health, such as COVID-19, Ebola and Dengue.[10] Most importantly, the impact of climate change could be imbalanced across territories, and this may in turn affect global economic inequality.[11–14]

Quantifying the potential impacts of climate change is critical for planning appropriate climate policies.[15] The Paris Agreement aims to keep global warming below 1.5°C or 2°C above pre-industrial levels, the Nationally Determined Contributions (NDCs) imply warming of 2.5–3°C,[16] and the policy goals for radiative forcing peaks and net zero or negative emissions are instead consistent with about 2–2.5°C of global warming according to projections in Shared Socioeconomic Pathways (SSP) database. More stringent temperature targets imply higher mitigation costs,[17] therefore, understanding the impacts of mitigation burdens and the potential benefits of avoided damages are critical for evaluating the role of stringent climate policies in economic benefits in terms of growth and inequality.[18,19] In particular, the potential and uncertain impacts of warming limits need to be quantified on multiple levels to guide coordinated global policies and promote national mitigation actions.[20,21] In particular, some developing countries with fast-growing economies need to make increasingly ambitious mitigation and adaptation efforts.

We empirically estimate the climate and economic growth nexus from 147 countries over the period of 1961–2017 by accounting for differences between historical and future climate damages, providing updated econometrics-based damage functions. On this basis, we project the potential impacts of warming limits ranging from strict to lenient, taking into account both mitigation costs and climate damages. In addition, we build an uncertainty analysis framework, incorporating four dimensions: Representative warming scenarios, climate damage functions, policy costs, and the mitigation burden effect on economic growth, to explore future climate-economic linkages. We then assess the climate policy actions in terms

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of three typical economic dimensions: (1) The impact of climate damages on economic growth; (2) the economic cost of different policy efforts to mitigation and the benefits deriving from the avoided damage, and (3) their impacts on cross-national inequality.

Our results provide new insights to global climate governance under the Paris Agreement. The findings highlight that the benefits of avoided damage may overweight cost impact by the end of this century, although climate policies slow the pace of economic growth. Moreover, as compared to the 2°C goal, pursuing the 1.5°C goal may slow economic catch-up of poor countries in the short to medium term, but improves global economic inequality in the long run, especially in the second half of this century. This situation may change when moving to a fast-growing and fossil-powered world, inequalities will gradually decline then begin to rise after 2065, because the disproportionate impact of climate damages gradually outweighs the expected convergence of economic growth between poor and rich countries,[22] and climate policies further exacerbate global inequality by burdening the poor around the world.

RESULTS

Estimated climate-economic response

We first estimate the short-term effects of annual weather changes on economic growth using balanced panel datasets. Recent literature indicates that temperature variable enter in first difference or as deviation from the long-run means to better control for its trending nature.[23,24] Given this, our empirical strategy includes temperature change ($\Delta T_{i,t}$) and its interaction ($T_{i,t} \times \Delta T_{i,t}$), which are our variables of interest. In variants (3)-(6) of Table 1, we find that when temperature changes are included, temperature levels ($T_{i,t}$ and $T_{i,t}^2$) are not significant, but its interaction ($T_{i,t} \times \Delta T_{i,t}$) is significantly negative at the 1% level. This implies that an extra 1°C warming ($\Delta T_{i,t} = 1$) gradually decreases economic growth as $T_{i,t}$ increase (see Figure 1). Further, our findings show that an additional 1°C significantly increases GDP by 0.61–0.97% in countries with cold climate (T = 1°C), however, decreases GDP by 1.15–1.92% in countries with hot climate (T = 30°C). In addition, we include the rate of temperature change ($\Delta Tr_{i,t}$) into the specifications, which reflects the speed of temperature change. The results show that for the same amount of warming ($\Delta T_{i,t}$), the faster the temperature rises, the slightly lower the economic growth. The findings are still robust for different periods and country sizes (Table S2). For the nonlinear variants (2)–(6), the findings show that global productivity peaks when the average annual temperature is between 8.73°C and 12.87°C. We find no evidence that precipitation affect economic growth.

It has been observed that hot countries tend to be poor,[7] which could be explained by some historical reasons, such as colonialism or dependency from richer countries. In addition, poorer countries tend to grow faster than the richer because of convergence of economic growth among countries.[22] To better identify the effect of warming on economic growth, we control for potential confounders in the baseline specification (variant (3) of Table 1), such as whether country *i* is poor or hot (below-median PPP-adjusted per capita GDP/above-median annual average temperature in the first year), and whether it was once a colony, as well as the interaction term $T_{i,t} \times \Delta T_{i,t}$ (Table S1). Our results show that, under the same climate condition, an extra 1°C warming has greater adverse effects on poor/colonized countries than the rich/non-colonial countries (Figures 1A and 1B). Overall, hot countries, also the poor, are more sensitive to temperature change, compared to cold countries (Figures 1A–1D). Our results are robust for estimates of different periods and country sizes (Figures 1E–1H). Further, we estimate the lagged effect of temperature changes on growth (Table S3), finding that countries with hot or cold weather are significantly affected by temperature changes only with 0–2 lags (Figures 1I–1N). It implies that the lagged effects comprise up to at most three years and then become weaker.

Further, we explore the long-term effects of climate change on economic growth. Climate variables are defined as deviations of temperature and precipitation in terms of moving averages of at least the last 30 years (see STAR Methods for details).[23] The results are shown graphically in Figures 1O–1R. Overall, deviations of 1°C from the historical norm significantly reduce GDP by 1.03–2.93% in countries with hot climate (T = 30°C) (Table S4). These effects are somewhat larger than estimates of the short-term weather effects (1.15–1.92%, Table 1). This may because that the multi-decade moving average better captures short-term weather deviations from long-term climate norms. Although our estimates may overestimate climate damage, owing to the neglected role of long-term adaptation in economic growths, it is unlikely to offset them entirely.[23]

Table 1. The short-term effects of annual weather changes on growth

Dep. Var.: $\Delta lnGDP$	(1)	(2)	(3)	(4)	(5)	(6)
ΔT			0.0105***	0.00694***	0.00751***	0.00984***
			(0.0024)	(0.002095)	(0.0026)	(0.003097)
$T \times \Delta T$			−0.000816***	−0.000795***	−0.000634***	−0.000971***
			(0.0002)	(0.000166)	(0.0002)	(0.000234)
ΔT r			−0.0000319*	−0.0000326*	−0.0000307*	−0.0000314*
			(0.000017)	(0.000017)	(0.000017)	(0.000017)
T	−0.0052**	0.0089***	−0.0032	−0.0031	0.0025	0.0028
	(0.0022)	(0.0031)	(0.0021)	(0.0021)	(0.0041)	(0.0041)
$T2$		−0.0005***			−0.0002	−0.0002
		(0.0001)			(0.0001)	(0.0001)
ΔP			−0.0003	−0.0007	−0.0010	0.0001
			(0.0007)	(0.0008)	(0.0009)	(0.0010)
$P \times \Delta P$			0.0000	0.0000	0.0001	−0.0000
			(0.0000)	(0.0000)	(0.0000)	(0.0000)
Observations	5016	5016	4826	4826	4826	4826
Period	1961–2017	1961–2017	1961–2017	1961–2017	1961–2017	1961–2017
No. Countries	88	88	88	88	88	88
Fixed effects	Country,Year	Country, Year	Country, Year	Country, Year	Country, Year	Country, Year
Weather (T, P)	Contempo-raneous	Contempo-raneous	Contempo-raneous	Lagged	Contempo-raneous	Lagged
P controls	Linear	Squared	Linear	Linear	Squared	Squared
Time trend	Squared	Squared	Squared	Squared	Squared	Squared
BIC	−17033	−17028.4	−16495.8	−16494.5	−16482.7	−16481.8
T_{peak} (°C)		9.86	12.87	8.73	11.85	10.13
ME at 1°C		0.0080***	0.0097***	0.0061***	0.0069***	0.0089***
S.E.		(0.0029)	(0.0023)	(0.0020)	(0.0025)	(0.0029)
ME at 30°C		−0.0182***	−0.0139***	−0.0168***	−0.0115***	−0.0192***
S.E.		(0.0047)	(0.0032)	(0.0040)	(0.0033)	(0.0048)

Note: Comparing the nonlinear variants of columns (3)-(6), column (3) presents a stronger fit (a lower Bayesian Information Criterion (BIC) value), and it strikes a balance between allowing non-linearity while limiting over-fitting. Therefore, we consider variant (3) as our baseline specification. Standard errors in parentheses and clustered at country level. ***, **, and * mean significance at 1%, 5%, and 10% levels, respectively. M.E. denotes the marginal effect of temperature change ($\Delta T_{i,t}$). In addition, the average annual temperature at which global productivity peaks (T_{peak}) is differently determined for nonlinear specifications (see Equation 13 for details). For variant (2), T_{peak} refers to the $T_{i,t}$ at $M.E. = \partial \Delta Ln(y_{i,t})/\partial T_{i,t} = 0$, i.e., $T_{peak} = -\beta_1/2\beta_2$, as in Burke et al.[11] As for variants (3)-(6), since $T_{i,t}$ doesn't significantly affect growth after including $\Delta T_{i,t}$, the T_{peak} is calculated as the temperature at $M.E. = \partial \Delta Ln(y_{i,t})/\partial \Delta T_{i,t} = 0$ (Kalkuhl and Wenz[25]), i.e., $T_{opt} = -\sum_{m=0}^{L} \alpha_{1,i,m} / \sum_{m=0}^{L} \alpha_{2,i,m}$.

Impacts of warming limits on economic growth

Warming limits would affect inequality through mitigation costs and avoided climate damages, with effects going in opposing directions.[19] Under a certain SSP, achieving climate targets suggests more mitigation costs and less climate damage. We construct an uncertainty analysis framework (See Figure S2 and STAR Methods for details) to assess whether stringent climate policies entail economic gains and which territories will experience benefits. According to the Phase 6 of the Coupled Model Intercomparison Project (CMIP6), we select four representative SSP-RCP scenarios to describe different warming pathways, i.e., SSP1-19 (1.5°C), SSP1-26 (2°C), SSP5-34 (mitigated) and SSP5-85 (unmitigated) (See STAR Methods for details).

At the country level, both the magnitude and the uncertainty of potential benefits are heterogeneous. Although the mitigation cost under the stringent mitigation target reduces national economic growth, 31% of the countries encompassing about 15.77% of projected global population exhibit a >54.17% chance of experiencing economic gains from the more stringent 1.5°C target (SSP1-19) compared to the 2°C target

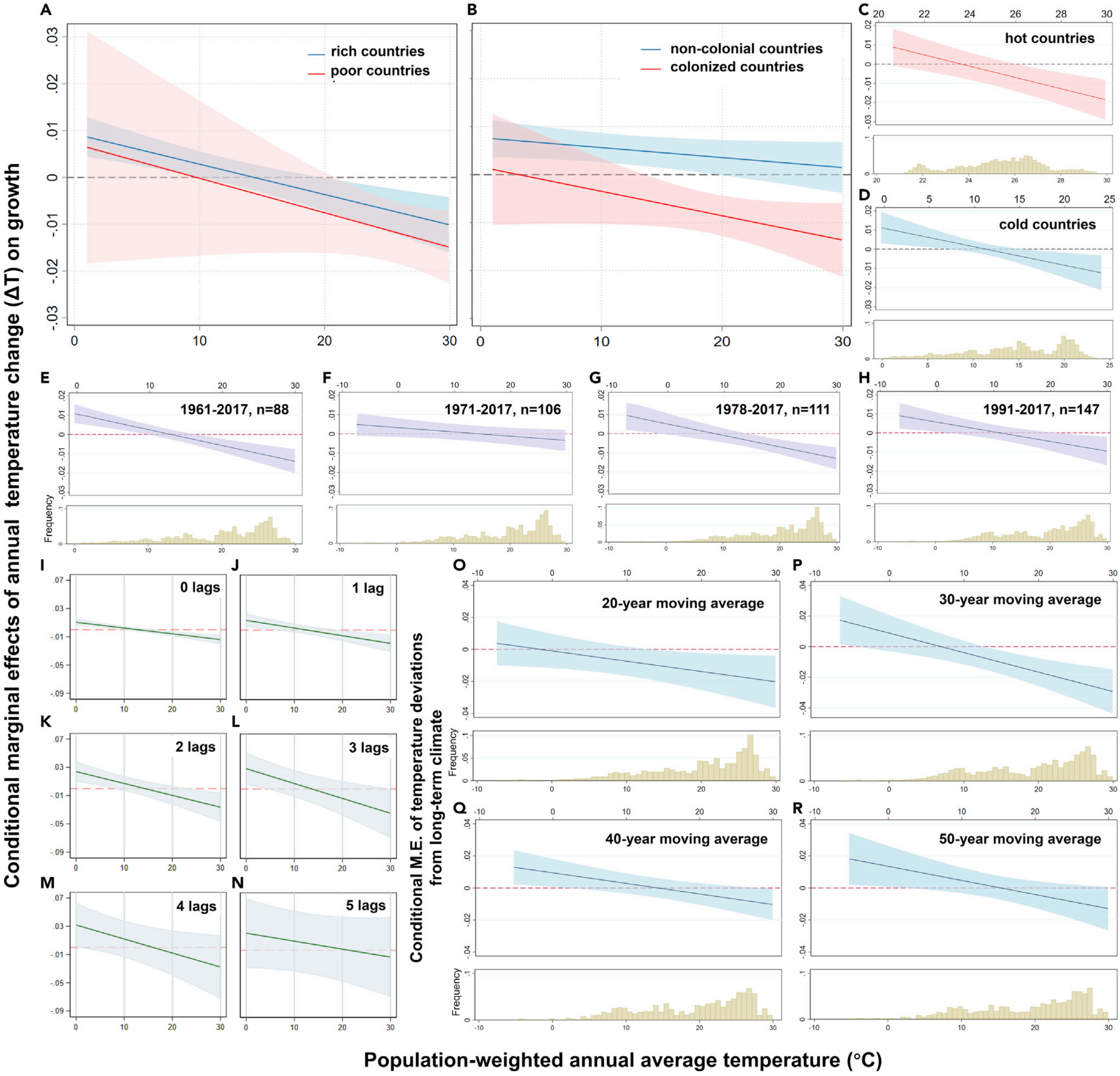

Figure 1. Conditional marginal effect of temperature change on economic growth

(A–D) The effect of annual temperature change on growth in poor/rich, colonized/non-colonial and hot/cold countries.

(E–H) Estimates of temperature-growth linkages across various periods and country scales.

(I–N) The lagged effects of temperature change on economic growth, notably, marginal effects are the cumulative effects over lags.

(O–R) Long-term impacts of climate change on growth. Shaded area represents the 95% confidence interval.

(SSP1-26) (Figures 2A and 2C) (Table S5). These countries are mostly among the poorest in the world and are concentrated in Africa and Asia (e.g., Madagascar, Somalia, Laos and Cambodia), implying that the benefits of avoided climate damage may outweigh the regressive effect of mitigation costs on economic growth.

Further, we find that the median/mean of relative impacts is negative (Figure 2E), suggesting that on average, economic losses occur worldwide. In other words, from the cumulative perspective (2015–2100) (Figures 2A and 2B), a smaller share of countries/populations will benefit from stringent warming limits. Given the discrepancy in historical responsibilities of emissions, developing countries are required to

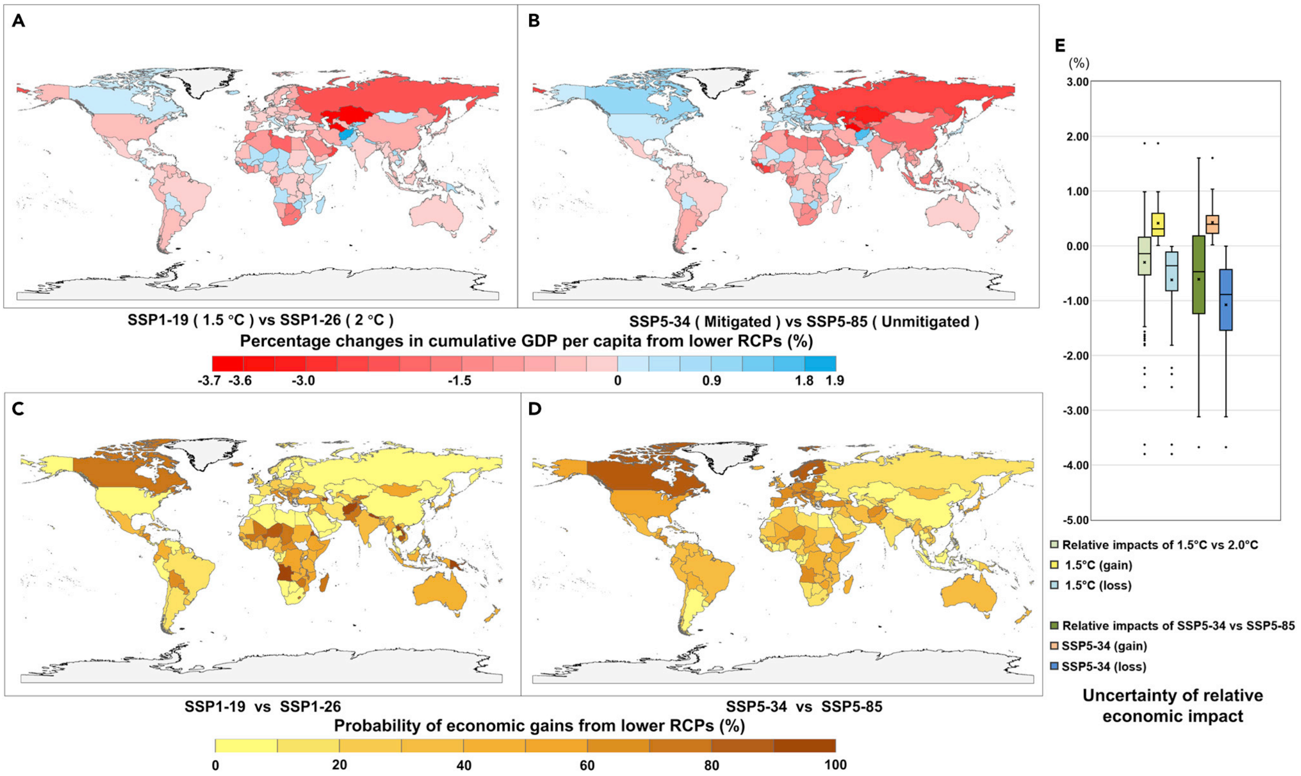

Figure 2. Country-level impact of warming limits in low RCP relative to high RCP

(A and B) Median estimates of relative changes in cumulative GDP per capita at 1.5°C (SSP1-19) compared to 2°C (SSP1-26) (A), and the estimates under mitigated scenario (SSP5-34) versus unmitigated scenario (SSP5-85) (B) during 2015–2100 (discount rate: 3%). Positive and negative values in the legend of A, B indicate economic gains and losses, respectively, in lower RCP.

(C and D) The probability of economic gains from 1.5°C compared to 2°C (C), and this probability from mitigated scenario compared to unmitigated scenario (D). Probability of economic gains is calculated from predictions under the uncertainty analysis.

(E) Median estimates of economic impacts of low RCP versus high RCP across countries. Box-Whisker plot shows the median (line), mean (cross symbol), the first and third quartile (box), and dots indicate outliers.

take a different path from developed countries to tackle global warming. For example, the developing countries may take a green and low-carbon path, which is likely to slow economic growth and then lead to economic losses compared to a fast-growing path, even impose a financial burden for some lagging countries.[26] Notably, the estimated benefits of avoided damage in our study are likely to be the lower bound. This is because that our estimates do not consider potential co-benefits, such as risks to health, loss of biodiversity, and substantial sea-level rise, from which mitigation of global warming could avoid the disproportionate losses, especially for developing countries.[3,27,28]

This story changes in our follow-up analysis when looking at different time scales. The following results indicate that the strict climate policy could boost growth by avoiding significant climate damage in the second half of this century (Figure 3), and global economic inequality will improve in the long term (Figure 4).

Although the Paris Agreement focuses on 1.5 and 2°C targets, the targets of emission peak and carbon neutrality are actually consistent with about 2–2.5°C of global warming, according to projections in SSP database. Specifically, in CMIP6, the SSP5-34 scenario sets global emissions to peak around 2040 and begin to achieve net zero or negative emissions between 2060 and 2070, with a global warming of 2–2.5°C by 2100, we therefore use this scenario for our analysis. The finding shows that 31% of countries encompassing about 28.97% of projected global population exhibit a 50–93.75% chance of experiencing benefits at SSP5-34 (mitigated scenario) relative to SSP5-85 (unmitigated scenario) (Table S5), which are mainly advanced industrialized countries (the USA has a 56.25% chance of positive benefits; Japan 50%; France 62.50%; Germany 62.50%; Canada 87.50%); In contrast, many developing countries are unlikely to benefit from the mitigation scenario (SSP5-34) (China only has a 6.25% chance of economic gains, versus

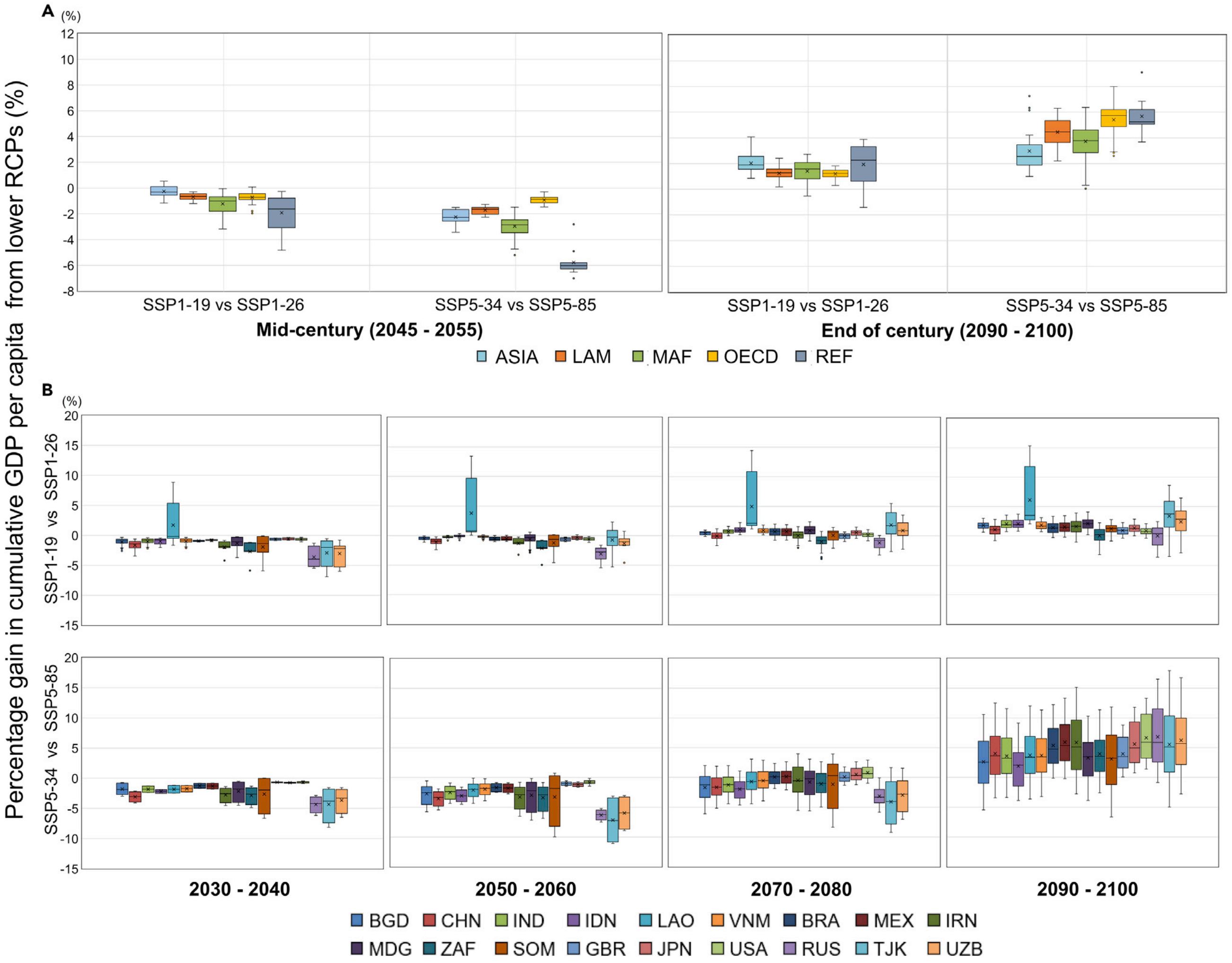

Figure 3. Uncertainty of relative economic impacts in low emission scenario at regional and national levels

(A) Median estimates of relative impacts within regions, for mid-century (2045–2055) and the end of the century (2090–2100).

(B) Relative impacts for representative countries at different periods across all scenarios. Box-Whisker plot shows the median (line), mean (cross symbol), the first and third quartile (box), and dots indicate outliers. The representative countries come from the five regions (see STAR Methods), including five major economies (United States, China, Japan, UK and Russia), seven developing countries (India, Brazil, Mexico, South Africa, Iran, Tajikistan and Uzbekistan), four countries vulnerable to natural disasters (Bangladesh, Laos, Indonesia and Vietnam) and two of the poorest coastal countries in the world (Madagascar and Somalia).

12.5, 12.5 and 37.5% for India, South Africa and Brazil) (Figures 2B and 2D). The finding suggests that, in the fossil-fueled future, developed industrialized countries benefit more from mitigation. This may attribute to the fact that most industrialized countries have peaked their emissions and entered the carbon neutrality channel, which greatly challenges the developing countries at present.

At the regional level, the results show economic losses in low RCP scenario during the mid-century (median estimates across SSPs; Figure 3A). It indicates that, in the short term, the regressive effect of mitigation costs on growth is greater than the benefits of avoided climate damage. Conversely, at the end of this century, the findings show significant economic gains in low RCP (median estimates; Figure 3A), suggesting that the benefits of avoided damage may dominate the costs impact in the long term. Further, we select eighteen representative countries, encompassing 47.96–48.75% of projected global population from five regions, to conduct our analysis. The result shows that during 2030–2060, there are economic losses in these countries when transferring from 2°C (SSP1-26) to 1.5°C (SSP1-19), indicating the substantial mitigation costs required to meet the 1.5°C goal in the early years. However, with one exception, pursuing the 1.5°C goal may help Laos reap substantial benefits from reducing catastrophic floods from the first half

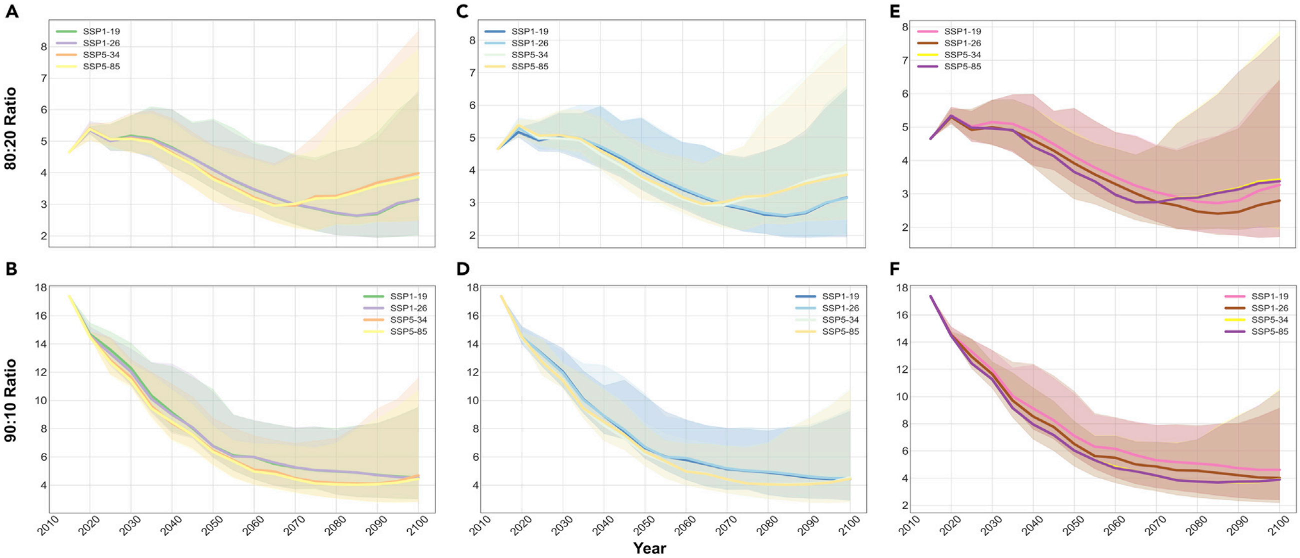

Figure 4. Evolution of inequality trends driven by climatic and economic factors

The inequality indexes (80:20 and 90:10 ratios) evolve over time under three mitigation distribution assumptions, i.e., equivalent burden case (A, B); income-related burden case (C, D); and the case ignoring mitigation efforts and only considering climate factors (E, F). Solid lines represent the median estimates of the inequality indexes in four representative warming scenarios.

of this century.[29] This may be because of the fact that Laos is the least developed country in the world with poor infrastructure, making it difficult to withstand the increasing meteorological disasters associated with global warming above 1.5°C.[30]

Thereafter, most of the representative countries gradually obtain economic gains after 2060 to 2070 (median estimates; Figure 3B). In SSP5, the results show that there are non-negligible economic losses in the mitigated scenario (SSP5-34) compared to the unmitigated scenario (SSP5-85) during 2030–2080 (except for the US, Japan, Brazil and Mexico over 2070–2080); However, from 2080 to 2090, all the representative countries are gradually benefit from SSP5-34 (median estimates; Figure 3B). In general, countries will benefit almost decades earlier from warming limits in SSP1 relative to SSP5. The reason for this may be mitigation costs are likely to be less burdensome for economic growth under the sustainable path (SSP1) than the fossil fuel development path (SSP5), especially for backward countries, which reinforces the result that mitigation would reduce inequalities in a sustainable future. Notably, poor countries vulnerable to natural disasters, such as Laos, could benefit from the more stringent 1.5°C target starting even earlier in the first half of this century.

Impacts of warming limits on inter-country economic inequality

The socioeconomic storylines assume that future economic catch-up between developing and developed countries will reduce global inequality trends.[31] However, climate-driven inequalities still exist.[18] Based on the uncertainty analysis framework, we estimate the evolution of inequality trends over time driven by both climatic and economic factors. Referring to Taconet et al.,[19] we further postulate the differentiated distribution of mitigation efforts within regions in two scenarios, i.e., equivalent burden and income-related burden (see STAR Methods for details). In addition, we re-estimate the inequality trends by combining methods from typical studies of Burke et al.[11] and Kalkuhl and Wenz[25] (only account for climate factors) with our updated data (1961–2017). The 90:10 and 80:20 ratios are chosen to measure income inequality between the top and bottom income deciles (90:10 ratio) and quintiles (80:20 ratio) (see STAR Methods for details),[32] because the situation of the poorest and the richest countries largely contributes to economic inequality.[33]

From the perspective of different radiative forcing scenarios under a specific socioeconomic path, our results show that, in the first half of this century (mainly between 2015 and 2045), global inequality is slightly greater under the 1.5°C policy (SSP1-19) compared to the 2°C policy (SSP1-26) for the equivalent burden scenario (median estimates; Figures 4A and 4B). This situation is similar when moving to the income-related burden scenario during 2015–2040 (90:10 ratio; Figure 4D), despite the median estimate of 80:20 ratio shows that global inequality is consistently smaller at 1.5°C compared to 2°C (Figure 4C). The findings indicate that, in the sustainability path (SSP1), the costs impact on global inequality could slightly larger in 1.5°C compared to 2°C during the first half of the 21st century. Thereafter, in the second half of the century, inequality is likely to improve more under 1.5°C than 2°C, despite a growing uncertainties over time. Our results suggest that the pursuit of 1.5°C goal, as compared to 2°C, may slow economic catch-up of poor countries in the short to medium term, but global inequality will improve in the long run due to disproportionate climate damage avoidance among countries.

When moving to a fossil-fueled development path (SSP5), we find consistent results that global inequality is larger in SSP5-34 than in SSP5-85 (median estimates; Figures 4A–4D). This could be because under the SSP5-34 scenario, the world begins to achieve net-zero or negative emissions between 2060 and 2070. It implies that low emission scenario in the fossil-fueled development path could exacerbate global inequality, beacuse the abatement burden is likely to be heavier for lagging regions/countries than for advanced industrialized countries. The inequality trends calculated by the conventional method (Figures 4E and 4F) are similar to ours, except that global inequality in SSP1-19 is consistently greater than that in SSP1-26 because the classical methods only consider climate factors while ignoring mitigation efforts.

From the perspective of the shared socioeconomic pathways, the median estimates of the 90:10 ratio show less inequality in SSP5 compared to SSP1, and then these estimates tend to be equal at the end of the century. This could attribute to that the low emission path (SSP1) slows down national growth rates worldwide; as a result, the tendency toward convergence is slower than the high emission path (SSP5). It is worth noting that the path of the 80:20 inequality declines in the short to medium run, but starts to grow again after 2065 (2085) in SSP5 (SSP1) in almost all cases. This inter-country economic inequality increases more in SSP5 than in SSP1. It implies that climate damages could gradually undermine the expected convergence across countries, especially in a fast-growing and fossil-driven world. A rapidly developing world will continue to exacerbate global warming, which could lead to disproportionate climate damage and irreversible catastrophe (such as sea level rise flooding island nations). The finding also serves as a warning for underdeveloped regions that are emitting lots of pollutants and not actively taking climate action.

Figure 5 depicts the distribution of per capita GDP levels across countries in 2100, and we find further evidence that global inequality could improve more in 1.5°C compared to 2°C. Projections are based on our baseline specification. The results show that the number of the poorest (richest) countries with GDP per capita below 20 (above 170) (US $1,000) is more in the 2°C scenario compared to that in the 1.5°C scenario (Figures 5A and 5B) in 2100. It implies that income inequality is greater among countries under the 2°C scenario, highlighting the synergy between pursuing the stringent 1.5°C target and economic inequality alleviation. In SSP5, we find that in general GDP per capita is higher in the mitigated scenario than the unmitigated scenario, as shown by fewer poor countries (GDP per capita below 40) and more rich countries (GDP per capita above 200) in SSP5-34 compared to that in SSP5-85 (Figures 5C and 5D). The reason for this is that in the unmitigated scenario with the highest global temperature, an extra 1°C warming would generate heightened economic damages across countries due to the downward-sloping marginal effects of temperature change on growth.

DISCUSSIONS

Differentiated climate policy analysis provides a diverse perspective for research of global climate governance. The typical methods that are used in existing studies, such as Burke et al.,[11] Pretis et al.[21] and Kalkuhl and Wenz,[25] to explore future climate-economic linkages ignore the impact of mitigation costs under climate policies and how climate actions will reduce historically estimated climate damage. These methods were actually used under an strong assumption: diverse climate policies, e.g., those corresponding to achieve the 1.5 and 2°C goals, have the same impact on national economic growth under a specific SSP path (e.g., SSP1-19 and SSP 1–26), and the economic growth only damaged by warming. However, it is costly to reduce emissions toward the 2°C or 1.5°C warming limits, which in turn burdens economic growth. For example, Hof et al.[17] find that the economic cost to reach the 1.5°C goal may be at least 3-fold that of the 2°C goal. In other words, the impact of mitigation cost on economic growth could be much higher when facing a stricter climate goal, especially in the short- and mid-term.

Given this, we construct an uncertainty analysis framework to assess the climate policy actions in terms of three economic dimensions: (1) The impact of climate damages on economic growth; (2) the economic cost

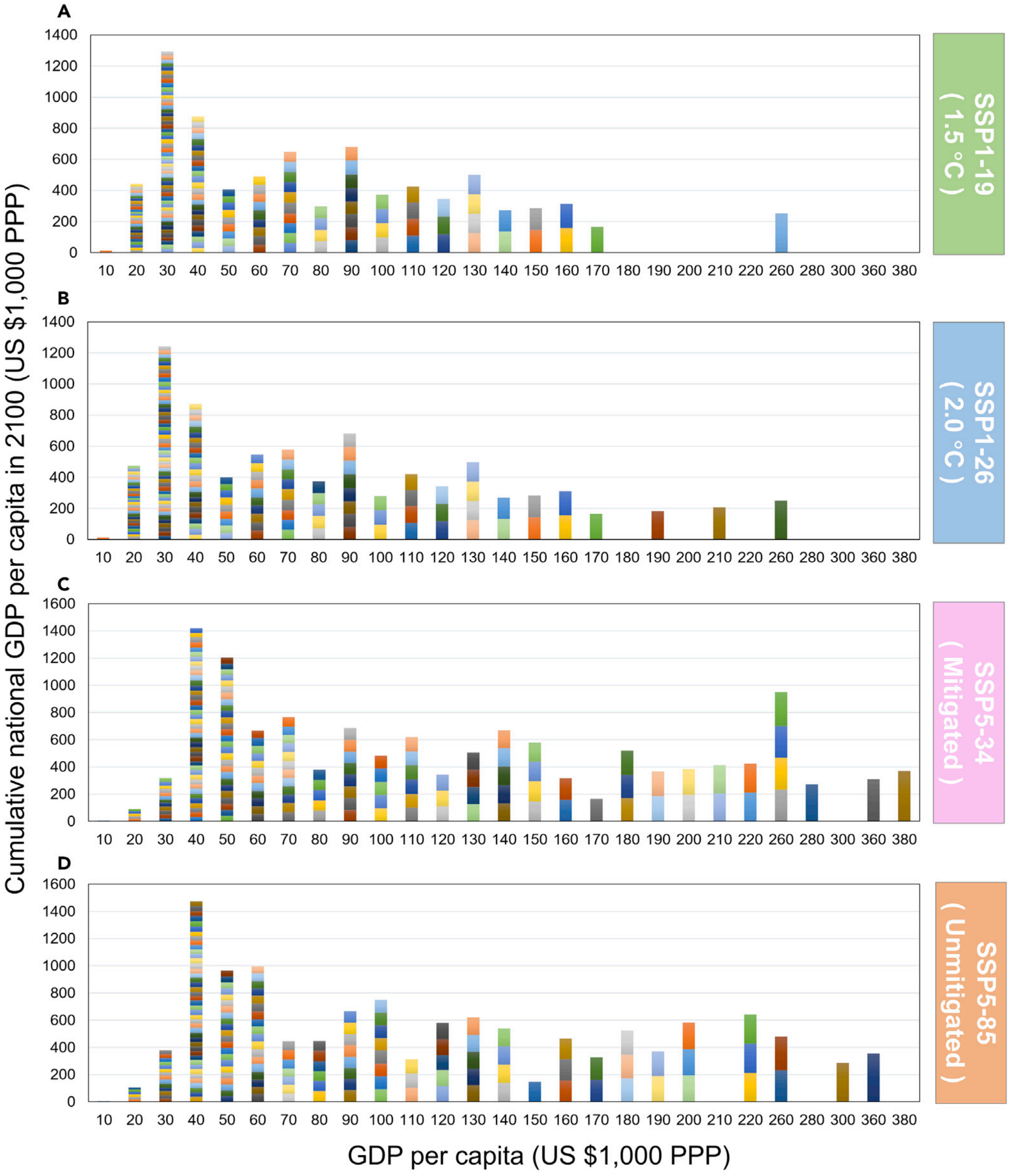

Figure 5. Income distribution in 2100 under the estimated climate-economic linkages

The distribution of national per capita GDP in 1.5°C scenario (SSP1-19) (A), 2°C scenario (SSP1-26) (B), gap-filling mitigated overshoot scenario (SSP5-34) (C), and unmitigated scenario (SSP5-85) (D).

of different policy efforts to mitigate emissions and the benefits deriving from the avoided damage, and (3) their impacts on cross-national inequality.

First, in our baseline model, weather variables enter in first difference or as deviation from the long-run means to better control their trending nature, because temperature level is a trend variable that may bias the estimates of the climate-growth equation.[23,24] We find that temperature level ($T_{i,t}$) does not significantly affect growth, but it acts as a moderator variable affecting the relationship between temperature changes ($\Delta T_{i,t}$) and growth. Our results are robust to a set of robustness checks, including controlling for historical and socioeconomic factors, and estimates for different time periods and country sizes. This conclusion differs from that of Dell et al.[12] and Burke et al.,[11] but largely in line with Kalkuhl and Wenz.[25] Meanwhile, we include one of many other factors (e.g., the rate of temperature change) that identify the difference between historical estimates and future climate damages, implying that ambitious climate actions will increase adaptative responses and slightly reduce economies' sensitivity to warming.

Second, we incorporate policy cost parameters reflecting the extent of mitigation efforts into conventional econometric-based prediction equations, which helps quantifying the impact of mitigation efforts on growth. These parameters are estimated by multiple IAMs. We find that climate policies shift the economic growth trajectory downwards, with potential policy benefits accruing to climate-vulnerable countries, and the benefits of damage avoidance would exceed policy costs in the long run. This result could largely contribute to the extant literature. Actually, ignoring the substantial mitigation costs required to pursue the stringent 1.5°C target may overestimate climate benefits. For example, Burke et al.[20] find that 71% of countries, covering 90% of the global population, gain a >75% chance to benefit from the 1.5°C warming limit (relative to the 2°C goal), whereas this value could be 31% through our study despite a lower chance (>54.17%).

Third, our results show that global inequality declines in the short to medium run, but starts to grow after 2065 (2085) in SSP5 (SSP1) in most cases. This result contrasts with Taconet et al.[19] who find that inequality increases again after reduction only under the highest emission pathway, whereas aligns with Nyiwul[34] and Soergel et al.,[26] suggesting that without progressive redistribution, climate policies could impose a financial burden on the poor globally. This finding underscores the importance of equitable international burden-sharing mechanisms to achieve climate goals.

Conclusions

In this paper, we develop an uncertainty analytic framework by combining three economic dimensions and four warming limits, we then evaluate whether stringent climate policies entail economic benefits in terms of growth and inequality. Several critical findings are obtained.

First, we find that the benefits of avoided damage could overweight policy costs in the long run, despite climate policies slow the pace of economic growth. This finding substantially contributes to the existing literature. Specifically, in a fossil-fueled future, 31% of countries, covering 28.97% of global population, have a 50–93.75% chance to benefit from warming limits relative to a world without mitigation; these countries are, however, mainly advanced industrialized countries, such as the US and Germany. When moving to a sustainable world, some poor countries in Africa and Asia (e.g., Madagascar and Laos) tend to benefit from the more stringent 1.5°C target (relative to the 2°C goal). In addition, representative countries, encompassing about half of global population, could benefit almost decades earlier in SSP1 (2060–2070) than in SSP5 (2080–2090) under a relatively low radiative forcing scenario. Notably, poor countries vulnerable to natural disasters, such as Laos, could benefit from the more stringent 1.5°C target even earlier in the first half of this century. It implies that the pursuit of 1.5°C goal can reduce the catastrophic damage of extreme weather events, and this is particularly true for climate vulnerable territories.

Second, the results indicate that, compared with the 2°C goal, pursuing the 1.5°C target may slow economic catch-up of poor countries in the short to medium term, but improves global inequality in the long run, especially in the second half of the century, despite a growing uncertainties over time. It highlights that moving toward the 1.5°C target could synergistically cope with climate mitigation and economic inequality alleviation. This provides sufficient evidence to support ambitious mitigation under the Paris Agreement.

Third, when moving to a fast-growing and fossil-powered future, rapid development first leads to a reduction in global economic inequality, but this downward trend rebounds and rises again after 2065. It is attributed to the disproportionate impact of climate damages alters the tendency for economic growth to converge, and climate policies further burdens the poor countries worldwide. Our work is a wake-up call for regions that are not actively taking climate actions, and underscores the importance of immediate and forceful mitigation actions and equitable international burden-sharing mechanisms. Developed countries should pay more attention to poor countries and provide necessary financial and technical support to help them improve green production technology. Efforts should also be made to share the benefits of the Paris climate goals with countries around the globe.

Limitations of the study

Our results are subject to several caveats. First, mitigation efforts are allocated within regions in terms of two typical principles, i.e., equivalent burden and income-related burden, which may not cover all the complicated cases in reality. Second, it may be the fact that countries in hotter climate are already poor for other complex reasons, such as political or economic dependence on richer countries. Our heterogeneity analysis does not control for all potential confounders that might affect economic growth. Third, given the positive role of increased long-term adaptation,[35] such as technology advance in reducing the climate vulnerability of economies, our estimates may overstate the impact of future climate damage on growth. Although we consider some discrepancy between the historically estimates and future climate damage, it is fairly limited and cannot capture the full adaptative effect in future socioeconomic scenarios. Fourth, our work lacks an assessment of potential co-benefits, such as health risks and biodiversity loss,[3,27] the estimated benefits of avoided damage are therefore likely to be the lower bound. Last, some unprecedented changes resulting from warming, such as substantial sea-level rise, could exacerbate the disproportionate impacts.[28]

STAR★METHODS

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2022.105734.

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AUTHOR CONTRIBUTIONS

Conceptualization: Y.T., and H.D.; Methodology: Y.T., H.D. and S.Y.; Data collection: Y.T., and S.Y.; Writing – original draft: Y.T.; Writing – review and editing: H.D. and Y.T.; Visualization: Y.T., and S.Y.

DECLARATION OF INTERESTS

The authors declare no competing financial interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Country-level GDP per capita growth	World Bank	https://data.worldbank.org.cn/
Projections of future economic growth	SSP database	https://tntcat.iiasa.ac.at/SspDb/
Observed climate data	University of Delaware	http://climate.geog.udel.edu/
World population density	NASA	https://doi.org/10.7927/H49C6VHW
Projections of climate data	CMIP6	https://esgf-node.llnl.gov/projects/cmip6/
Software and algorithms		
Stata	Stata	Stata 17
Arcgis	Esri	Arcgis 10.2
Matlab	MathWorks	R2020a

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Hongbo Duan (hbduan@ucas.ac.cn).

Materials availability

The study did not generate new materials.

Data and code availability

- The sources of the datasets supporting the current study have been presented in the method details section - "observed climate and socio-economic data" and "scenario data for climate projections". Relevant data and codes can be available on request from the lead contact.
- This paper does not report original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Influence mechanisms and theoretical analysis

In order to reveal the internal relationship between climate change and economic inequality, this paper clarifies and summarizes the influence mechanisms of climate change on economic growth, as shown in Figure S1. We explain how does climate change affect global economic inequality in terms of population migration, capital depreciation, crops yield decline, economic output reduction, ecological damage, and unequal expenditure and environmental costs.

Further, we conduct a theoretical analysis. Based on neo-classical economic growth theory, this paper incorporates weather variables into the Cobb-Douglas production function. We make two assumptions, one about the optimal temperature to maximize global productivity, and the other about the impact of mitigation actions on growth, as follows.

Hypothesis 1: There is an average annual temperature at which global productivity peaks

Based on Solow's (1956) neo-classical economic growth theory,[36] this study incorporates climate variables into the Cobb-Douglas production function to explore the effect of temperature on economic growth. According to the research of Deryugina and Hsiang and Burke et al.,[11,37] we assume that capital and labor do not rapidly reallocate across locations in response to temperature changes, but temperature changes may harm worker health, which would increase disease incidence, mortality and corresponding healthcare costs, and thereby reduce comprehensive labor and capital productivity $f(T)$. Assume that there are a large number of firms in the area j at time τ in industry i in the given economic system. The production function exhibiting constant returns to scale can be expressed as:

$$F[K(T),A(T)L(T)]_{ij\tau} = f\left(T_{ij\tau}\right)K_{ij\tau}^{\alpha}L_{ij\tau}^{1-\alpha} \qquad \text{(Equation 1)}$$

where $f(T)$ denotes comprehensive labor and capital productivity affected by temperature shock. Considering that both temperature levels and temperature changes affect economic growth,[25] we assume there exists an optimal temperature threshold (T^{*}). Following Dell et al.,[12] the marginal effect of temperature changes on growth can be expressed as:

$$f\left(T_{ij\tau}\right) = e^{\psi\left(T_{ij\tau}\right)} = e^{\alpha_1\Delta T_{ij\tau} + \alpha_2 T_{ij\tau}\Delta T_{ij\tau} + \beta_1 T_{ij\tau} + \beta_2 T_{ij\tau}^2}, a > 0, b < 0$$

$$\partial e^{\psi(T)}\Big/\partial\Delta T_{ij\tau} = \alpha_1 + \alpha_2 T_{ij\tau}\begin{cases} > 0, \textit{for } T > -\dfrac{\alpha_1}{\alpha_2} = T^{*} \\ \leq 0, \textit{for } T \leq -\dfrac{\alpha_1}{\alpha_2} = T^{*} \end{cases} \qquad \text{(Equation 2)}$$

Assuming that $U_{ij\tau} = K_{ij\tau}^{\alpha}L_{ij\tau}^{1-\alpha}$ represents the total productive mass resource in the area j at time τ (such as day) in industry i, and exhibits the spatial and temporal distribution of input resource at the micro-level. The output of firms can be simplified as $F(K, L, T)_{ij\tau} = f(T_{ij\tau})\, U_{ij\tau}$. To evaluate the total output, for example GDP, we need to aggregate the output in the specified area at the specified time. The total output in country J during period t (such as year) at the macro-level is:

$$Y_{Jt} = \sum_{i}^{I} F(K,L,T)_{ij\tau} = \sum_{i}^{I} f\left(T_{ij\tau}\right)U_{ij\tau} = \sum_{i}^{I}\int\limits_{\tau\in t}\int\limits_{j\in J} f\left(T_{ij\tau}\right)U_{ij\tau}d\tau dj \qquad \text{(Equation 3)}$$

$U_{ij\tau}$ denotes the distribution of productive resource in the area j during time τ. We can compute productive resource R_i at the macro-level by aggregating the productive resource in the given area and period. Since it is hard to obtain information about the temporal and spatial distribution of productive resource, it is difficult to evaluate total productive resource R_i by integrating the quantity of resources in the area j during time t. Based on the research of Burke et al.,[11] we define the marginal distribution function $g_i(T_{Jt} - \overline{T})$ which reflects the effect of temperature change relative to the annual mean temperature on reallocation of productive resource within industry i. In addition, we assume that $g_i(T_{Jt} - \overline{T})$ does not change in shape across countries or years. The total mass of productive resource R_i is the integral of $g_i(T_{Jt} - \overline{T})$ overall possible temperatures:

$$R_i = \int_{-\infty}^{+\infty} g_i(T_{Jt} - \overline{T})dT = \int\limits_{\tau\in t}\int\limits_{j\in J} U_{ij\tau}d\tau dj \qquad \text{(Equation 4)}$$

In order to compare the marginal effect of temperature changes on countries with different sized economies, we can obtain the average comprehensive productivity Y_{Jt}/R_i by dividing the total output Y_{Jt} by the total productive resource R_i. We define two new variables $\Delta T = T - \overline{T}_{Jt}$ and $\Delta T^{*} = T^{*} - \overline{T}_{Jt}$ to represent the deviations of temperature and temperature threshold, respectively. Then we differentiate Y_{Jt}/R_i with respect to the annual mean temperature in country J during period t:

$$\frac{\partial\left(\frac{Y_{Jt}}{R_i}\right)}{\partial\overline{T}_{Jt}} = \frac{1}{R_i}\frac{\partial Y_{Jt}}{\partial\overline{T}_{Jt}} = \frac{1}{R_i}\frac{\partial}{\partial\overline{T}_{Jt}}\left[\int_{-\infty}^{+\infty} f_i\left(T_{j\tau}\right)g_i(T_{Jt} - \overline{T}_{Jt})dT\right] = \frac{1}{R_i}\frac{\partial}{\partial\overline{T}_{Jt}}\left[\int_{-\infty}^{+\infty} f_i(\Delta T + \overline{T}_{Jt})g_i(\Delta T)d\Delta T\right]$$

$$\text{(Equation 5)}$$

It is difficult to integrate the marginal distribution function $g_i(\cdot)$due to the lack of its concrete form, but we can indirectly evaluate it by using the change in annual mean temperature ($\Delta T_{j\tau}$). We divide the total output into two parts according to the temperature threshold, namely one part below the temperature threshold and another part above this threshold. Define $r_{i1}(\overline{T}_{Jt})$ to denote the ratio of accumulation change in input factor resulting from temperature change to the total productive resource R_i in industry i when the temperature is below the temperature threshold. Similarly, we can define $r_{i2}(\overline{T}_{Jt})$ to denote the ratio of accumulation change in input factor resulting from temperature change to the total productive resource R_i in industry i when the temperature is above the temperature threshold. Equation 5 can be transformed into:

$$\frac{\partial\left(\frac{Y_{Jt}}{R_i}\right)}{\partial \overline{T}_{Jt}} = \frac{1}{R_i}\frac{\partial}{\partial \overline{T}_{Jt}}\left[\int_{-\infty}^{\Delta T^* + \overline{T}_{Jt}} f_i(\Delta T + \overline{T}_{Jt}) g_i(\Delta T) d\Delta T + \int_{\Delta T^* + \overline{T}_{Jt}}^{+\infty} f_i(\Delta T + \overline{T}_{Jt}) g_i(\Delta T) d\Delta T\right]$$

$$= e^{\psi\left(T_{ij\tau}\right)}\psi'\left(T_{ij\tau}\right)\left[\frac{\int_{-\infty}^{\Delta T^* + \overline{T}_{Jt}} g_i\left(\Delta T_{j\tau}\right) d\Delta T}{R_i} + \frac{\int_{\Delta T^* + \overline{T}_{Jt}}^{+\infty} g_i\left(\Delta T_{j\tau}\right) d\Delta T}{R_i}\right]$$

$$= e^{\psi\left(T_{ij\tau}\right)}\psi'\left(T_{ij\tau}\right)\left[r_{i1}\left(\Delta T_{j\tau}\right) + r_{i2}\left(\Delta T_{j\tau}\right)\right] = e^{\psi\left(T_{ij\tau}\right)}\psi'\left(T_{ij\tau}\right)$$

$$\text{where } r_{i1}\left(T'_{Jt}\right) = \frac{\int_{-\infty}^{T^*} g_i\left(\Delta T_{j\tau}\right) d\Delta T}{\int_{-\infty}^{+\infty} g_i\left(\Delta T_{j\tau}\right) d\Delta T} \quad r_{i2}\left(T'_{Jt}\right) = \frac{\int_{T^*}^{+\infty} g_i\left(\Delta T_{j\tau}\right) d\Delta T}{\int_{-\infty}^{+\infty} g_i\left(\Delta T_{j\tau}\right) d\Delta T} = \frac{\int_{-\infty}^{+\infty} g_i\left(\Delta T_{j\tau}\right) dT - \int_{-\infty}^{T^*} g_i\left(\Delta T_{j\tau}\right) d\Delta T}{\int_{-\infty}^{+\infty} g_i\left(\Delta T_{j\tau}\right) d\Delta T} \quad \text{(Equation 6)}$$

Then we let the right-hand side of Equation 6 equal zero in order to identify the optimal temperature for the comprehensive productivity Y_{Jt}/R_i; namely the following condition needs to be satisfied:

$$\frac{\partial\left(\frac{Y_{Jt}}{R_i}\right)}{\partial \overline{T}_{Jt}} = e^{\alpha_1 \Delta T_{ij\tau} + \alpha_2 T_{ij\tau} \Delta T_{ij\tau} + \beta_1 T_{ij\tau} + \beta_2 T_{ij\tau}^2}(\alpha_1 + \alpha_2 T_{Jt}) = 0 \Rightarrow \widehat{T} = -\frac{\alpha_1}{\alpha_2} = T^* \quad \text{(Equation 7)}$$

We can find that the optimal temperature T^*, namely the optimal temperature threshold, which confirms hypothesis 1. Let $\varphi(\overline{T}_{Jt}) = \int_{-\infty}^{+\infty} e^{\alpha_1 \Delta T + \alpha_2 T \Delta T + \beta_1 T + \beta_2 T^2}(\alpha_1 + \alpha_2 T) d\overline{T}_{Jt} + C$, then we have $Y_{Jt} = \varphi(\overline{T}_{Jt}) R_i$.

Hypothesis 2: Mitigation efforts could slow the warming rates and thus reduce future climate damage to economic growth

Historically, most countries have taken less measures to mitigate greenhouse gas emission, and have expended less resources in mitigation efforts. To curb future global warming, most countries need to increase their mitigation efforts in the future, and it is of great importance to take earlier actions to cope with climate change. Assuming that mitigation actions will affect the labor and capital productivity:

$$Y_{Jt} = M_{Jt}(\Delta T_{Jt}) F[K(T), A(T) L(T)]_{Jt} \quad \text{(Equation 8)}$$

where $M_{Jt}(\Delta T_{Jt}) \in [0, 1)$ is the mitigation cost factor with respect to limited warming ΔT_{Jt}. Assuming that F is linearly homogeneous in K and L, and then we divide Equation 8 by the population (L_{Jt}) to get per capita output:

$$y_{Jt} = M_{Jt}(\Delta T_{Jt}) F[k(T), A(T)]_{Jt} \quad \text{(Equation 9)}$$

where k denotes capital per capita. We take the total differentiation of $F(\cdot)$, and let $dF = F$, $\varDelta K = K$, $\varDelta A = A$ to get:

$$dF = \frac{\partial F}{\partial k}\Delta k + \frac{\partial F}{\partial A}\Delta A = \frac{\partial F}{\partial k} k + \frac{\partial F}{\partial A} A \quad \text{(Equation 10)}$$

Taking the logarithm of Equation 9 and derivation, and then taking Equation 10 in, we obtain:

$$g_y = \frac{d \ln y_{Jt}}{dt} = \frac{M_{Jt}'(\Delta T_{Jt})}{M_{Jt}(\Delta T_{Jt})}\frac{d\Delta T}{dt} + \frac{1}{F}\left[\frac{\partial F}{\partial k}\frac{dk(T_{Jt})}{dt}\frac{dT}{dt} + \frac{\partial F}{\partial A}\frac{dA(T_{Jt})}{dt}\frac{dT}{dt}\right]$$

$$= \frac{M_{Jt}'(\Delta T_{Jt})}{M_{Jt}(\Delta T_{Jt})}\Delta \dot{T} + \frac{1}{F}\frac{\partial F}{\partial k}\frac{dk(T_{Jt})}{dt}\dot{T} + \left(1 - \frac{\partial F}{\partial k}\frac{k}{F}\right)\frac{d \ln A(T_{Jt})}{dt}\dot{T} \quad \text{(Equation 11)}$$

Let $(k/F)(\partial F/\partial k) = \Phi$, $d \ln A(T)/dt = g_A(T)$ and $\dot{T} = \Delta T$, where $g_A(\cdot)$ denotes the labor productivity. Based on Nordhaus and Boyer,[38] we assume the depreciation rate of total productive resource is δ, and the saving rate is s, capital stock changes per capita can be written as $\dot{k}(T) = dk/dt = sy - \delta k$. Substituting from Equation 11, we obtain per capital growth:

$$g_y = \frac{M_{Jt}{}'(\Delta T_{Jt})}{M_{Jt}(\Delta T_{Jt})}\Delta\dot{T} + \left[\Phi\left[s\frac{\varphi(\overline{T}_{Jt})R_{Jt}}{K(T_{Jt})} - \delta(T_{Jt})\right] + (1-\Phi)g_A(T)\right]\Delta T \qquad \text{(Equation 12)}$$

Hence, per capital growth can be divided into two parts. Part one is $\frac{M_{Jt}{}'(\Delta T_{Jt})}{M_{Jt}(\Delta T_{Jt})}\Delta\dot{T}$, implying the impact of mitigation efforts M_{Jt} on economic growth, which is related to the warm-limiting target ΔT and warming rate $\Delta\dot{T}$. Part two is $\left[\Phi\left[s\frac{\varphi(\overline{T}_{Jt})R_{Jt}}{K(T_{Jt})} - \delta(T_{Jt})\right] + (1-\Phi)g_A(T)\right]\Delta T$, describing the effect of temperature (change) on capital depreciation and labor productivity. Active mitigation actions could reduce the extent of temperature change ΔT, hence reducing capital depreciation and productivity losses due to climate damage. Thereby hypothesis 2 is verified.

Short-term weather-economic relationship

Through the mechanism analysis on the potential linkages between global warming and economic growth, we construct our main regression model, given as below:

$$\Delta Ln\left(y_{i,t}\right) = c_{i,t} + \sum_{m=0}^{L}\alpha_{1,i,m}\Delta\boldsymbol{T}_{i,t-m} + \sum_{m=0}^{L}\alpha_{2,i,m}\boldsymbol{T}_{i,t-m}\Delta\boldsymbol{T}_{i,t}$$
$$+ \alpha_3\Delta\boldsymbol{T}r_{i,t} + \beta_1\boldsymbol{T}_{i,t} + \beta_2\boldsymbol{T}_{i,t}^2 + p_i(t) + v_i + \mu_t + \varepsilon_{i,t} \qquad \text{(Equation 13)}$$

where i is country, t is year, y is GDP per capita, and according to $d\,ln[y(t)]/dt = dy(t)/[dt \times y(t)]$, it can be approximately transformed into the difference form: $d\,ln[y(t)] \approx \Delta y/[\Delta t \times y(t)] = [y(t) - y(t-1)]/\ y(t) = growth(t)$ in tiny period Δt. $\boldsymbol{T} = (T, P)$ is a vector of population-weighted annual average temperature (in °C) and annual total precipitation (in mm), $\Delta\boldsymbol{T}r_{i,t}$ is the rate of temperature change, $p_i(t)$ is country-specific polynomial time trends, v is the country fixed effects that capture national specific shocks, μ is year fixed effects that account for global covariate shocks, such as economic crises or El Niño,[25] and ε is the random error. In consideration of the long-time span of the sample, the evolution of political systems, technological progress, population migration, trade liberalization and other influencing factors in a country will slowly but continuously affect capital accumulation, population growth and labor productivity over time. Therefore, we use nonlinear time trends $p_i(t)$ to identify other factors that slowly change, with the exception of weather. Besides, as the effect of weather shocks on economic production is a long-lasting process, temperature and precipitation has lagged effects on economic output.[12,24] Therefore, we construct the Distributed Lag Nonlinear Model as Equation 13, where m and L denote the lags and maximum lags, respectively.

Long-term climate-economic relationship

To further investigate the long-term impact of climate change (i.e., decades) on economic growth, we define climate variables as deviations of temperature and precipitation from their historical norms.[23] Our empirical strategy is as follows:

$$\Delta Ln\left(y_{i,t}\right) = c_{i,t} + \alpha_{1,i,m}\Delta\boldsymbol{x}_{i,t,m} + \alpha_{2,i,m}\boldsymbol{T}_{i,t-m}\Delta\boldsymbol{x}_{i,t,m} + \alpha_3\Delta\boldsymbol{T}r_{i,t} + \beta_1\boldsymbol{T}_{i,t} + p_i(t) + v_i + \mu_t + \varepsilon_{i,t} \qquad \text{(Equation 14)}$$

where $\Delta\boldsymbol{x}_{i,t} = \left|\boldsymbol{T}_{i,t} - \boldsymbol{T}^{*}_{i,t-1}\right|'$, $\boldsymbol{T} = (T_{i,t}, P_{i,t})'$, $\boldsymbol{T}^{*}_{i,t-1} = (T^{*}_{i,t-1}, P^{*}_{i,t-1})'$, $T^{*}_{i,t-1}$ and $P^{*}_{i,t-1}$ are the historical norms of climate variables. $\left|\boldsymbol{T}_{i,t} - \boldsymbol{T}^{*}_{i,t-1}\right|$ denotes the positive and negative (absolute) deviation of weather variables from their long-run means. Climate norms are typically computed using 30-year moving average,[39] according to which we consider the moving averages of temperature and precipitation of country i.[23] To check the robustness of our estimates, we also consider historical norms computed using 20-, 40-, and 50-year's moving averages. The multi-decadal moving average of temperature and precipitation are calculated as $T^{*}_{i,t-1} = M^{-1}\sum_{m=1}^{M} T_{i,t-m}$ and $P^{*}_{i,t-1} = M^{-1}\sum_{m=1}^{M} P_{i,t-m}$, where $M = 20, 30, 40$ and 50, respectively.

Scenario designing

We mainly consider four SSP-RCP scenarios (Figure S3), i.e., SSP1-19, SSP1-26, SSP5-34 and SSP5-85, the details are given as below:

SSP1-19: this scenario is a combination of socioeconomic sustainability and very-low radiative forcing (1.9 W/m^2) by the end of the century, which would inform a possible goal of limiting global mean warming to below 1.5°C above pre-industrial levels. In this scenario, immediate and ambitious reduction actions are required.

SSP1-26: the scenario describes sustainable socioeconomic development with low radiative forcing (2.6 W/m^2) by the end of the century, which would achieve the below 2°C warm-limiting target above pre-industrial levels. Similarly, this situation requires immediate and substantial emission reductions.

SSP5-34: this is a new gap-filling mitigated overshoot scenario with medium/low radiative forcing in CMIP6. The scenario follows SSP5-85, an unmitigated baseline scenario, through 2040, and then substantially negative net emissions thereafter. It explores the climate science and policy implications of a peak and decline in forcing during the 21st century. Under this scenario, global countries prioritize economic development from present to 2040, with business-as-usual greenhouse gas emissions; then aggressively reduce emissions after 2040 and strive to achieve net-zero or negative emissions.

SSP5-85: it is an unmitigated scenario with socioeconomic development dominated by fossil fuels and high radiative forcing (8.5 W/m^2) by the end of the century. This is a scenario with no climate policy and the highest global average temperature compared to other scenarios. This scenario implies a rapid development of the global economy based on fossil fuels, producing large amounts of greenhouse gases throughout the 21st century.

SSP database defines five regions: (1) the OECD 90 and EU member States and candidates (OECD); (2) countries from the Reforming Economies of Eastern Europe and the Former Soviet Union (REF); (3) most Asian countries with the exception of the Middle East, Japan and Former Soviet Union States (ASIA); (4) Countries of the Middle East and Africa (MAF); (5) Countries of Latin America and the Caribbean (LAM). In the five regions (OECD, REF, ASIA, MAF and LAM), country-level GDP per capita gradually approached regional GDP per capita in the second half of the 21st century (except for a few oil-rich countries such as United Arab Emirates, Kuwait and Qatar).

Figure S3 depicts temperature projections in four representative SSP-RCP scenarios. Compared to the pre-industrial levels, the global mean surface air temperature would increase 1.479°C (SSP1-19), 1.936°C (SSP1-26), 2.364°C (SSP5-34) and 6.180°C (SSP5-85) in 2100 (Figure S3A). Moreover, there are disproportionate regional differences in global temperature changes relative to the current climate (2003–2017) (Figures S3B–S3E). In general, the warming rate of the land surface is higher than that of the ocean in 2100.[40] Influenced by human activities, the surface air temperature will increase significantly in 2100, especially in some developing regions. For examples, temperatures are projected to increase by 1.568°C to 5.634°C in India, 2.466°C to 7.120°C in Central Africa, and 2.291°C to 10.686°C in Eastern Mexico (Figures S2B–S2E). On the contrary, there is no obvious warming in Europe, and there is even a cooling in Iceland under climate policies (Figures S3B–S3D). In addition, the temperature in Arctic will increase more than 9°C in 2100, which is significantly warmer than the global average temperature under the SSP5-85 scenario (Figure S3E).

Projected impacts of warming on economic growth

We estimate the climate impacts on economic growth. Following Burke et al.,[11] we allow GDP per capita to evolve according to:

$$y_{i,t,RCP} = y_{i,t-1,RCP} \times \left[1 + g_{i,t,baseline} + g_{i,t,RCP}(\Delta T_{i,t})\right] \quad \text{(Equation 15)}$$

where $\Delta T_{i,t}$ is temperature change in country i during year t, $g_{i,t,baseline}$ is the growth projected in a baseline without climate change impacts, and $g_{i,t,RCP}(\Delta T_{i,t})$ is the loss of economic growth due to national temperature changes.

We note that this method (Equation 15) does not take into account the impact of mitigation costs on economic growth under climate policies, nor does it consider how future climate actions will reduce historically estimated climate damage. Therefore, we modify the method of Burke et al.[11] to estimate the impact of climate warming on future economic growth:

$$y_{i,t,RCP} = y_{i,t-1,RCP} \times \left[1 + M_{i,t,RCP}(\Delta T_{i,t}) \times g_{i,t,baseline} + g_{i,t,RCP}(\Delta T_{i,t}) + A(\Delta T_{i,t})\right] \quad \text{(Equation 16)}$$

where $A(\Delta T_{i,t}) = \alpha_3 \Delta Tr_{i,t}$ is the moderating damage index estimated by econometric regressions, indicating the small difference between historical and future climate damage due to changes in warming rate. This difference partly reflects how future climate action will reduce historically estimated climate damage in future socioeconomic and climate scenarios. $M_{i,t,RCP}$ is the mitigation burden index, describing a change in growth rate due to climate policies, which implies that stricter climate policies (leading to lower RCPs) shift the economic growth trajectory slightly downward under a specific SSP path. In the absence of climate policy (business-as-usual scenarios, BAU), there are no mitigation costs, therefore $M_{i,t,RCP}(\Delta T_{i,t}) = 1$. Referring to the study of Taconet et al.,[19] we further postulate that the mitigation burden affects national economic growth in two scenarios, reflecting differential distributions of mitigation efforts: First, we hypothesize that the extent to which mitigation burden affects national per capita growth rate within a region is related to country-level per capita income (income-related burden scenario). Second, we assume regional per capita mitigation burden has equal-per-capita effect across countries within a region (equivalent burden scenario). Then we define the mitigation burden index as follows:

$$M_{i,t,RCP}(\Delta T_{i,t}) = 1 + \frac{growth_{r,t,M} - growth_{r,t,BAU}}{growth_{r,t,BAU}} \times W_{i,t} \quad \text{(Equation 17)}$$

where $growth_{r,t,M}$ and $growth_{r,t,BAU}$ represent the per capital growth rate in region r projected by integrated assessment models (IAMs) under a mitigated scenario and a business-as-usual scenario (BAU) without climate impacts, respectively. $W_{i,t}$ indicates that the impact of mitigation burden on growth is related to per capita income in country i. In the income-related burden scenario, $W_{i,t}$ is calculated as the ratio of GDP per capita in country i to that in region r, implying that when the per capita GDP of country i is lower than that of the corresponding region r (i.e., $W_{i,t} < 1$), the income level of country i is relatively low and therefore the mitigation efforts available are limited; In the equivalent burden scenario, mitigation efforts generate an equal burden on economic growth of countries in region r, regardless of income level, thus $W_{i,t} = 1$. The SSP database provides regional projections of growth rate for each SSP-RCP scenario. Based on the impact of mitigation burden on regional economic growth, we calculate the effect of mitigation efforts on national growth under climate policy scenarios. Each scenario has two or three policy cost estimates from IAMs including an endogenous growth module (AIM/GCE, REMIND-MAGPIE and MESSAGE-GLOBIUM), as they represent the effect of mitigation on growth.

Further, we construct an uncertainty analysis framework, incorporating four dimensions: representative warming scenarios (see STAR Methods for detailed scenario definitions), econometrics-based damage functions, mitigation costs, and mitigation burden effect on economic growth, to explicit future potential climate-economic linkages (Figure S2).

Measuring international inequality

Evaluating global economic inequality often requires long timeseries of household surveys from global countries, which is very fragmentary and sparse.[13,41] Given the limitations on the available micro-data, measures of global inequality tend to rely on country-level metrics.[13,19] The population-weighted country-level metrics is critical to accurately estimate the trends in global inequality.[32] This is owing to income distribution within a country is subject to policy choices that would be difficult to predict in the future.[19] Moreover, international inequality represents by far the largest source of individual inequality, the situation of the poorest and the richest countries largely contributes to economic inequality.[33] Thus, we choose 90:10 and 80:20 ratios to calculate international inequality between the top and bottom income deciles (90:10 ratio) and quintiles (80:20 ratio). Both metrics are included in the eight most popular indices of income inequality identified by Sala-i-Martin.[32] The population-weighted "90:10" is the ratio of country-level per capital GDP located at the top decile divided by the corresponding per capital GDP at the bottom decile,[13,32] with GDP per capita values listed in ascending order for each year (from 2015 to 2100). A similar definition applies to the "80:20" ratio. An increase in the ratio of 90:10 (80:20) means a larger per capita income gap between countries in the top decile (quintile) and those in the bottom decile (quintile), and a greater degree of global economic inequality.

Observed climate and socio-economic data

The observed climate data comes from the Terrestrial Air Temperature and Precipitation: 1900–2017 Gridded Monthly Time Series, Version 5.0.[42] This dataset provides 0.5-degree spatial resolution temperature and precipitation raster data for global land areas interpolated from weather stations. Combining the world population density raster data,[43] this paper computes the population-weighted temperature and precipitation at the national level. Compared with area-weighted mean value, the population-weighted value can prevent geographically large, sparsely populated areas such as deserts and tropical rainforests from becoming the dominant factor of the mean value of their spatial units, while actually having little impact on economic production. Population weighting can correct the interference effect of sparsely populated areas on the climatic mean value.

Socioeconomic data, such as per capital economic growth rate, is obtained from the World Development Indicators (WDI) database. Projections of future economic growth rate are taken from the Shared Socioeconomic Pathways (SSP) database, which is provided by International Institute for Applied Systems Analysis (IIASA). The SSP Database provides growth projections generated by three different research groups (OECD, IIASA and PIK); we focus on the projections from the OECD group, as this group predicts more countries than others.

Scenario data for climate projections

Scenario analysis of different warming controls uses the data from the Scenario Model Intercomparison Project (ScenarioMIP), which is the primary activity within Phase 6 of the Coupled Model Intercomparison Project (CMIP6). The CMIP6 produces a series of updated global climate model (GCM) outputs. To provide key datasupport for future climate change, CMIP6 combines representative concentration pathways (RCPs) and shared socioeconomic pathways (SSPs) under different designed emission scenarios, which make future scenarios more reasonable. To analyze temperature characteristics for future periods, we use four representative SSP-RCP scenarios from the CMIP6 (SSP1-19, SSP1-26, SSP5-34 and SSP5-85). For our study, we use monthly surface temperature for the future period (2015–2100), and the future temperature projections are provided by dozens of global climate models (GCMs) running under four forcing pathways. Considering the availability of four representative SSP-RCP scenarios, as well as securing the same realization number and initial conditions (variant level "r1i1"), only ten GCMs are available. They are CanESM5, CNRM-ESM2-1, FGOALS-g3, GISS-E2-1-G, GISS-E2-1-H, MIROC-ES2L, IPSL-CM6A-LR, MIROC-ES2L, MRI-ESM2-0 and UKESM1-0-LL. To simplify the analysis, we average these available GCM outputs as future temperature projections. Notably, the horizontal resolutions of the available climate models are different. To get multimodel ensemble mean-based results, we downscale the GCM outputs to a 0.5-degree resolution by using the bilinear interpolation method.