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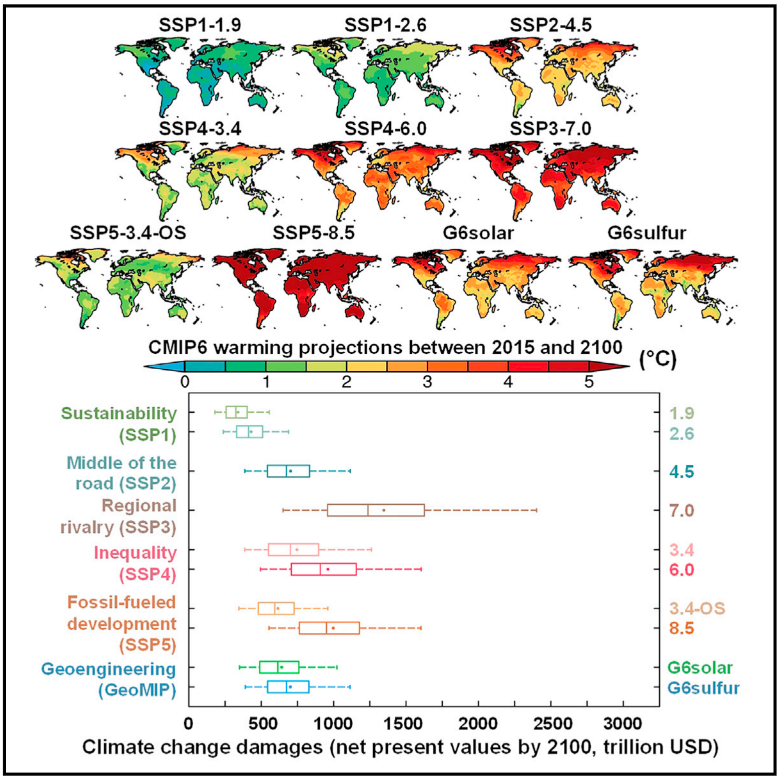
Solar geoengineering and carbon removal significantly lower economic climate damages

Graphical abstract



Highlights

- Improved climate impact assessment by integrating 48 CMIP6 models with PAGE-ICE IAM
- G6 geoengineering and SSP5-3.4-OS have similar temperature-related climate damage
- G6 geoengineering and SSP5-3.4-OS have higher overall costs than SSP1
- Cost-effective mitigation may combine emissions cuts and moderate geoengineering

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In brief

Our study addresses the limitations of integrated assessment models in simulating climate change, with a specific focus on geoengineering. By assimilating climate projections from 48 CMIP6 models into the PAGE-ICE model, we evaluate the economic implications of various scenarios, including radical solar geoengineering and carbon dioxide removal. Our findings highlight the importance of considering these strategies alongside conventional mitigation and adaptation actions. This research provides valuable insights for policymakers and risk managers in formulating effective climate change policies and strategies.

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Solar geoengineering and carbon removal significantly lower economic climate damages

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SCIENCE FOR SOCIETY Climate change poses urgent socio-environmental challenges, demanding innovative approaches to accurately assess impacts and identify effective solutions. While traditional mitigation targets emission reduction and cleaner energy, concerns that future emissions will breach temperature targets motivate exploring more radical options like solar geoengineering and carbon dioxide removal. We find that supplementing politically pledged mitigation with moderate solar geoengineering can achieve the 1.5°C target, with climate damages similar to the sustainable development pathway. Here, "climate damages" refers to the adverse impacts of climate change on various economic sectors, quantified through modules, including socioeconomic projections, climate modelling, and impact assessments. We compare alternative futures so policymakers and stakeholders can more realistically evaluate responses to climate change, including combinations of radical and diverse mitigation measures.

SUMMARY

Quantifying climate change impacts informs policy decisions and risk management. However, integrated assessment models have inherent problems in simulating geoengineered climates, limiting their capacity to assess the efficacy and risks of geoengineering as complementary measures to conventional strategies. Here, we improve climate-induced economic impact assessment, without considering social and ecological damages, for 12 scenarios by assimilating projections from 48 climate models into the PAGE-ICE model. The sustainable development pathway, including considerable implicit carbon dioxide removal, cost-effectively mitigates climate change impacts, as can scenarios that combine politically pledged emissions reductions with moderate solar geoengineering (SAI-1.5). Additionally, we find that combining solar geoengineering with no mitigation (G6) or implementing delayed but stringent carbon dioxide removal (SSP5-3.4-OS) can respectively reduce end-of-century climate damages to one-half or a one-quarter of the baseline SSP5-8.5 scenario. Our findings highlight the importance, potential benefits, and trade-offs of integrating these strategies with conventional mitigation and adaptation actions.

INTRODUCTION

Global surface temperatures have risen by approximately 1.1°C since the industrial revolution,[1] with global temperature records being broken repeatedly, highlighting the urgency of addressing climate change. Even if international pledges to curb greenhouse gas (GHG) emissions are honored in full, peak temperatures are still likely to exceed pre-industrial levels by 2°C.[2,3] The global energy crisis caused by geopolitical conflicts and extreme weather has placed many countries on a more difficult path than expected to meet their stated emission reduction targets. Given the likelihood of the world overshooting the desirable temperatures from GHG emissions policies, climate interventions to limit temperature rises, such as solar geoengineering (SG) and carbon dioxide removal (CDR), should be explored as additions to conventional mitigation and adaptation actions. Estimates of climate change impacts are central to policy decisions and climate risk management, yet impact studies have largely been in relation to particular temperature targets such as 1.5°C or 2°C above pre-industrial.[4–6] Climate change damages and the social cost of carbon have been compared in a common modeling framework for sets of future scenarios.[7–13] However, these studies have only evaluated various GHG mitigation actions and have not addressed additional measures such as SG. SG aims to address global warming by altering the Earth's radiative balance, specifically through techniques like injecting aerosols into the stratosphere or deploying reflective surfaces in space to reflect sunlight away from the Earth's surface, thus counteracting the warming effects of GHGs.[14,15] Unlike traditional mitigation efforts that require long-term emissions reduction, SG's effects are more immediate, direct, and reversible.[16] However, it does not address the root cause of climate change, leading to unique challenges and risks.[17] Additionally, SG may have varying regional impacts, resulting in uneven distribution of benefits and risks across the globe.[18] Existing integrated assessment models (IAMs) face challenges in incorporating SG scenarios because of their limited ability to accurately represent the complex and uncertain impacts of geoengineering on global climate patterns and regional climate dynamics.[19–21] However, with the rapidly growing profile of geoengineering in the scientific and policy communities,[22–24] it is increasingly pertinent to compare the economic impacts of geoengineering scenarios against other scenarios in terms of climate damages.

The Scenario Model Intercomparison Project (ScenarioMIP) in Coupled Model Intercomparison Project Phase 6 (CMIP6) provides a suite of emission scenarios for exploring future climate change, spanning 1.5°C to 5°C of warming over the 21st century.[25] Some of these scenarios are familiar, especially the SSP2-4.5, which is close to the outcome implied by national pledges made at the time the 2015 Paris Agreement was signed,[26] and the SSP5-8.5 "business-as-usual" scenario that defines an absence of mitigation policies. Other scenarios are less well-known, such as the SSP5-3.4-OS scenario with aggressive CDR, which assumes that climate change mitigation is delayed but vigorously pursued. SSP5-3.4-OS follows the same emission pathway as SSP5-8.5 until 2040, with global CO_2 emissions overshooting from a peak of approximately 70 Gt/yr to a zero-emissions threshold in 2070 and negative emissions of −20 Gt/yr in 2100.[25] In comparison, the SSP1-1.9 scenario, which is aligned with the 1.5°C target, has emissions peaking at approximately 40 Gt CO_2/yr in 2020, and reports its first negative emissions in 2060, with −14 Gt/yr of emissions in 2100 through CDR.[25] SSP5-3.4-OS seems to be tempting from a global development perspective, but the technologies required to implement the ensuing decarbonization type of geoengineering are arguably more speculative and costly than those specified by the SG scenarios.[27–29] The Geoengineering Model Intercomparison Project Phase 6 (GeoMIP6) describes geoengineering scenarios that might be used as potential options and emergency tools to offset climate warming.[14] The design goal of the G6sulfur and G6solar experiments is to reduce forcing from the high forcing scenario (SSP5-8.5) to the medium forcing scenario (SSP2-4.5) by stratospheric aerosol injection (SAI) and the less feasible method of solar irradiance reduction.[14] Studies have pointed to the potential of idealized SG to moderate key climate hazards and reduce inter-country income inequality.[16,18] SG may face fewer technical and financial hurdles than CDR and can lower temperatures faster.[22] Comparisons with baseline scenarios demonstrate the effectiveness of geoengineering scenarios, but a full comparative assessment is needed to provide more consistent science-based recommendations to policymakers. The G6 experiments are based on SSP5-8.5 and are, therefore, not a viable option; SG and CDR can help to manage overshoot, but cannot be considered as a plan B substitute for emissions reduction.[30,31] Hence, the economic impacts of climate policies that combine mitigation measures with SG, specifically the SAI simulations aiming for the 1.5°C target (SAI-1.5) under the SSP2-4.5 scenario,[20,32] should be evaluated.

Economic growth is influenced by climate change in numerous dimensions and at multiple scales.[4] Quantification of climate damages is a challenging task that typically involves four distinct modules: a socioeconomic module to project future population, economic and GHG emission pathways, a climate module to model the Earth system's response to GHG emissions and other anthropogenic forcing, an impact module that uses damage functions to construct links between regional and sectoral economic impacts (usually monetized as a percentage of the gross domestic product [GDP]) and climate variables (mainly annual mean surface temperature), and a discounting module to compress future climate damages into net present values.[11,33] Efforts to better assess climate change impacts have focused on the impact module, including improving damage functions[34,35] and incorporating a larger set of climate risks into assessments.[36–38] A recent study highlights that the core reason for the inconsistency in climate impact assessment among IAMs is the difference in climate modules rather than damage functions.[39] Therefore, enhancing the precision of climate modeling can bolster the level of confidence in climate change risk assessments. The CMIP6 generation of climate models represent a completely different class of models from the tremendously simplified climate modules of IAMs.[33] They are actually Earth system models (ESMs) that include physically based, self-consistent energy and momentum exchanges, as well as biogeochemical reactions across the earth system, with improved spatial resolution and better parameterization of subgrid cell processes than previous generations of CMIP models.[40] Thus, incorporating recent advances in climate research into well established IAMs is both an opportunity and a necessity for improving climate damage projections.

Here we explore radical SG and CDR scenarios that may be used to limit temperature overshoot, along with a range of mitigation scenarios, from an economic perspective. To enhance the accuracy of climate damage projections, we assimilate climate projections from 48 CMIP6 ESMs into the latest Policy Analysis of Greenhouse Effect – Ice, Climate, Economics (PAGE-ICE) cost-benefit IAM,[37] thereby compensating for the inherent limitations of IAMs in climate simulation and providing more reliable climate change impact assessments. We find that the G6 geoengineering experiments, partially offsetting climate warming, result in temperature-related climate damages comparable with those of delayed but stringent mitigation (SSP5-3.4-OS). By supplementing politically pledged mitigation with moderate SG (SAI-1.5), there is potential to achieve the 1.5°C warming target while also limiting climate change damages to a level similar to that of the sustainable development

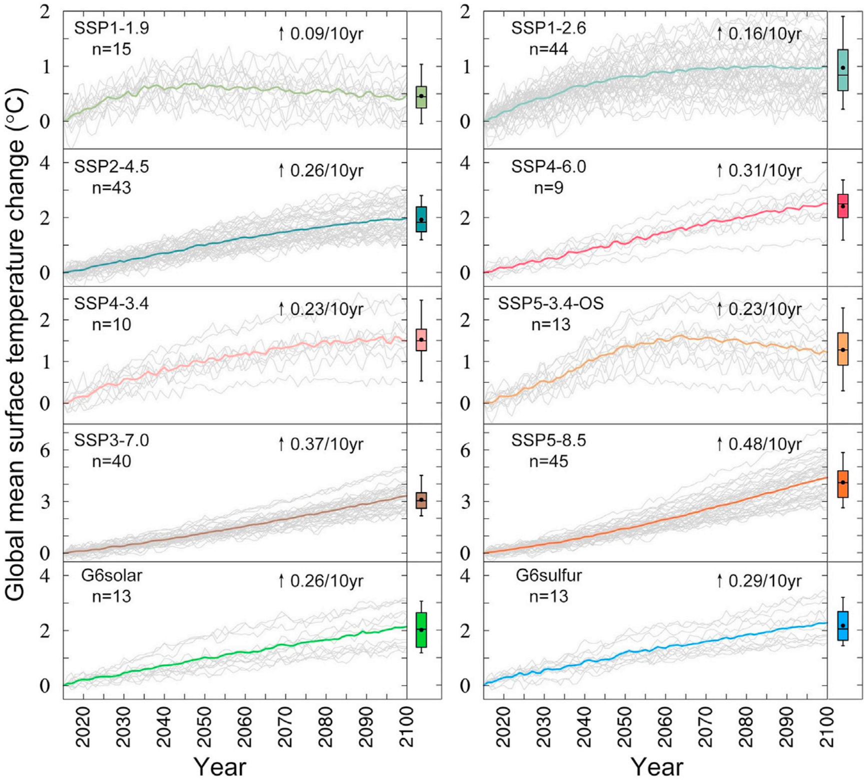

Figure 1. Projected global surface temperature change

Time series of the individual simulations (gray lines) and ensemble means (colored lines) from equally weighting all available CMIP6 models (Table S1). The annotations on the left show the scenarios and the number of simulations used, and those on the right show the warming trend values calculated from the linear least-squares fitting of the ensemble means. Boxplots show the global mean warming for 2090–2100. Whiskers, 5%–95% range; boxes, 25%–75% range; horizontal lines, median; dots, mean.

pathway (SSP1-1.9), which involves aggressive mitigation and implicit CDR. All scenarios with relatively low and globally equitable climate damages require drastic cuts in GHG emissions, and we recognize that the potential damage caused by both CDR and SG geoengineering has not yet been fully explored. Nevertheless, evaluating the economic impacts of these potential courses of action within the same framework is informative. By evaluating various scenarios and their economic impacts, our study contributes to the knowledge base of strategies for mitigating climate change, providing challenging insights for policymakers and stakeholders.

RESULTS

Methods summary: Warming trajectories

CMIP6 models have removed considerable uncertainty from climate predictions and enabled tighter projections to be made of their economic consequences. We used output from 48 CMIP6 models (Table S1) that have estimated global and regional temperatures for the period 2015–2100 under eight scenarios from ScenarioMIP and two from GeoMIP6 (Figures 1 and 2) as inputs to our economic analyses. The SSPx-y form of the ScenarioMIP scenarios has x representing the five different future storylines provided by the shared socioeconomic pathways, with SSP1 to SSP5 corresponding with sustainable development, middle-of-the-road, regional rivalry, inequality, and fossil-fueled development, respectively; y is the radiative forcing level reached in 2100, and the range from SSP1-1.9 to SSP5-8.5 spans ambitious mitigation to inaction.[25] Since both SSP5-3.4-OS and G6 experiments use SSP5-8.5 as a basis, they can be used to compare CDR overshoot with SG. Although actual deployment of SG via SAI would use a more sophisticated strategy[19] than the G6sulfur specification of injection into the lower equatorial stratosphere, the G6 experiments have already been performed by 6 ESMs with 13 simulations (Table S1).

The ensemble global warming rate over the 21st century ranges from approximately 0.09°C to 0.48°C per decade, with a 5-fold difference between the highest and lowest (Figure 1). Global warming is likely to exceed the crucial 1.5°C target in the near-term (2021–2040) under all scenarios (Figures S1 and S2). In the mid-term (2041–2060), projected global warming ranges from 1.5°C to 3°C, with comparable inter-scenario and inter-model differences. In the long term (2081–2100), the projected warming ranges from 1.6°C ± 0.3°C (SSP1-1.9) to 4.9°C ± 1.0°C (SSP5-8.5), while geoengineering limits warming to approximately 3°C, like SSP2-4.5°C and 0.5°C higher than SSP4-3.4 and SSP5-3.4-OS. Higher latitudes, such as Siberia, Greenland, northern Canada, and Alaska, exhibit the most pronounced warming in almost all scenarios (Figure 2), attributed to the phenomenon of Arctic amplification. In contrast, lower latitude regions like India and Latin America show the least warming.

Four scenarios that each represent ambitious control of global temperatures by different means can be compared directly: SSP2-4.5, SSP5-3.4-OS, G6solar, and G6sulfur (Figure S3). In terms of the cooling effects, delayed but vigorous mitigation > moderate mitigation > G6 SG > G6 sulfate geoengineering. The cooling effect of overshooting mitigation (SSP5-3.4-OS) is remarkable at high Arctic latitudes (>5°C) (Figure S3), which would help to maintain stability in the permafrost region and avoid additional soil carbon release.[41] The differences between G6sulfur and G6solar, particularly at northern high and mid latitudes, can be largely attributed to the uniform reduction of solar irradiance in G6solar and the focused increase in optical depth in the tropics induced by stratospheric sulfate aerosols in G6sulfur.[42] Regional differences in cooling by geoengineering and CDR overshoot raise potential climate justice and transgenerational equity pitfalls in geoengineered pathways, but regional differences are also certain to arise in GHG forcing scenarios and grow with radiative forcing.[18]

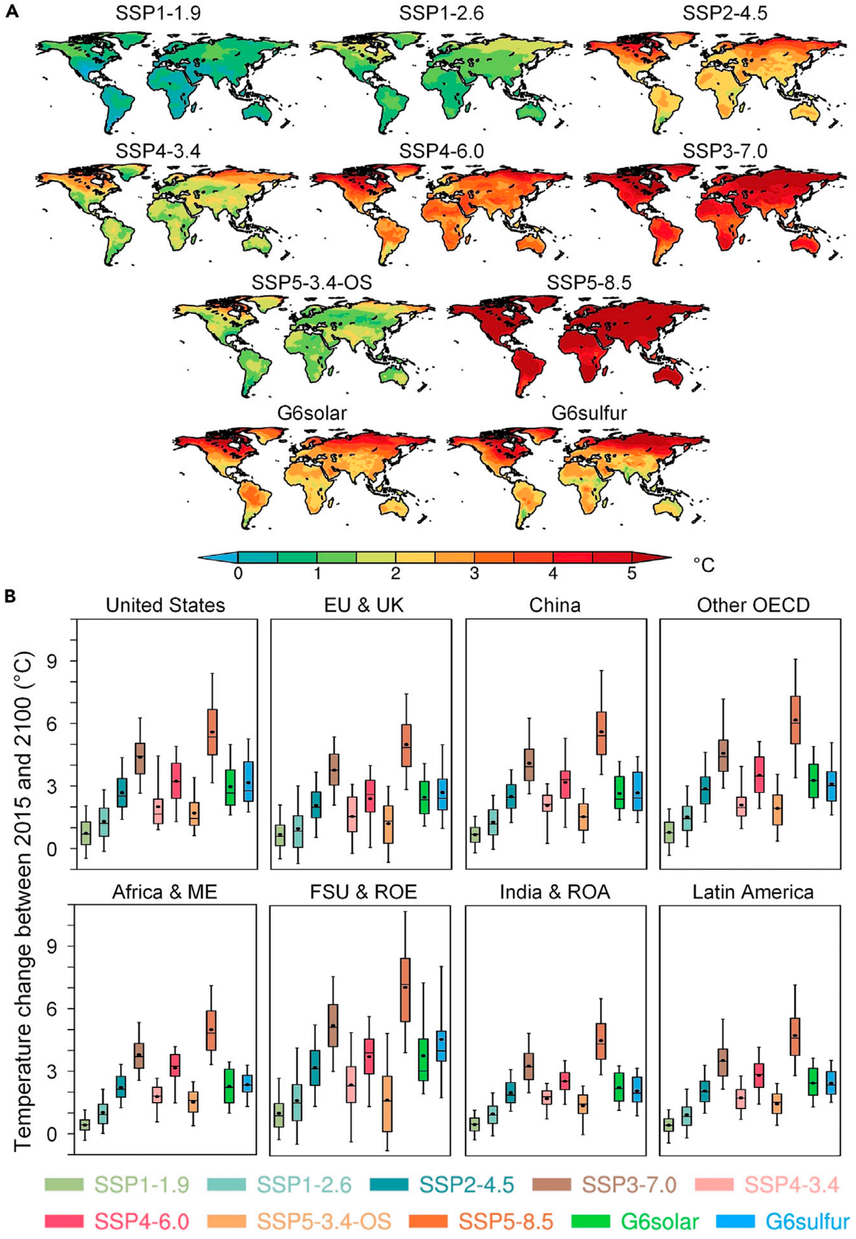

Figure 2. Projected regional warming between 2015 and 2100

(A) Spatial distributions of global land surface warming under eight ScenarioMIP scenarios and two GeoMIP6 experiments. Results are the ensemble means estimated using the models in Table S1. All models are bilinearly interpolated into the same 1° × 1° grid.

(B) Boxplots of regional temperature change. Whiskers, 5%–95% range; boxes, 25%–75% range; horizontal lines, median; dots, mean. EU, European Union; FSU, Former Soviet Union; ME, Middle East; OECD, Organization for Economic Co-operation and Development; ROA, Rest of Asia; ROE, Rest of Europe.

Economic costs

After assimilating CMIP6 simulations into the impact module of PAGE-ICE IAM[37] (Figure S4), we explored the uncertainty of climate damage with an ensemble of 100,000 Monte Carlo simulations, producing a probability distribution for each scenario. All estimates are shown in purchasing power parity dollars rather than market exchange rate dollars because we are more concerned with the relative size of different economies and their losses than with international trade between economies, and we denote thousands by k. Per capita economic losses caused by climate change range from \$0.1 to 10 k/yr, depending on both scenario and region (Figure 3). The most extensive climate change damages occur under the SSP3-7.0 and SSP5-8.5 scenarios, which have no climate policies, when per capita losses increase at rates of 2%–4% per year, reaching \$5.3 k/yr (5%–95% range, \$3.7–\$7.1 k/yr) and \$5.2 k/yr (\$2.3–\$10.6 k/yr) in 2100. In contrast, adopting a sustainable development pathway and stringent mitigation efforts could reduce climate change impacts by a factor of 5–10, with \$0.5 k/yr (\$0.2–\$1.2 k/yr) and \$1.0 k/yr (\$0.4–\$2.2 k/yr) for SSP1-1.9 and SSP1-2.6, respectively.

Scenario and regional differences in climate change impacts increase after considering population and economic growth (Figures S5; and S6). For pathways that follow the Paris Agreement and the UN Sustainable Development Goals, climate change impacts on global GDP at the end of the century are held to about 1%, with 0.6% (0.2%–1.4%) for SSP1-1.9 and 1.2% (0.4%–2.5%) for SSP1-2.6. SSP5-8.5 has climate change damages of \$38.6 trillion/yr (\$16.8–\$77.7 trillion/yr) in 2100, or 3.7% (1.6%–7.4%) of global GDP. The intermediate pathway (SSP2-4.5) has an approximately 2°C lower warming than SSP5-8.5 (Figure S1), but the adverse effects of climate change are comparable as a percentage of GDP, as the GDP per capita is one-half of SSP5-85, resulting in a lower discounting of future damages. Under the regional rivalry (SSP3) and inequality (SSP4) scenarios, uneven development and large wealth disparities lead to high societal vulnerability to climate change. Climate change damages reach high levels of 5.0% (2.8%–8.0%) and 8.7% (5.3%–13.4%) of GDP under the low (SSP4-3.4) and medium (SSP4-6.0) emission pathways, respectively. Under the worst case scenario (SSP3-7.0), climate change damages reach 20% (12%–34%) of global GDP in 2100.

Economic benefits from the cooling effects with SG and CDR overshoot compared with SSP5-8.5 start to emerge after the mid-century. G6solar and G6sulfur are not significantly different, and, from approximately 2060 onward, their economic benefits will be weaker than the deferred but strictly mitigated SSP5-3.4-OS. By 2100, climate damages under the G6 and SSP5-3.4-OS scenarios are about 1.6% (0.7%–3.3%)

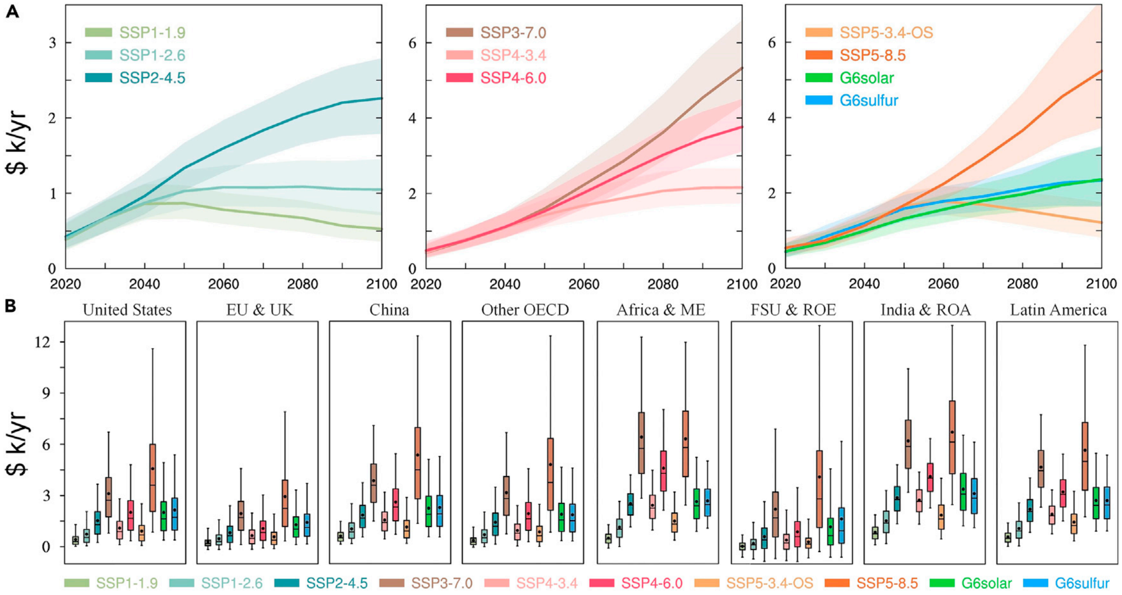

Figure 3. Projected economic impacts of climate change (per capita, thousands of dollars per year)

(A) Time series of global impacts under different scenarios.

(B) Regional impacts for 2091–2100. In (a), lines represent median projections and shaded areas show 25%–75% quantiles. For the boxplots in (b), whiskers, 5%–95% range; boxes, 25%–75% range; horizontal lines, median; dots, mean. Results and uncertainty ranges are from 100,000 Monte Carlo runs of PAGE-ICE model. EU, European Union; FSU, Former Soviet Union; ME, Middle East; OECD, Organization for Economic Co-operation and Development; ROA, Rest of Asia; ROE, Rest of Europe.

and 0.9% (0.3%–1.9%) of global GDP, respectively (Figure S6). Hence, our G6 simulation halved (45%) SSP5-8.5 damages, while the CDR-overshoot intervention decreased damages to one-quarter (23%).

Regional disparities

Climate change poses global risks, with impacts that vary spatially (across regions) and temporally (across generations). We illustrate this using an equity-weighting scheme that assigns different weights to climate damages suffered by countries at different levels of development, to reflect the fact that the poor lose more in terms of well being than the rich.[43] Our damage assessments of the stringent mitigation scenarios are generally consistent with previous multi-scenario climate impact assessments,[8,10] but under the worse future scenarios (especially the SSP3 scenario) ours are higher because we choose to value equity in PAGE-ICE. Weighting climate damage by per capita income emphases regional economic development differences and justice issues.

Climate change damages are concentrated in developing regions under the inequality scenario (SSP4-6.0) (Figure 4A), and all regions are adversely affected under the regional rivalry scenario (SSP3-7.0) (Figure 4B), with relative impacts increasing with decreasing GDP per capita and increasing temperature (Figure 4C). The impact of warming on different regions depends mostly on their temperatures today. Developing regions such as Africa, South Asia, and Latin America can expect to endure losses that exceed the global average because they face unprecedented adaptation challenges in the wake of warmer temperatures. This is grossly disproportionate to their contribution to GHG emissions, especially under the lower development scenarios, and they are less likely to benefit from economic opportunities such as a seasonally ice-free Arctic Ocean.[44] Regional economic disparities will be exacerbated by climate change for more than three-quarters of the global population, undermining efforts to eradicate extreme poverty.[45]

For the populous and climate-damaged regions of India, Africa, and the Middle East, our G6 and SSP5-3.4-OS simulations reduce climate damages to approximately 45% and 25% of the SSP5-8.5 scenario (Figure S7), which is comparable with the global average ratio. Meanwhile, climate damages in the former Soviet Union region are decreased by approximately 65% (G6solar and G6sulfur) and 90% (SSP5-3.4-OS) of what it would have been, as initial warming could be beneficial while significant warming poses a heightened risk. The estimated climate losses per capita for each region in 2100 vary across the SSP5-8.5, G6solar, G6sulfur, and SSP5-3.4-OS scenarios, with ranges of \$3.0–6.7, \$1.2–3.4, \$1.5–3.1, and \$0.3–1.9 k/yr, respectively (Figure S7). Therefore, the implementation of SG and CDR-overshoot can decrease regional economic disparities exacerbated by climate change. From another perspective, warmer developing countries can decrease vulnerability and mitigate the adverse impacts of climate change through economic development. In Africa and the Middle East, warmings of 4.7°C (SSP3-7.0) and 5.8°C (SSP5-8.5) (Figure 2) lead to per capita climate losses close to \$5.8 k/yr by 2100 (Figure 3), but these represent 40% and 5.2% of the GDP (Figure S6). However, the fitted surface in Figure 4C underestimates the impacts of climate change on highly developed, hot regions; hence, economic development alone cannot fully mitigate climate change damages without concomitant stringent mitigation efforts.

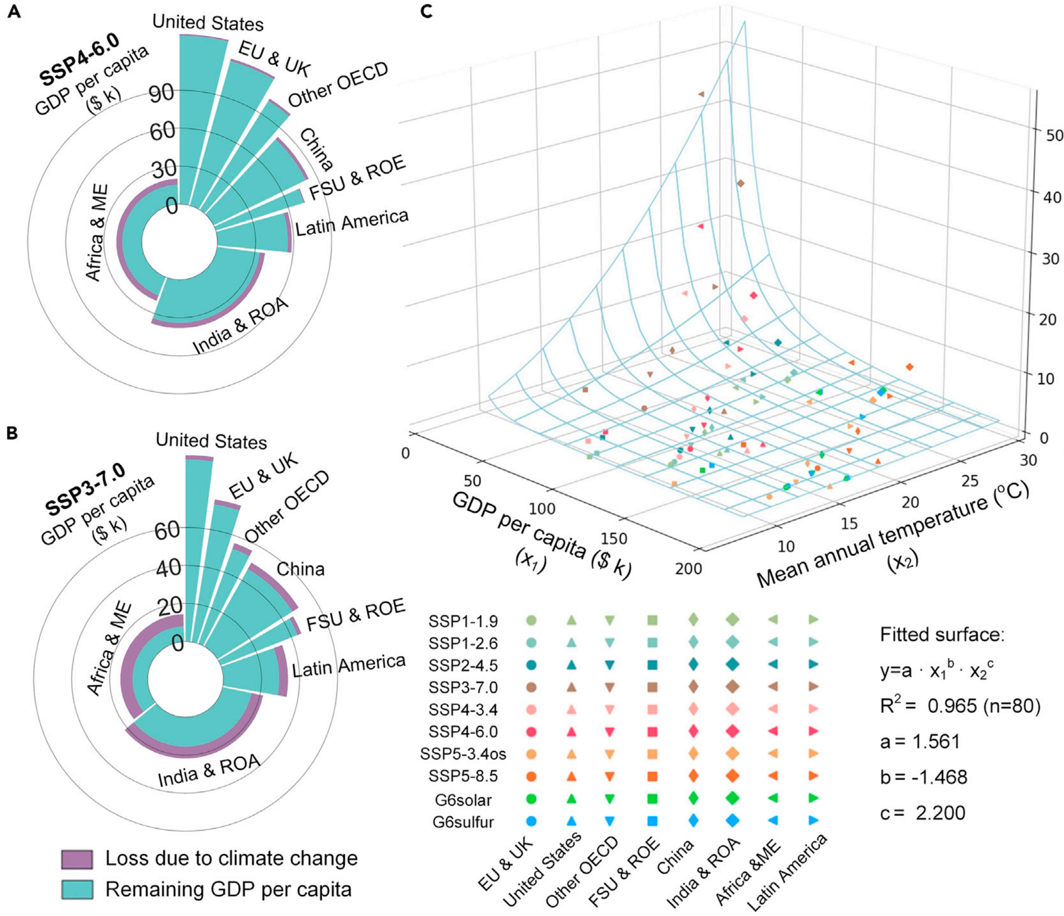

Figure 4. Regional disparities in climate change impacts

(A and B) Impacts of climate change on regional GDP per capita in 2100 under high emissions and uneven development scenarios.

(B) Relationships of climate change damages, mean annual temperature, and GDP per capita. In (A), inequality scenario (SSP4-6.0), and (B), regional rivalry scenario (SSP3-7.0), bar widths are proportional to the regional population in 2100. In (C), mean annual temperatures and climate change damages as the percentage of GDP are year 2100 values. The fitted surface (C) shows that poorer and warmer countries are more vulnerable to climate change than richer ones. Results are mean values from 100,000 Monte Carlo runs of PAGE-ICE model. EU, European Union; FSU, Former Soviet Union; ME, Middle East; OECD, Organization for Economic Co-operation and Development; ROA, Rest of Asia; ROE, Rest of Europe.

Combined approach

Here, we examine the SAI-1.5 experiments[20,32] to achieve the 1.5°C target. These combine SG with the SSP2-4.5 background emissions scenario that aligns with the Paris Agreement's Nationally Determined Contributions mitigation measures. Specifically, the experiments injected approximately 10 Tg of SO_2 per year, with the injection rates adjusted each year using a feedback algorithm to maintain not just the global mean temperature, but the interhemispheric and equator-to-pole temperature gradients. Simulations start either in 2035 (SAI-1.5-2035) or 2045 (SAI-1.5-2045), and continue until 2069, producing a cooling of approximately 1°C.[20] As a comparison, the G6 experiments involve injecting 29 ± 9 Tg of SO_2 per year in the latter part of the century, producing a cooling of approximately 2°C.[46] This additional set of experiments has only been simulated by the CESM2(WACCM6) model with 10 ensemble members and so lacks the multi-model uncertainty aspect present in the G6 experiments. Moreover, the SAI-1.5 simulations end in 2069 rather than running to 2100. This was dictated by the desire to produce policy-relevant scenarios, where the most critical decision may be when to start, rather than longer term issues that become increasingly dominated by technological change and the SSP pathway.[20] As with any geoengineering deployment, the risk assessment of SAI-1.5 would be strongly influenced by termination strategy with uncertain long-term environmental and social impacts, and which we do not include here.

CESM2(WACCM6) ensemble mean simulations (Figure 5A) of global temperatures under the SSP2-4.5 emissions scenario rise to approximately 1.5°C above pre-industrial levels around 2030, rising further to approximately 2.6°C by 2069, which is close to the ensemble mean of 43 models (Figure 1). However, the SAI-1.5-2035 experiment, deployed from 2035 onward, succeeds in limiting the global average temperature to close to the 1.5°C target. Delaying the SG start date by 10 years produced a bigger overshoot, with the peak temperature rise dropping from 2°C to approximately 1.3°C. Spatially, the cooling in most regions for the SAI-1.5-2035 experiment is approximately 1°C, with a stronger cooling effect toward the poles (Figure 5B). In

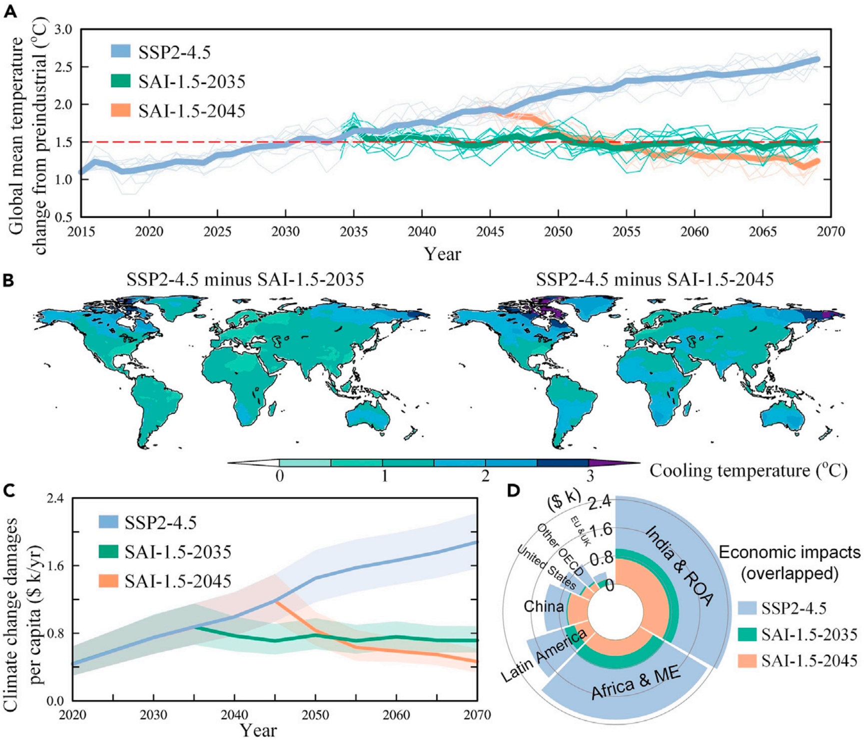

Figure 5. Projected impacts of combined mitigation and geoengineering

(A) Global temperature changes relative to pre-industrial levels from 2015 to 2069 simulated by the CESM2(WACCM6) model (ten ensemble members; mean shown in thicker lines). Red dashed line corresponds to the 1.5°C target.

(B) Ensemble mean spatial distributions of the cooling effects of SAI-1.5-2035 and SAI-1.5-2045 relative to SSP2-4.5 in 2069.

(C) Time series of global per capita damages caused by climate change. Lines represent median projections and shaded areas show 25%–75% quantiles. Results and uncertainty ranges are from 100,000 Monte Carlo runs of PAGE-ICE model.

(D) Regional economic impacts per capita of climate change in 2069. Values under the SSP2-4.5 scenario are used as background to demonstrate the effects of SAI-1.5 experiments in mitigating climate change damages. Bar widths are proportional to the regional population in 2069. EU, European Union; FSU, Former Soviet Union; ME, Middle East; OECD, Organization for Economic Co-operation and Development; ROA, Rest of Asia; ROE, Rest of Europe.

contrast, SAI-1.5-2045 results in an additional cooling of about 0.5°C in regions such as Africa and Latin America. These differences are presumably just stochastic, since the same model and SG methods are used in both sets of simulations.

Projected climate change damages follow trajectories similar to global temperatures (Figure 5C), with per capita economic losses by 2069 estimated to be $1.9 k/yr ($1.2–$2.8 k/yr), $0.7 k/yr $ (0.4–$1.2 k/yr), and $0.5 k/yr ($0.2–$1.1 k/yr) under the SSP2-4.5, SAI-1.5-2035, and SAI-1.5-2045 scenarios, respectively. The corresponding percentages of GDP are 4.4% (2.8%–6.6%), 1.7% (0.9%–2.9%), and 1.1% (0.4%–2.5%), respectively. As a comparison, the SSP1-1.9 scenario, which aims to achieve the 1.5°C target through sustainable development, projects per capita losses of $0.7 k/yr ($0.3–$1.4 k/yr) over the same period, corresponding with 1.3% (0.6%–2.7%) of the GDP. In addition, the regional disparities in the economic impacts of climate change are largely mitigated for both SAI-1.5 experiments (Figure 5D). The losses borne by developing regions such as India, Africa, and Latin America, which represent roughly three-quarters of the global population, are reduced by approximately 60% and 75%, respectively, under the SAI-1.5-2035 and SAI-1.5-2045 scenarios.

Overall assessment

We discount the equity-weighted climate damages by the utility rate of interest, the pure time preference (PTP) rate, and aggregate to obtain the net present values (NPVs) of climate damages in this century (Figure 6 and Table 1). Since the SAI-1.5 scenarios end in 2069, the NPVs of climate damages for all 12 climate scenarios are aggregated up to the year 2069. The NPVs by 2069 for the SAI-1.5-2035 and SAI-1.5-2045 scenarios are $271 trillion ($140–$457 trillion) and $283 trillion ($146–$484 trillion), respectively, which are comparable with the values for the SSP1-1.9 scenario and approximately 60% of those for SSP2-4.5 (Table 1). Over the 21st century, scenarios with higher GHG emissions and slower economic growth would lead to greater economic losses, and these losses would be borne primarily by developing regions. Under the SSP3-7.0 scenario with high mitigation and adaptation challenges, the NPV of climate change damages is projected to be $1,347 trillion ($651–$2,402 trillion) (Table 1), with most of the adverse effects falling on developing regions. Climate change damages are substantially avoided in the sustainable development scenarios, with SSP1-1.9 at $340 trillion ($180–$556 trillion) and SSP1-2.6 at $430 trillion ($238–$688 trillion). In addition, the NPVs are close to $1,000 trillion for SSP5-8.5 and SSP4-6.0, compared with approximately $700 trillion for SSP2-4.5, SSP4-3.4 and G6sulfur, and approximately $600 trillion for SSP5-3.4-OS and G6solar.

The reduction in uncertainty in damage projections due to assimilating CMIP6 climate simulations is shown in Figure 6. An earlier study evaluated ScenarioMIP emission scenarios with the PAGE-ICE climate module[9] (as in Figure 6B, but with old-fashioned damage functions), which yielded both higher expected climate damage estimates and a larger range of uncertainties than using updated damage functions and assimilating the CMIP6 climate simulations (Figure 6A). Climate simulations directly from PAGE-ICE have higher uncertainties than CMIP6 model simulations and tend to overestimate global warming under low emission and overshoot scenarios (Figure S8). This is not caused by changes between CMIP6 and earlier generations of climate models that IAM were calibrated against, because CMIP6 models have larger ranges in their equilibrium and

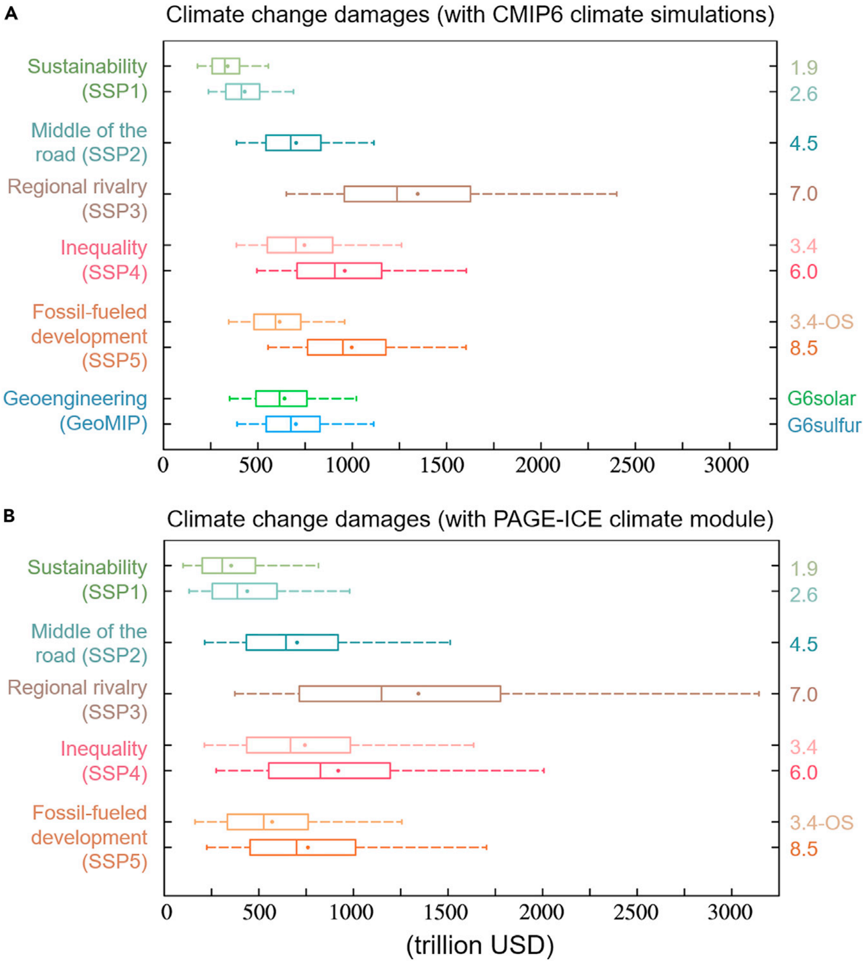

Figure 6. Reduced uncertainty in climate damage assessment with CMIP6 climate simulations

(A and B) NPVs (until 2100, equity weighted, PTP discounted) of the aggregate climate damages (A) with CMIP6 climate simulations and (A) with PAGE-ICE climate module.[9] Whiskers, 5%–95% range; boxes, 25–75% range; vertical lines, median; dots, mean. Results and uncertainty ranges are from 100,000 Monte Carlo runs of PAGE-ICE model.

transient climate responses to GHG than their predecessors.[47] Rather, it is caused by the over-simplified physics in the IAM models. Furthermore, the lack of three-dimensional transport in the IAM climate modules means that regional warming estimates are produced by simple scaling of global mean warming and regional amplification factors and so fail to capture the scenario-dependent regional variability present in the CMIP6 results (Figure S9). Simulated climate change damage is highly nonlinear with temperature, and thus reducing uncertainty later in the century will disproportionately help to reduce uncertainty in climate change damage assessments. In agreement with a recent across-IAMs study,[39] our findings suggest that synthesizing state-of-the-art information on climate science into the climate module of IAMs can help to improve the accuracy and consistency of climate damage assessments.

The total economic effects of climate change include climate change damages and the costs of mitigation and adaptation (Table 1). Costs of climate action for scenarios except G6 are available from PAGE-ICE IAM (Figure S4). Implementing SAI is estimated to cost tens of billions per year,[27] much lower than estimated climate change damages and ambitious abatement costs. Beyond the direct engineering costs, the potential ecological side effects of geoengineering remain relatively unexplored[31] and beyond the scope of this paper; thus, estimates of their overall economic impacts cannot yet be provided. Overall, the benefits of mitigation actions will outweigh the costs of inaction, reducing the negative economic impacts of climate change. The economic benefits of GHG emission reductions can be observed under both the fossil-fueled development pathway (SSP5) with high mitigation challenges and low adaptation challenges, and the world of inequality (SSP4) with low mitigation challenges and high adaptation challenges. The difference in NVPs is approximately $90 trillion ($28–$160 trillion) between SSP4-6.0 and SSP4-3.4, and approximately $280 trillion ($150–$540 trillion) between SSP5-8.5 and SSP5-3.4-OS. The total economic impacts of climate change under the SSP1-1.9 and SSP1-2.6 scenarios are much lower than the other scenarios, demonstrating that, of these scenarios, sustainable development is the optimal pathway to avoid climate change damages. The assessment of climate change damages remains subject to profound uncertainties due to issues such as the range of equity weighting and discounting parameters, the expression of economic and non-economic damages, and tipping points (Figure S10). However, uncertainties cannot overshadow strong indications that implementing stringent mitigation measures is a cost-effective pathway to reduce climate change damages, and that SSP3-7.0 (regional rivalry) is a more worrisome scenario than even SSP5-8.5 (Table 1).

DISCUSSION

Quantifying the economic damages of climate change is critical for societal decision-making, but estimating climate damages under different mitigation efforts and climate actions is challenging because of the complex uncertainties associated with multi-system coupling and the heterogeneity of climate impacts across regions, sectors, and generations.[4,6,33] Strictly following emission pledges might achieve the 2°C goal,[2,3] but research into radical climate interventions is growing.[22–24] As complements to conventional mitigation, geoengineering technologies have altered the way people think about climate policy.[48] While some may be attracted to SG by its low deployment costs and

Table 1. NPVs of climate damages, adaptation and mitigation costs, and total economic effects

Scenario	Description	Climate damages by 2069	Climate damages by 2100	Adaptation and mitigation costs by 2100	Total economic effects by 2100
SSP1-1.9	sustainable development, low-emission, aligned with the 1.5°C target	277 (143–455)	340 (180–556)	194 (138–255)	534 (318–811)
SSP1-2.6	sustainable development, low-emission, aligned with the 2.0°C target	324 (175–516)	430 (238–688)	105 (78–130)	535 (316–818)
SSP2-4.5	middle-of-the-road, moderate emissions	452 (243–732)	703 (387–1115)	36 (25–51)	739 (412–1166)
SSP3-7.0	regional rivalry, high emissions, no mitigation	671 (330–1228)	1347 (651–2402)	10 (3–15)	1357 (654–2417)
SSP4-3.4	inequality, low to moderate emissions	492 (255–863)	747 (386–1261)	161 (105–243)	908 (491–1504)
SSP4-6.0	inequality, high emissions	563 (293–969)	960 (495–1604)	40 (24–63)	1000 (519–1667)
SSP5-3.4-OS	fossil-fueled development, CDR overshoot	466 (272–709)	615 (345–960)	79 (63–103)	694 (408–1063)
SSP5-8.5	fossil-fueled development, high emissions, no mitigation	555 (316–835)	997 (553–1603)	2 (1–3)	999 (554–1606)
G6solar	reduce forcing from SSP5-8.5 to SSP2-4.5 by solar irradiance reduction	421 (235–666)	641 (350–1022)	N.A.	N.A.
G6sulfur	reduce forcing from SSP5-8.5 to SSP2-4.5 by SAI	474 (270–731)	701 (390–1113)	N.A.	N.A.
SAI-1.5-2035	SAI starting in 2035 with SSP2-4.5 emissions, targeting 1.5°C	271 (140–457)	N.A.	N.A.	N.A.
SAI-1.5-2045	SAI starting in 2045 with SSP2-4.5 emissions, targeting 1.5°C	283 (146–484)	N.A.	N.A.	N.A.

Data are presented as means (5%–95% range) in trillions of dollars. Total economic effects equal climate damages plus adaptation and mitigation costs. The costs and total economic effects of the four geoengineering experiments are not presented because their potential side effects have not been fully assessed.

rapid payoff, and see it as an inevitable response to climate change,[49] many more will be concerned about the attendant risks and uncertainties.[48] The moral hazard of geoengineering technologies arises from the psychological effect of risk compensation, potentially inhibiting emissions reductions if viewed as a standalone solution.[50] Even if the moral hazard itself does not undermine mitigation, policymakers may still avoid using geoengineering because of the anticipated moral hazard, despite potential benefits for all.[51] Effective communication strategies are therefore essential for geoengineering governance, as public awareness of these technologies is limited, and their acceptance level strongly depends on the framing of information.[52]

Geoengineering governance is highly vexatious,[23,24] may inhibit mitigation,[24] has the potential to both exacerbate and reduce conflict,[22] and is less accepted by the public in the Global North than the Global South.[53] Studies to date indicate more equitable outcomes for SG compared with unmitigated GHG scenarios.[16,18] However, only by comparing geoengineering with a range of abatement options in the same framework and overcoming the profound uncertainties associated with climate damage estimates will it be possible to provide comprehensive information for policy decisions. In this study, we focus on incorporating the latest advances in climate research into a refined IAM to reduce uncertainty in climate simulations and thus improve climate damage projections. While previous studies have estimated climate damages under a range of mitigation scenarios,[8–10] our methodology reduces the uncertainties by assimilating the latest CMIP6 climate simulations and extends the range of scenarios to include SG and overshoot with huge negative emission rates. The linear scaling schemes based on GHG levels that are used in the climate emulator modules incorporated within IAM cannot accommodate SG scenarios which, by design, have different climates than expected from their GHG concentrations. Since shortwave radiative forcing in SG is inherently different from longwave GHG forcing, the global fingerprint of SG climates is different from pure GHG climates.[14,16–20] This fingerprint will vary according to the details of the SG being simulated. For example, relative overcooling of the tropics and undercooling of the polar regions is seen in the G6 and similar experiments,[14,17] which is different by design from the pattern produced by the feedback algorithm and range of injection latitudes used in the SAI-1.5 experiments.[20,32] Changes in tropospheric circulation will be imposed by radiatively active species into the stratosphere[54] and by the large regional contrasts in radiative forcing implicit in marine cloud brightening.[15] Until these are included in the IAM, our approach of coupling the IAM with CMIP6 ESMs better captures the global and regional climate features of large-scale CDR and SG, facilitating broader climate policy cost-benefit analysis.

We find that just the temperature-related climate damages alone under the G6solar and G6sulfur experiments are comparable to the supposedly more complete cost estimate of the overall impacts under the SSP5-3.4-OS scenario (Table 1), and their overall economic costs are higher than the sustainable development pathway that combines active mitigation with CDR (SSP1). Our conclusions are based on PAGE-ICE IAM and CMIP6 climate simulations. Future research could explore the impact of using different IAMs, damage functions, climate models, equity weights, and risk preference options on the simulation of climate change damages. But perhaps of greater relevance are more simulations of the complex and more likely deployment strategies than specified by the G6 and SSP5-3.4-OS scenarios, such as the SAI-1.5 simulations that are so far limited to just a single ESM. Earlier deployment or setting more aggressive temperature targets may make CDR and SG-based solutions seem to be more economically attractive, but potential side effects and difficulties in practical deployment also pose greater risks. The negative emission rates required to comply with the SSP5-3.4-OS and SSP1 scenarios far exceed the rates of natural climate solutions[55] and imply reaching net zero emissions far sooner than existing global climate agreement commitments. There are technical and ethical considerations in relying on unproven negative emissions technologies[28,29] necessary for the extreme reductions demanded by SSP5-3.4-OS, while pursuing an unfettered emissions policy until 2040. Furthermore, the fat-tailed nature of the damage as a function of temperature means that irreversible (tipping point) impacts[56] from overshoot scenarios make them inherently riskier than lower emission, and perhaps SG, scenarios.

While our analysis reflects a deliberate scope designed to streamline the assessment process, it is essential to recognize that the impacts of climate change extend far beyond economic considerations. Factors such as social well being, ecosystem health, and cultural heritage preservation are crucial aspects that are not within the purview of this economic-centric analysis. These multifaceted dimensions of climate change impacts, although beyond the scope of our study, merit separate and thorough examination to provide a holistic understanding of the complex challenges posed by climate change. Future research can expand on our approach by incorporating additional impact dimensions, providing a more comprehensive view of climate change risks and mitigation trade-offs. The combined SAI and moderate mitigation measures (Figure 5) suggest (albeit with a single ESM) that the 1.5°C target may be achieved while limiting economic climate damages to a level comparable with the politically and technologically challenging sustainable development pathway. Scientific uncertainties surrounding the effectiveness, scalability, and long-term impacts of SG and CDR techniques necessitate comprehensive research, rigorous modeling, and robust international collaboration to mitigate the risks inherent in unintended consequences and to inform responsible decision-making.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Yating Chen (chenyt2016bnu@gmail.com).

Materials availability

This study did not generate new unique materials.

Data and code availability

All CMIP6 model data used in this work are available from the Earth System Grid Federation (https://esgf-node.llnl.gov/projects/cmip6, last access: 1 July 2023). The SAI-1.5 experimental data are available from MacMartin et al. (2022).[20] The socio-economic projections are available from the Shared Socioeconomic Pathways Database (https://tntcat.iiasa.ac.at/SspDb, last access: 1 July 2023). The PAGE-ICE software can be downloaded from Yumashev et al. (2019).[37] Scripts for plotting and data processing are available from https://github.com/labtry/PAGE-ICE-with-CMIP6.

Overall framework

IAMs quantify climate damage using a climate module to model the Earth system's response to GHG emissions and an impact module to quantify the economic impacts of climate change.[33] The PAGE IAM (Figure S4) has been widely used, for example, for the assessment of social costs of carbon[57] and costs of Arctic permafrost degradation.[41] PAGE-ICE includes IPCC AR5 climate science and economics as well as nonlinear Arctic feedbacks.[37] As with other IAMs, PAGE's climate module is based on a simple zero-dimensional box model to simulate the response of the climate system to GHG emissions. Exchanges of mass and energy between atmospheric, oceanic, and terrestrial carbon pools are prescribed and, in contrast with full ESMs, the complex feedback between carbon and the climate system are thus poorly defined in the simplified IAM climate modules.[58]

We overcome these limitations by generating scenario-dependent Gaussian distributions to express the simulated global and regional warmings from the mean and standard deviation of the CMIP6 climate simulations (Figure S8; and S9). Global and regional temperature changes are then translated into economic impacts for multiple regions and sectors based on the impact module of PAGE-ICE. Climate impacts are assumed to be caused by temperature changes alone, as abundant evidence shows that temperature is the major determinant of economic damage in both abatement and geoengineering scenarios.[8,18,59] Locally, there may be more important factors in climate damage than temperature, but they are rare or unexplored to date. SG imposes additional disturbances over pure GHG scenarios by changing long- and short-wave radiative forcing, which changes humidity and circulation patterns.[15,17] While looking at temperature damages alone undoubtedly ignores the potential impacts of SG on precipitation patterns in localized areas,[60] all analyses to date indicate that temperature responses and their uncertainties dominate precipitation responses in climate damage assessments at the global scale.[16,18]

Each module contains a varying number of uncertainty parameters, some of which are calibrated by specialized models and expert judgment, but most of which are approximated by triangular distributions.[37] Except for the specifically noted options, the parameters used in this study follow the recommended settings of PAGE-ICE.[37] In 100,000 Monte Carlo simulations, these parameters are sufficiently perturbed to cover the possible combinations of parameter distributions and to obtain probability distributions of the output estimates.

Input data

We use socioeconomic data and anthropogenic emission projections released by the Shared Socioeconomic Pathways Database[61] to quantify climate change damages and assess mitigation costs. Socioeconomic data include annual rates of change in regional population and GDP (Figure S11), and anthropogenic emissions (Figure S12) are grouped into six major categories: CO_2, CH_4, N_2O, sulfate aerosols, linear gases (perfluorinated carbons, hydro-fluoro-carbons, and sulfer hexafluoride), and residual GHGs (modeled as additional radiative forcing). These input data are mapped to eight world regions and harmonized with the historical inventory for the base year 2015. We assume that the two G6 scenarios follow the same socioeconomic development and GHG emission pathways as SSP5-8.5.

Simulation of sea level rise

The CMIP6 models only report global mean sea level rise (SLR) caused by changes in thermal structure ("zostoga") and do not have reliable estimates of water flux inputs from land/glaciers,[62] so in this study we use PAGE-ICE's dynamic emulator to simulate SLR. The PAGE-ICE model uses a gamma distribution to model the time constant in the governing equation, and its distribution parameters are calibrated to introduce a fat-tailed risk of catastrophic SLR.[37]

Impact assessment

PAGE-ICE includes economic assessments for four broad categories of climate-driven impacts, including SLR (coastal flood damage and relocation), economic (direct and indirect damage to the overall economy), non-economic (ecosystem services and public health), and discontinuity (large-scale damage associated with tipping points). Of these, the economic impacts related to SLR are calibrated to ref.,[63] and the parameters for the non-economic impacts of

PAGE-ICE are updated according to the IPCC AR5 report.[5] Updates on climate tipping points and catastrophic SLR risks reduce the magnitude and uncertainty of discontinuous damages.[37] In addition, PAGE-ICE provides new damage functions for the economic sector based on a macroeconometric analysis of the impact of historical temperature shocks on economic growth in 166 countries by Burke et al.[34] We use the damage function "Burke, Pulled, Lag = 2, Consum-Only," which assumes that the economic impacts of temperature shocks last for 2 years and are taken entirely out of consumption.

Equity weighting and discounting

We choose the "Equity-weighting ON, PTP discounting" scheme as offered by PAGE-ICE, which multiplies the change in consumption by equity weights using the equity-weighting approach proposed by Anthoff et al.[43] Equity weights can correct for regional income differences by converting changes in consumption to utility, reflecting the fact that the same degree of damage affects poorer countries more than richer ones. Equity weights in PAGE-ICE are a function of residual consumption, with the reference value of the EU region in 2015 as the denominator and indexed by elasticity of marginal utility (EMUC). Since the EMUC is always greater than zero, the effect of equity weighting is to increase the impact valuation of regions that are poorer than the reference region and decrease the impact valuation of richer regions. Finally, the equity-weighted damages are discounted by the PTP rate.

Mitigation and adaptation

Mitigation costs depend on the levels of ambition of each region under a given emissions scenario relative to the estimated business-as-usual (BAU) trajectory. The BAU emission scenarios in PAGE-ICE are referenced to RCP8.5 and cover roughly the range between RCP6.0 and pathways beyond RCP8.5 because of uncertainty in long-term emission projections.[37] The marginal abatement cost curves in PAGE-ICE are calibrated based on the methodology described in ref.,[64] which considers technological advances in energy production and the levels of mitigation needed to achieve climate goals. Adaptation consists of autonomous adaptation to temperature-driven impacts and planned adaptation to SLR impacts,[37] with adaptation effects depending on regional temperature and SLR in the eight regions and the corresponding tolerable levels determined by the choice of planned adaptation expenditures.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.09.004.

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AUTHOR CONTRIBUTIONS

A.L., conceptualization, methodology, investigation, visualization, writing - original draft, and writing - review and editing; J.C.M., writing - review and editing, and funding acquisition; X.C., writing - review and editing, and funding acquisition; Y.C., conceptualization, methodology, and writing - review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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