LETTERS
https://doi.org/10.1038/s41558-020-0699-y
nature climate change

Climate effects of aerosols reduce economic inequality

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The climate effects of anthropogenic aerosols have masked some of the warming induced by GHGs[1] along with some impacts of that warming[2]. These temperature effects may be beneficial but are almost certainly overwhelmed by aerosols' negative health impacts[3]. Recent analyses of economic impacts have concluded that warming harms economies in warm climates, but provides economic benefits in cold climates[4]. Here we investigate whether aerosol-induced cooling would have a positive effect on less wealthy economies in hotter regions and a negative effect on wealthier economies in colder regions. Climate simulations over the historical period both with and without anthropogenic aerosol emissions, using a fully coupled ocean and atmosphere climate model, indicate that in year 2010 anthropogenic aerosol emissions were cooling the Earth by 0.72 ± 0.02 °C relative to a scenario without such emissions. Due to opposing economic impacts in different regions, the net economic impact of aerosol-induced cooling is likely to be small at the global scale. However, these results suggest that the cooling effects of anthropogenic aerosols benefit developing tropical economies while harming developed high-latitude economies, and thus the temperature effects of past aerosol emissions have probably diminished global economic inequality.

Anthropogenic aerosols, which originate primarily from fossil fuel combustion and biomass burning, have long been regarded as a major threat to air quality[5] and public health[3]. Previous studies have estimated that such aerosols cause 5.6–8.9 million premature air pollution deaths globally each year[3,6], and shorten life expectancy by ~0.64 yr for each 10 μg m^{-3} increase in concentration[7]. These health impacts are large and lead to correspondingly large economic damages. Meanwhile, these same aerosols scatter incoming solar radiation and interact with clouds[1,8], thereby masking some of the GHG-induced warming and related impacts[1], such as the intensification of the global hydrological cycle[9]. Globally, anthropogenic aerosols were estimated[10] to have an annual mean radiative forcing of −0.9 W m^{-2}, offsetting roughly one-third of the positive forcing from the increases in well-mixed GHG concentrations since the 1750s. Whereas the global forcing from anthropogenic aerosols has been a subject of much study[1–3] and has been reviewed by the IPCC[10], the economic effects of temperature changes caused by such aerosol emissions have not been assessed previously.

In addition to having impacts on natural systems, including ice sheets and ecosystems, that are difficult to monetize, global warming is expected to affect economic output by influencing productivity such as labour productivity and crop yields[4]. Economic impacts of global warming have been estimated using integrated assessment models (IAMs), which estimate losses of current global economic output based on changes in global mean temperature[11]. Several studies have also quantified country-level economic impacts of climate changes based on nonlinear empirical relationships between temperature and economic growth[4,12,13]. These relationships conclude that country-level economic growth peaks at an optimal temperature and decreases at higher or lower temperatures, which indicates that additional warming would harm economies in warm climates but benefit economies in cold climates[4]. While there is a lack of consensus regarding whether climate change impacts economic productivity, economic growth or both[14,15], it is clear that in the very hottest and very coldest places on our planet, per capita economic productivity is low, and that, other things being equal, economic productivity reaches a maximum at some intermediate temperature. If the economic effects of global warming are positive in relatively cold regions and negative for relatively hot regions, it is likely that the cooling caused by historical aerosol emissions would have economic effects of the opposite sign: positive in relatively hot regions and negative in relatively cold regions. Note that high-latitude regions could potentially benefit economically from warmer temperatures, even if those warming were to result in substantial disruption to natural systems[16].

Here, we analyse the spatial distribution of temperature changes induced by historical anthropogenic aerosols and estimate economic impacts for the current world. Details of our analytic approach are documented in the Methods. In summary, we employ the fully coupled ocean and atmosphere Community Earth System Model[17] (CESM v.1.2.2) to simulate two time-dependent scenarios from 1850 to 2019: 'With-Aerosol' applies the historical anthropogenic and natural forcers, historical up to 2005 and Representative Concentration Pathway 8.5 (RCP8.5) thereafter[18,19]; 'No-Aerosol' follows the same configuration but fixes the anthropogenic aerosol emissions, that is, emissions of black carbon, organic carbon, and sulfate aerosol and its gaseous precursor sulfur dioxide (SO_2), at the pre-industrial (that is, 1850) levels. Simulation of each scenario is branched into an eight-member ensemble starting from 1950, with slightly different perturbations in initial atmospheric states to ensure statistical significance of results. We then convert the simulated aerosol-induced changes in country-level surface air temperature (results averaged over the period 2000 to 2019 from eight ensemble members) into economic impacts in year 2010 using empirical macroeconomic relationships between temperature and growth in the gross domestic product (GDP) estimated by Burke et al.[4]. Following the 'No-Aerosol' scenario, we also conduct a pre-industrial sulfate scenario ('No-Sulfate') to investigate the impacts of the major atmospheric cooling forcer: sulfate aerosol[20] (see Methods). Unless stated otherwise, model results reported hereafter correspond to the mean value of a 20-year period centred on 1 January of the reported year. For example, temperature and changes reported for 2010 refer to the average value between 2000 and 2019.

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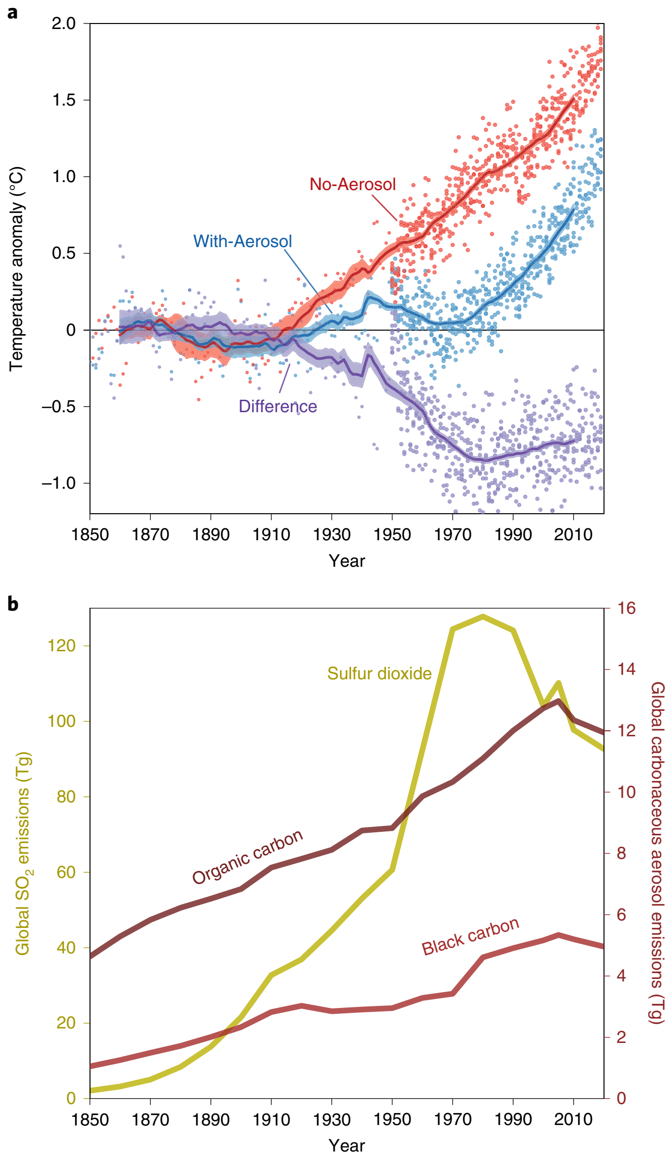

Fig. 1 | Trend of global mean surface temperature and anthropogenic aerosol emissions. a, Global mean surface temperature anomalies for scenarios with and without anthropogenic aerosol emissions and their difference. Shaded lines show the 20-year moving averages (that is, centred on 1 January of the reported year) of temperature anomalies and the standard errors. Filled dots represent the simulated annual mean surface temperature anomalies. Temperature anomalies are calculated relative to the simulated pre-industrial climatology (see Methods). Standard errors of the 20-year moving average of temperature anomalies are calculated with effective sample sizes adjusted for autocorrelation[32]. **b**, Global emissions for black carbon, organic carbon and sulfur dioxide (both sulfate and SO_2 emissions) during 1850–2020 with historical values up to 2000[18] and RCP8.5 values thereafter[19].

Figure 1 shows trends in simulated global mean surface air temperature anomalies in scenarios with and without anthropogenic aerosol emissions. Global mean surface air temperatures in the scenarios diverge in the early twentieth century (Fig. 1a), and the gap widens after the 1950s as global anthropogenic emissions of sulfate (that is, both sulfate and SO_2 emissions), a major cooling agent in the atmosphere[20], accelerate (Fig. 1a,b). Clean air policies in North America and Europe then drove the decline in global sulfate emissions after 1980 (Fig. 1b), while emissions of black carbon and organic carbon kept increasing[18] until 2000. Due to the relatively short lifetimes of aerosols, atmospheric burdens closely follow emissions. Global mean aerosol-induced temperature changes correspond to the temporal pattern of the global total sulfate emissions, due to sulfate's strong cooling capability[20], taking into consideration the temporal pattern of other aerosol emissions (that is, black carbon and organic carbon) and time lags in climate response associated primarily with the heat capacity of the oceans[21]. Twenty-year average results indicate that the greatest global mean temperature reduction due to anthropogenic aerosols (0.85 ± 0.02 °C; Fig. 1a) occurred around 1980—near the peak in global sulfate emissions. We estimate that anthropogenic aerosols reduced 2010 global mean surface temperature by 0.72 ± 0.02 °C, similar to estimates from previous studies[2,3,22]. Anthropogenic sulfate is estimated to be responsible for 0.55 ± 0.02 °C of this cooling (Supplementary Discussion 1 and Extended Data Fig. 1).

Temperature responses to aerosols are much less localized than the aerosols themselves (as indicated by aerosol optical depth) and exhibit substantial high-latitude amplification (Fig. 2 and Extended Data Figs. 2–4). Statistically significant cooling effects of anthropogenic aerosols are observed over most of Earth's land area and all populated areas, and also over large parts of the ocean (Fig. 2b and Extended Data Fig. 2b).

The spatial patterns of the simulated temperature responses to anthropogenic aerosols are similar to the patterns of warming driven by GHGs, but opposite in sign[23]. For example, maximum aerosol-induced cooling is observed at the Arctic region, which directly opposes the Arctic amplification of global warming that has occurred during the past decades[24]. Furthermore, our simulations show warming in the North Atlantic, a phenomenon opposite in sign but similar in character to changes seen in the twentieth century observations and greenhouse warming simulations[25], which could probably be attributed to the aerosol-forced enhancement of the Atlantic Meridional Overturning Circulation[26].

Our simulations show that, without anthropogenic aerosols, global mean temperature would have reached the year 2010 value around 1970; that is, on average, anthropogenic aerosols have effectively delayed global warming by 40 years. However, the time at which year 2010 temperatures would have been reached in the absence of aerosol emissions varies greatly among regions, in part due to differing temperature effects of regional aerosol emissions[27]. For example, western and central United States and western Europe are experiencing annual mean temperatures that would have occurred 40 to 60 years earlier in a world without anthropogenic aerosol emissions (Fig. 2c and Extended Data Fig. 2c). Temperatures in eastern China and northern India would have occurred more than 70 years earlier in the absence of anthropogenic aerosol emissions (Fig. 2c).

Figure 2d shows the country-level percentage changes in GDP in 2010 inferred from the Burke et al.[4] response function due to the aerosol-induced cooling in 2010. In this case, most countries in tropical and subtropical regions are benefitting from the cooling effects of aerosols, with the highest economic benefits observed over the Arabian Peninsula and South Asia (red shading in Fig. 2d). Among the investigated countries, 109 countries (65%), encompassing about 21% of global GDP and 59% of the global population, exhibit >90% likelihood ('very likely'[28]) of positive economic impacts from aerosol-induced cooling (Extended Data Fig. 5a). In contrast, aerosol-induced cooling is damaging economies at higher latitudes of the northern hemisphere (blue shading in Fig. 2d). Together, 30 countries (18%), encompassing about 21% of global GDP and 8% of the global population, exhibit >90% likelihood of negative economic impacts (Extended Data Fig. 5a). The specific quantities plotted in Fig. 2d (also see Extended Data Fig. 6) depend on the specific response function applied, but the general spatial character will be robust for any climate response function that represents declines in productivity in regions with annual mean temperatures substantially above or below 13.1 °C, which is the median estimate of the temperature optimum in Burke et al.[4].

Figure 3 shows the relationship of estimated country-level changes in temperature and GDP due to anthropogenic aerosols (also see Fig. 2d). Globally, we estimate that the year 2010 population-weighted annual mean surface temperature (black circles in Fig. 3) has been reduced by 1.0 ± 0.03 °C by these aerosols. However, despite this large temperature effect, the net effect on global GDP does not differ significantly from zero: our median estimate is that global GDP in 2010 US\$ is US$_{2010}$120.7 billion (90% confidence interval (CI): US$_{2010}$−95.1 to US$_{2010}$303.4 billion) or 0.19% (90% CI: −0.15% to 0.47%) larger in 2010 than it would be in the absence of anthropogenic aerosols. Although other climate response functions might produce larger regional economic effects, the net effect globally is likely to be small (Supplementary Table 1).

However, this global aggregation of economic impacts conceals substantial heterogeneity among countries (Fig. 3). As expected, cooling effects generally lead to economic damages to countries in cold climates (bluer circles in Fig. 3) but bring benefits to countries in warm climates (greener circles). For example, countries such as Finland and Iceland experience more than 1.2 °C declines in population-weighted annual mean temperature from anthropogenic aerosols. Consequently, GDP in these cold-climate countries is estimated to decline by 0.99–1.5%. Countries in South Asia and on the Arabian Peninsula (for example, Pakistan, Bangladesh, India, Oman and United Arab Emirates) also experience greater than 1.2 °C declines in annual temperature. Conversely, these hot-climate countries obtain notable economic benefits, more than 1.5% increment in GDP, from aerosol-induced cooling (Figs. 2d and 3). In contrast to countries whose year 2010 temperatures are more extreme, many major economies are in temperate regions with annual mean temperatures close to the economic optimum, and so are less affected by aerosol-induced cooling (Fig. 3). For example, temperature changes are estimated to be approximately −0.9 to −1.1 °C for the top three largest economies (that is, the United States, China and Japan) but their corresponding GDP benefits are small and subject to large uncertainty (Extended Data Figs. 7 and 8).

Figure 4 shows countries sorted by percentage changes in GDP due to aerosol-induced cooling from most negative (left) to most positive (right). Aerosol-induced cooling tends to benefit the economic productivity of developing countries (bluer shades) while harming developed countries (redder shades; also see Fig. 2d and Extended Data Fig. 7), which reduces global economic inequality (Extended Data Fig. 9). For example, aerosol-induced cooling reduces the ratio of per capita GDP between the top and the bottom population-weighted deciles (a common measure of inequality[29]) by 1.01% (90% CI: 0.59–1.56%), with a virtually certain likelihood (>99%) that the ratio reduces. Likewise, the aerosol-induced cooling reduces the ratio of per capita GDP between the top and bottom population-weighted quintiles (also a common measure of inequality[29]) by 1.06% (90% CI: 0.63–1.55%), with a virtually certain likelihood (>99%) that the ratio reduces (Extended Data Fig. 9 and Supplementary Table 1). Anthropogenic sulfate-induced cooling is also virtually certain to reduce country-level economic inequality (Supplementary Discussion 1 and Extended Data Fig. 10).

Our study isolates and quantifies the cooling effects of anthropogenic aerosols on surface temperatures and estimates country-

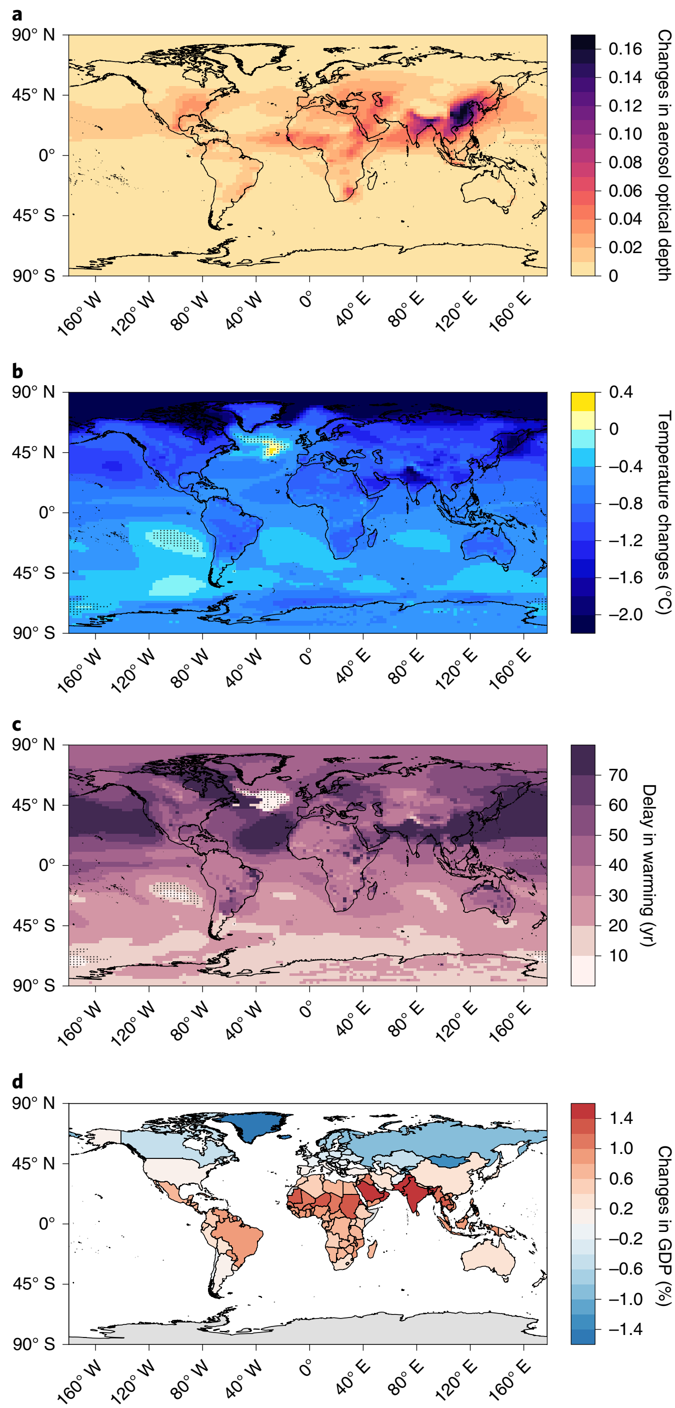

Fig. 2 | Spatial distribution of climatic and economic impacts introduced by anthropogenic aerosol emissions. a, Changes in aerosol optical depth at 550 nm in response to anthropogenic aerosols averaged over 2000–19. **b**, Changes in surface air temperature in response to anthropogenic aerosols averaged over 2000–19. **c**, The year that the 2010 temperature (averaged over 2000–19) would have occurred without anthropogenic aerosols. Results are calculated by comparing year 2010 temperature from the control scenario (that is, With-Aerosol scenario) with historical temperature (20-year running average) derived from the scenario with anthropogenic aerosol emissions set to 1850 levels (that is, No-Aerosol scenario); difference between 2010 and the central year of the matched time period is illustrated. **d**, Country-level changes in annual GDP in response to anthropogenic aerosol-induced cooling averaged over 2000–19 based on Burke et al.[4] response functions (see Methods). Grid markings in **b** and **c** indicate regions where aerosol-induced temperature changes are not statistically significant at the 95% confidence level via one-sample *t*-test with an effective sample size adjusted for autocorrelation[32]. Countries and regions with missing values are shaded in grey in **d**.

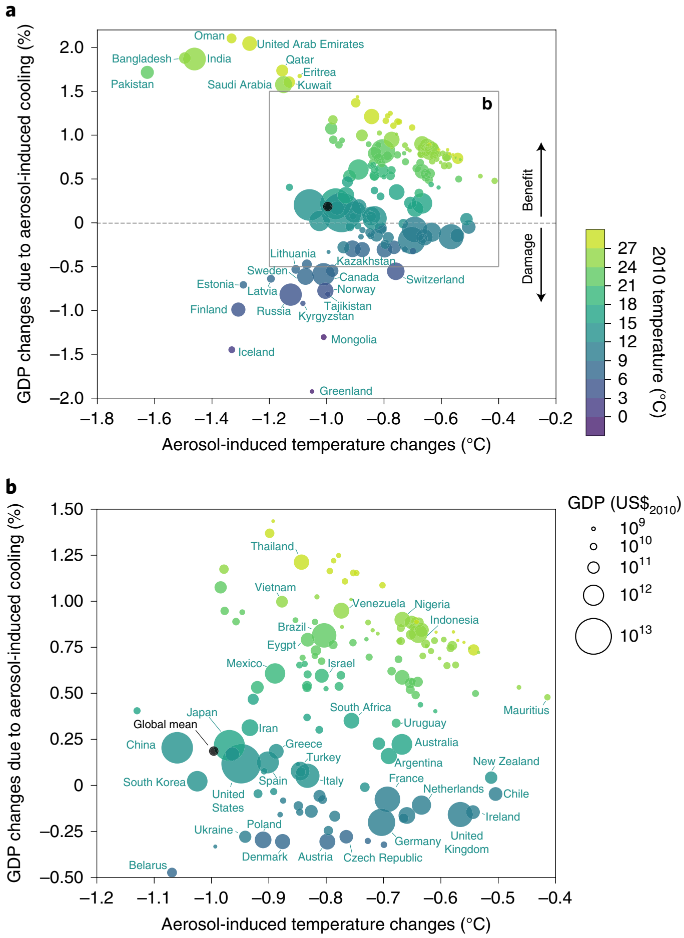

Fig. 3 | Country-level temperature changes and the associated annual GDP increment induced by anthropogenic aerosols. a, Results for all studied countries. **b**, Details of the area bounded by solid lines in **a**. Points are shaded by the year 2010 population-weighted surface air temperature of each country (derived from the ERA-Interim reanalysis data, see Methods), and the size of the points depicts country GDP in 2010, except for the global mean results (black circles). Temperatures and temperature changes shown in this figure are the country-level population-weighted mean results used to calculate associated economic impacts[4].

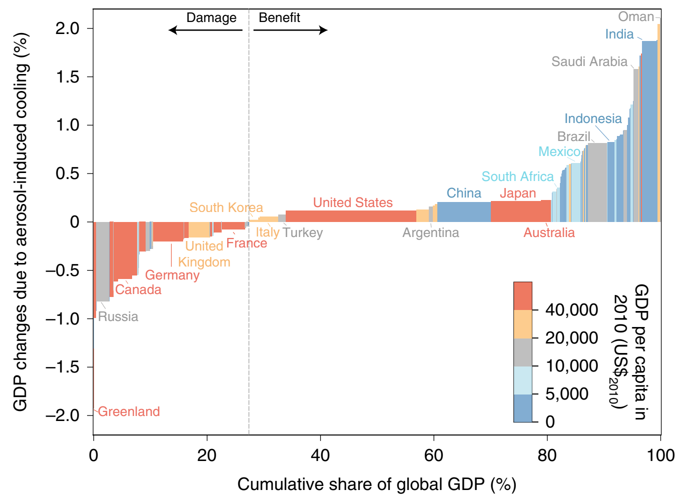

Fig. 4 | Country-level percentage changes in GDP associated with anthropogenic aerosol-induced cooling. Countries are sorted by percentage change in GDP attributable to aerosol-induced cooling from the lowest on the left to the highest on the right. The *x* axis shows the share of global GDP for each country. The area of each bar represents the country-specific fraction of aerosol-induced cooling GDP changes out of global GDP in 2010. Bars are shaded by the country-level GDP per capita in 2010. Countries that have large GDP increases from aerosol-induced cooling tend to have low per capita GDP, whereas countries that have large GDP decreases tend to have high per capita GDP. See Extended Data Fig. 7 for the same figure with error bars.

level economic effects of that aerosol-induced cooling. We find that the net economic effect on the global economy is negligible due to counteracting regional effects. Estimated regional economic impacts are sensitive to the choice of response function. A major debate surrounding response functions focuses on whether global warming affects current economic output or growth rates or both[14,15]. In this study we use a response function derived by Burke et al.[4] to calculate the country-level economic impacts of climate change in one year on economic productivity in that year (that is, nominal 2010) instead of the cumulative impacts. Our calculation of damages in year 2010 from climate change in 2010 demonstrates a spatial pattern of aerosols' climate effect that results in reduced global economic inequality; nevertheless, over many years, overall magnitudes would be larger if climate damage does impact GDP growth rates[30]. We test the sensitivity to the choice of response function and calculate the resulting range in global GDP changes attributable to aerosol-induced cooling as −0.1% to 0.51% (Supplementary Table 1), robustly indicating that aerosol-induced cooling has a relatively small effect on the global economy. For those response functions that could be applied at the country level, high probability of reduced global economic inequality is obtained from most of the response functions (Supplementary Table 1). Our global scale results depend primarily on the pattern of aerosol-induced changes in zonal mean temperature, but country-level results are influenced by variability from the zonal mean and thus are likely more model-dependent.

Because of the severe threats of aerosols on air quality and public health, strict policies have been gradually implemented by major emitters, including North America, Europe and East Asia[18,31]. Global efforts to reduce aerosol emissions to protect public health are expected to continue in the future[19]. Health benefits of reducing aerosol emissions almost certainly overwhelm any possible climate damage caused by these emission reductions[3]. Our results indicate that, motivated by health concerns, policies could be put in place to reduce aerosol emissions without risking substantial additional climate damage at the global scale; however, distributional effects remain a concern. Due to the divergent impacts of current anthropogenic aerosols on rich extra-tropical countries and poor tropical countries, all else being equal, climate effects of aerosol emission reductions will further exacerbate global economic inequality.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-020-0699-y.

Received: 5 April 2019; Accepted: 10 January 2020;
Published online: 17 February 2020

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Methods

Climate modelling. Simulations in this study are conducted in the Community Earth System Model v.1.2.2 (CESM 1.2.2) with fully coupled atmosphere (Community Atmosphere Model v.5, CAM5), ocean (Parallel Ocean Program v.2, POP2), land (Community Land Model v.4, CLM4) and sea-ice (Los Alamos Sea Ice Model v.4, CICE4) models[17]. The applied CAM5 atmosphere model provides a fully interactive aerosol scheme (three-mode Modal Aerosol Module, MAM3[33]) that incorporates the emission, transportation, scavenging and chemical processes of aerosols, and also considers the direct and indirect radiative impacts of aerosols. For our simulation, the resolution of CAM5 is 1.9° latitude by 2.5° longitude with 30 vertical layers. The ocean model applies a Greenland dipole grid system with a resolution of ~1°.

Two scenarios of transient simulations are conducted from 1850 to 2019. The reference ('With-Aerosol') scenario applies all historical anthropogenic and natural forcers. Historical forcing is used for 1850–2004 and RCP8.5 forcing is used thereafter. The pre-industrial aerosol scenario ('No-Aerosol') is identical to the With-Aerosol scenario except that anthropogenic aerosol emissions (that is, black carbon, organic carbon and sulfate and its precursor SO_2) are fixed at 1850 levels. Simulations of each scenario are branched into eight cases starting from 1950 with slightly different perturbations in initial states to ensure robust differences in signals between the two scenarios. Each scenario is then represented by an eight-member ensemble and the presented results on temperature are derived based on the ensemble mean values. Temperature changes during the years 2000–19 are averaged to represent the estimates for year 2010 climate. To generate Fig. 2c, 20-year running averages of temperature over each grid are also calculated. We report uncertainties of the simulated temperature as one standard error.

We also conduct a pre-industrial sulfate scenario ('No-Sulfate') to investigate the impacts of the major cooling forcer: sulfate aerosols. The No-Sulfate scenario is identical to the No-Aerosol scenario except that only anthropogenic emissions of sulfate (emissions of sulfate and its gaseous precursor SO_2) are fixed at 1850 levels. Climate and associated economic impacts of sulfate aerosols are estimated based on the With-Aerosol and No-Sulfate scenarios.

A 110-year repeating annual cycle simulation is conducted for year 1850 as the pre-industrial control simulation using the fully coupled CESM 1.2.2 model. The simulated 110-year temperature is averaged to provide the pre-industrial state in Fig. 1a and Extended Data Fig. 1. Anomalies of temperature simulated by the transient simulations (that is, With-Aerosol, No-Aerosol and No-Sulfate) relative to the pre-industrial state are then derived.

Estimation of economic impacts. To better represent the climatological temperatures from the real world, country-level climatological surface air temperature averaged over the period 2001–18 with a centre at 1 January 2010 is obtained from the ERA-Interim reanalysis dataset[34]. Comparisons between the climatological temperature calculated based on the ERA-Interim dataset and the CESM simulation are documented in Supplementary Discussion 2. Estimated economic impacts from different climatological temperature datasets are also compared in Supplementary Discussion 2.

The simulated aerosol-induced country-level temperature changes together with the climatological temperature obtained from the ERA-Interim dataset are then converted into country-level economic impacts using empirical macroeconomic relationships between temperature and growth in the GDP[4]. The relationships were estimated based on observed historical temperature and growth in GDP per capita by applying multiple bootstrapping approaches, which estimate a separate response function for each resample[4]. We use the main form of the response function in Burke et al.[4], which was quantified by sampling the historical data by country with no lags of temperature; ~1,000 sets of parameters for the response function from the bootstrapping results are applied. The simulated changes in country-level population-weighted temperature averaged over the period 2000–19 from each of the eight ensemble members are applied individually to the response function. Together, ~8,000 realizations of the economic impacts of aerosol-induced cooling are obtained for each country. The median estimates and 90% CI of the GDP impacts are then derived. The global impacts of aerosol-induced cooling are aggregated from the country-level results. The year 2010 country-level GDP data and population information are obtained from the World Bank database[35] and applied to calculate the economic impacts associated with aerosol-induced cooling in 2010. Several other forms of response functions are also applied in this study as sensitivity tests (see Supplementary Table 1).

Note that some response functions consider damage in a specific year caused by climate change in previous ones. In this work, we consider only climate damage caused by climate change occurring in the year that the damage occurs. Consideration of cumulative effects would be expected to change the magnitudes but not the spatial patterns or qualitative conclusions drawn here.

Data availability

All data used in this study are available at https://github.com/YixuanZheng/Aerosol_Inequality_2019.

Code availability

All scripts used to support the findings of this study are available at https://github.com/YixuanZheng/Aerosol_Inequality_2019.

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Acknowledgements

We thank F. Tong and L. Duan from the Department of Global Ecology, Carnegie Institution for Science, for their helpful comments on this work.

Author contributions

Y.Z., S.J.D. and K.C. conceived the study. G.G.P. helped with climate modelling. Y.Z. ran model simulations, conducted analysis and wrote the manuscript with contributions from all co-authors.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41558-020-0699-y.

Supplementary information is available for this paper at https://doi.org/10.1038/s41558-020-0699-y.

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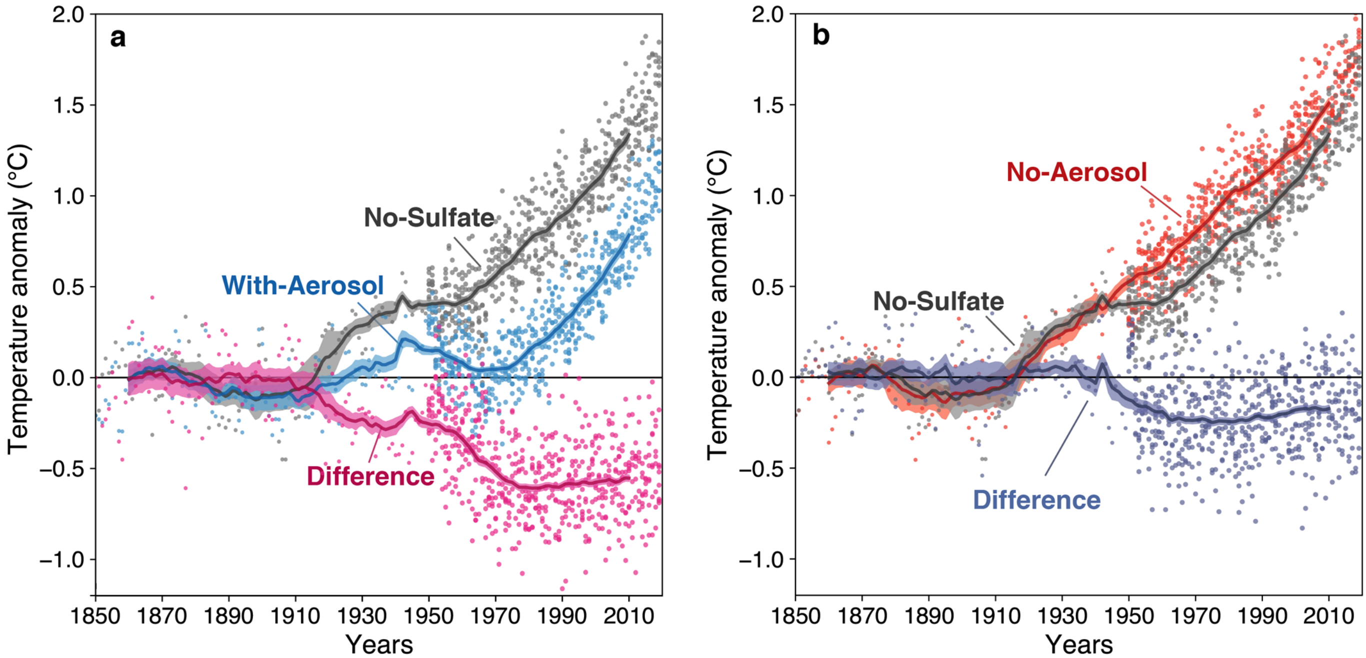
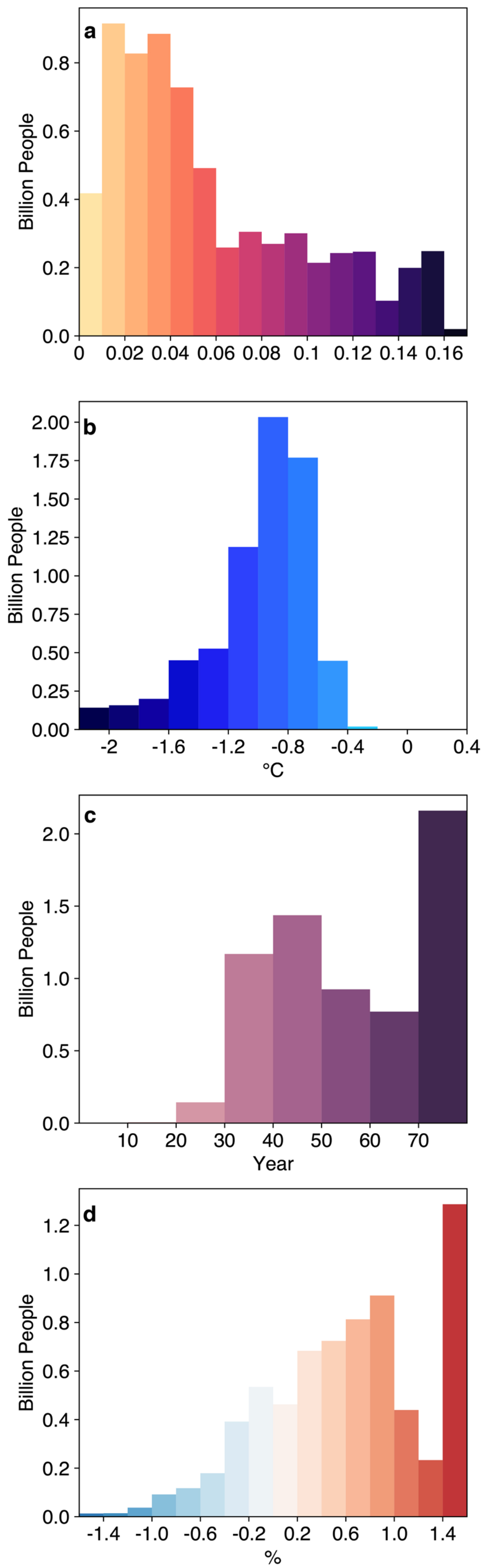
Peer review information *Nature Climate Change* thanks Luke Harrington, James Rising and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

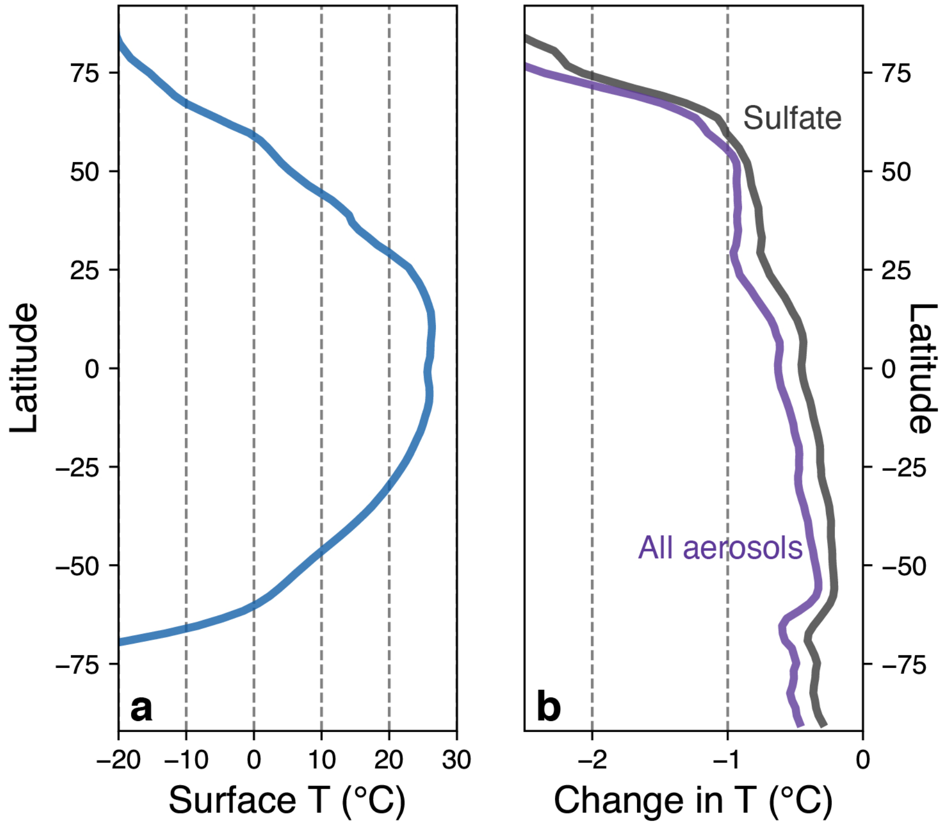


Extended Data Fig. 1 | Trend of global mean surface temperature in different forcing scenarios. (**a**) Global mean surface temperature anomalies for scenarios with anthropogenic aerosol and without anthropogenic sulfate aerosol emissions and their difference. (**b**) Global mean surface temperature anomalies for scenarios without anthropogenic aerosol and anthropogenic sulfate emissions and their difference. Shaded lines show the 20-year moving averages (that is, centered on 1 January of the reported year) of temperature anomalies and the standard errors. Filled dots represent the simulated annual mean surface temperature anomalies. Temperature anomalies are calculated relative to the simulated preindustrial climatology (see Methods). Standard errors of the 20-year moving average of temperature anomalies are calculated with effective sample sizes adjusted for autocorrelation[32].

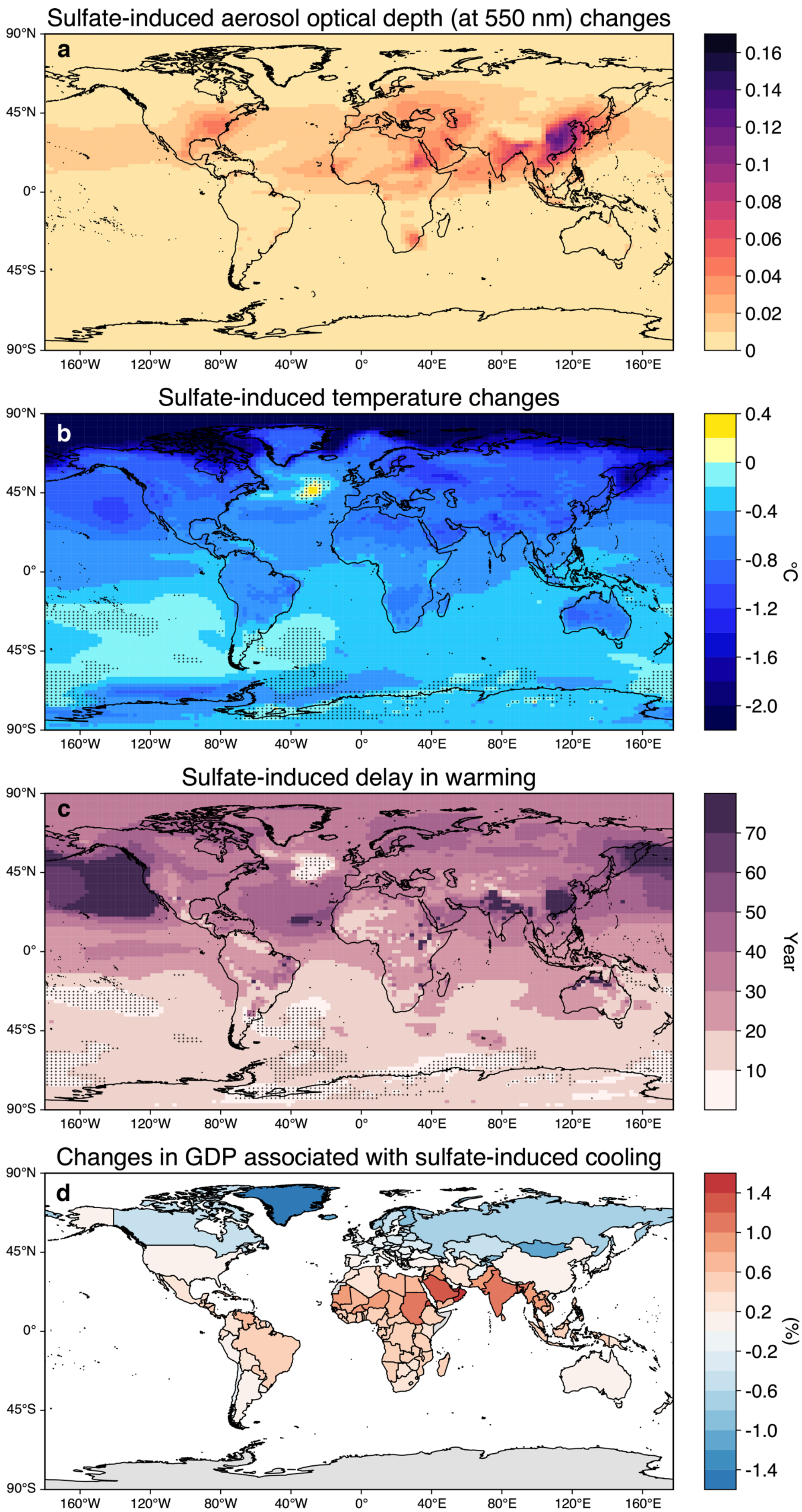


Extended Data Fig. 2 | See next page for caption.

Extended Data Fig. 2 | Population distribution of climatic and economic impacts of anthropogenic aerosol emissions. Identical to Fig. 2a–c but shows the population distribution: (**a**) Distribution of population exposed to aerosol optical depth; (**b**) distribution of population exposed to aerosol-induced temperature changes; (**c**) distribution of population exposed to different delays in GHGs-induced warming due to anthropogenic aerosols (that is, year in which 2010 temperatures would have been experienced without anthropogenic aerosol emissions). (**d**) Distribution of population exposed to percentage GDP changes associated with aerosol-induced cooling. Note that the scale of y-axis varies by subplots.

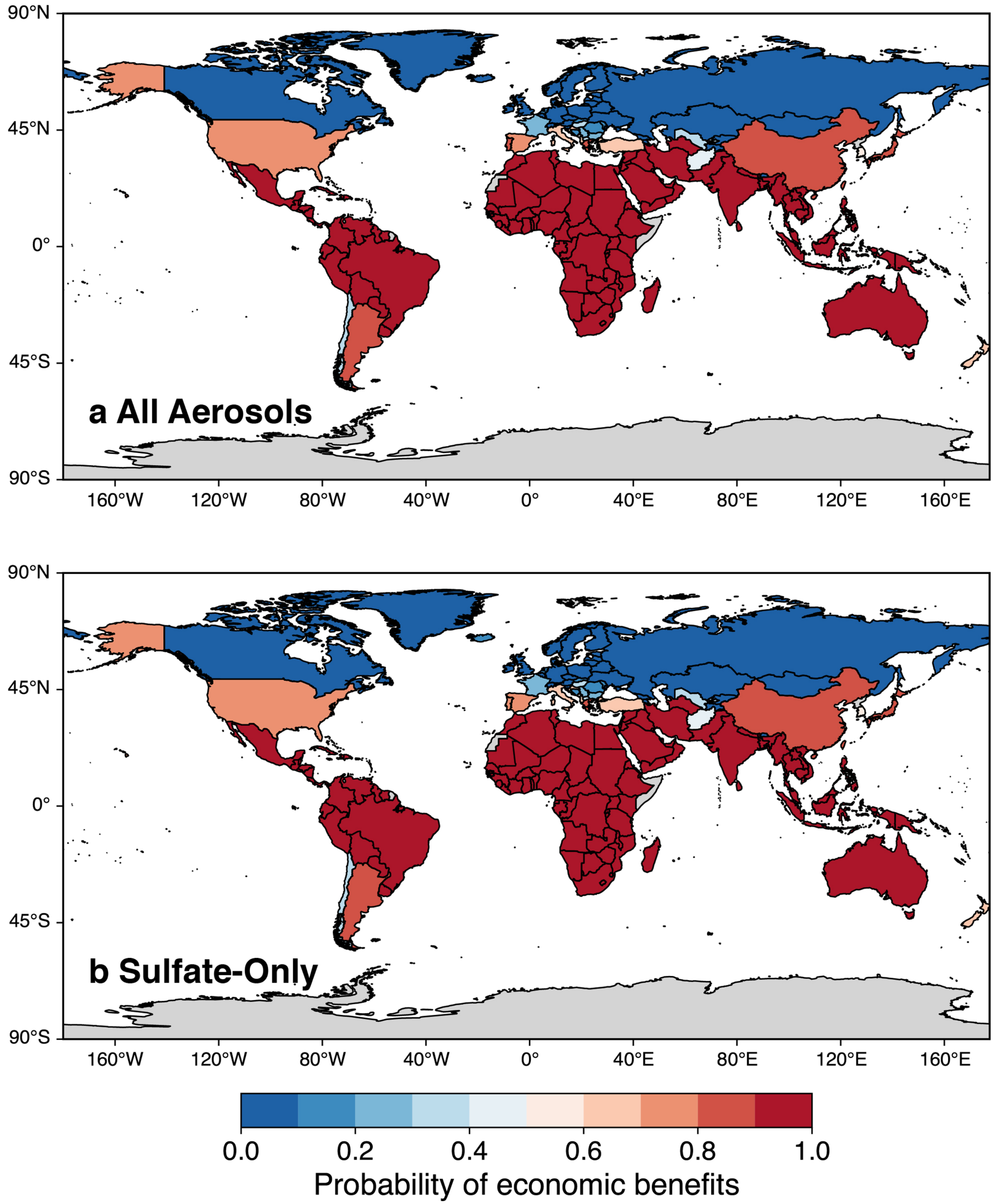


Extended Data Fig. 3 | Zonal mean climatological surface air temperature from With-Aerosol scenario (a) and changes induced by anthropogenic aerosols (b). Changes in zonal mean climatological surface air temperature induced by all aerosols is depicted by purple line and by sulfate only is depicted by the black line in (b).

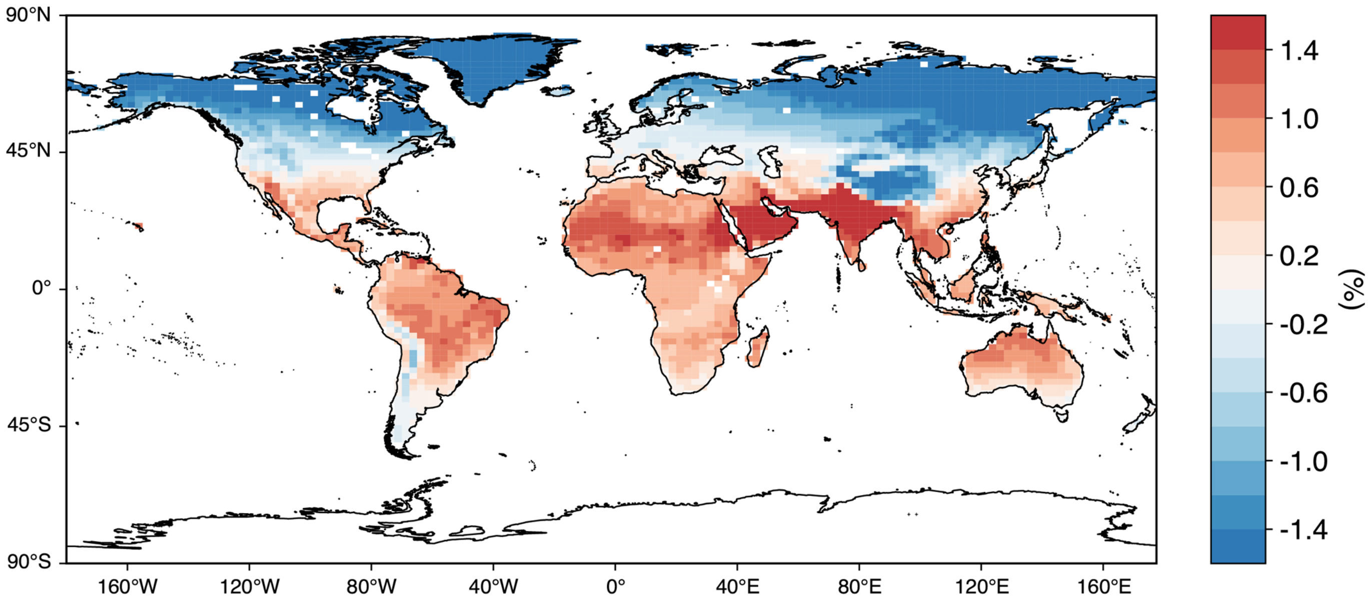


Extended Data Fig. 4 | See next page for caption.

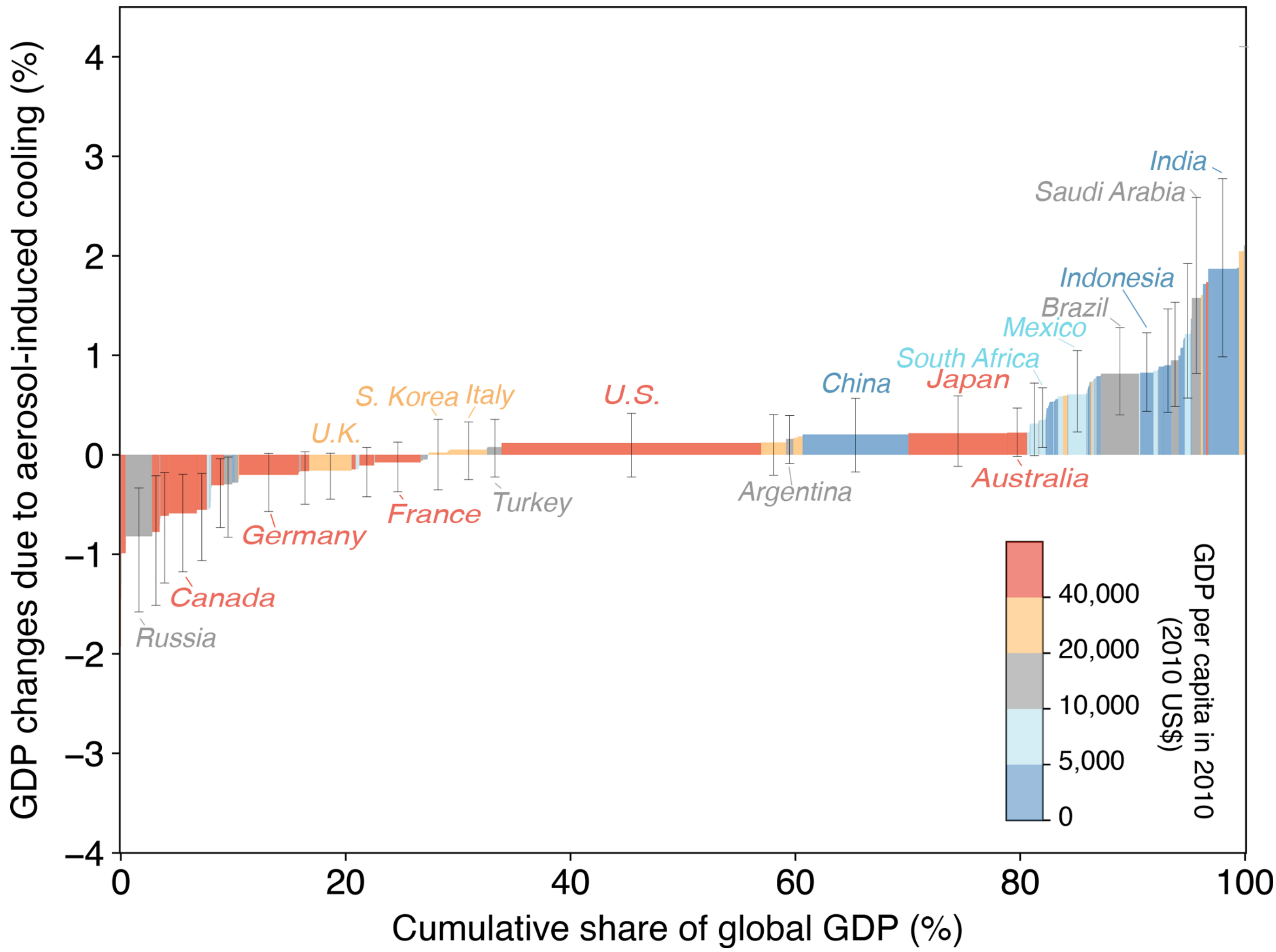
Extended Data Fig. 4 | Spatial distribution of climatic and economic impacts introduced by anthropogenic sulfate aerosol emissions. Same as Fig. 2 but shows the results for the impacts of anthropogenic sulfate aerosols. (**a**) Changes in aerosol optical depth at 550 nm (unitless) in response to anthropogenic sulfate aerosols averaged over 2000–19. (**b**) Changes in surface air temperature in response to anthropogenic sulfate aerosols averaged over 2000-19. (**c**) The year that year 2010 temperature (averaged over 2000-19) would have occurred without anthropogenic sulfate aerosols. Results are calculated by comparing year 2010 temperature from the control scenario (that is, With-Aerosol scenario) with historical temperature (20-year running average) derived from the scenario with anthropogenic sulfate emissions set to 1850 levels (that is, No-Sulfate scenario); difference between 2010 and the central year of the matched time period is illustrated. (**d**) Country-level estimates of changes in annual GDP in response to anthropogenic sulfate-induced cooling averaged over 2000-2019 based on Burke et al.[4] response functions (see Methods). Grid markings in (b) and (c) indicate regions that sulfate-induced temperature changes are not statistically significant at the 95% confidence level via one-sample *t*-test with an effective sample size adjusted for autocorrelation[32]. Countries and regions with missing value are shaded in grey in (d).



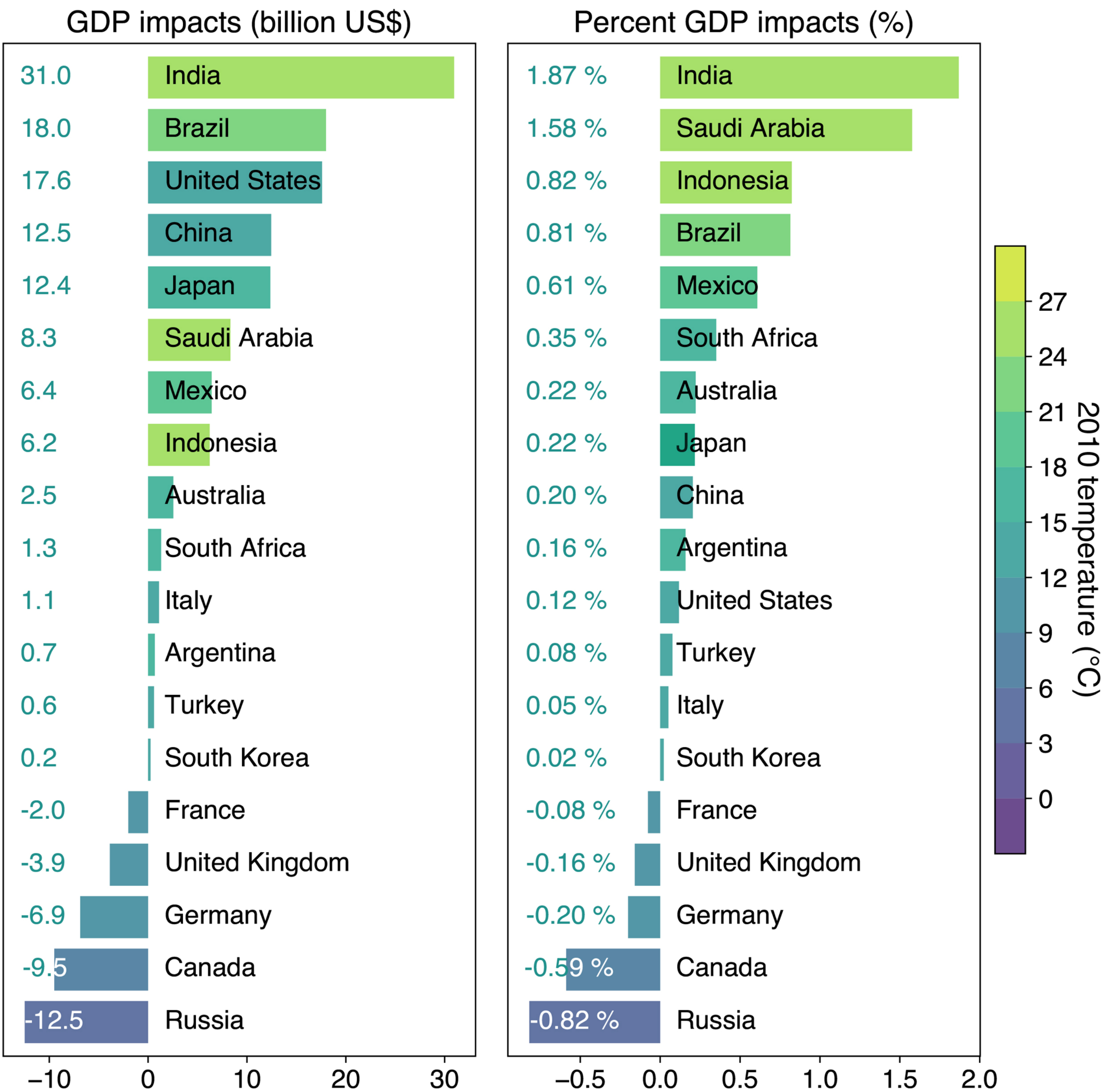
Extended Data Fig. 5 | The probability that cooling associated with anthropogenic aerosols has resulted in economic benefits at the country-level. (a) The probability associated with cooling induced by all considered aerosol (that is, OC, BC, and sulfate); (b) the probability associated with sulfate-induced cooling. The probability is calculated as the percentage of the ~8,000 realizations (see Methods) that show an increase in country-level GDP relative to a counterfactual world without anthropogenic aerosols. Here, low probability of benefits means a high probability of damages.



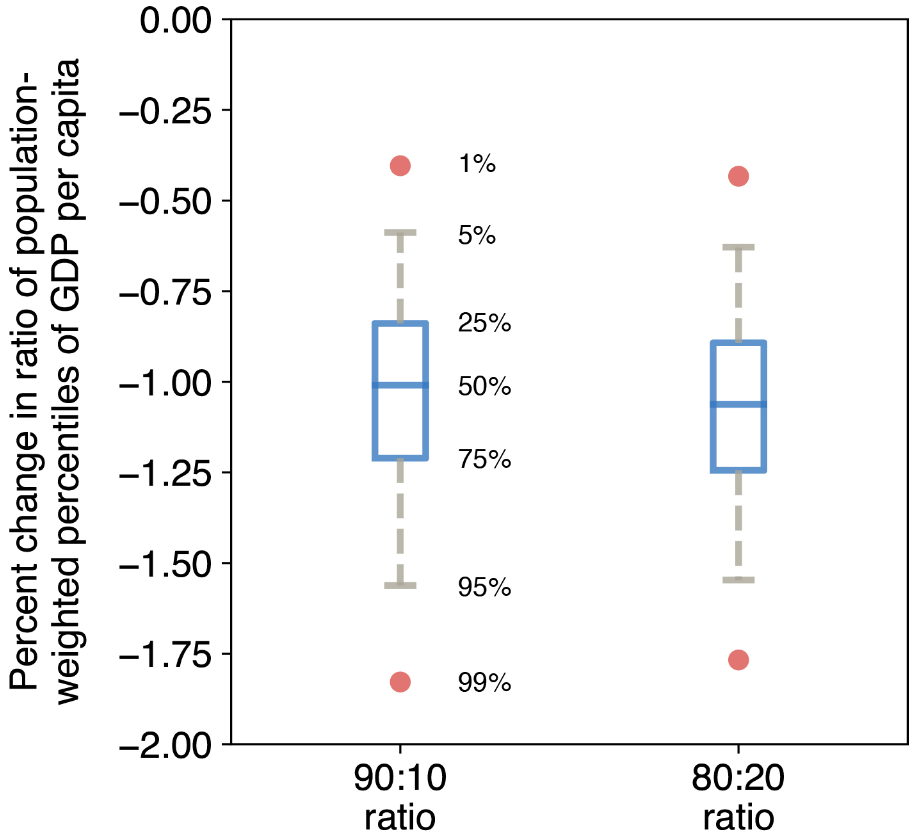
Extended Data Fig. 6 | Spatial distribution of economic impacts introduced by anthropogenic aerosol-induced cooling. Median estimates (of ~8,000 realizations, see Methods) of changes in annual GDP in response to anthropogenic aerosol-induced cooling averaged over 2000-19 based on Burke et al.[4] response functions. The ocean and large lakes are masked in white. Antarctica is also masked in white as it does not have any associated GDP.



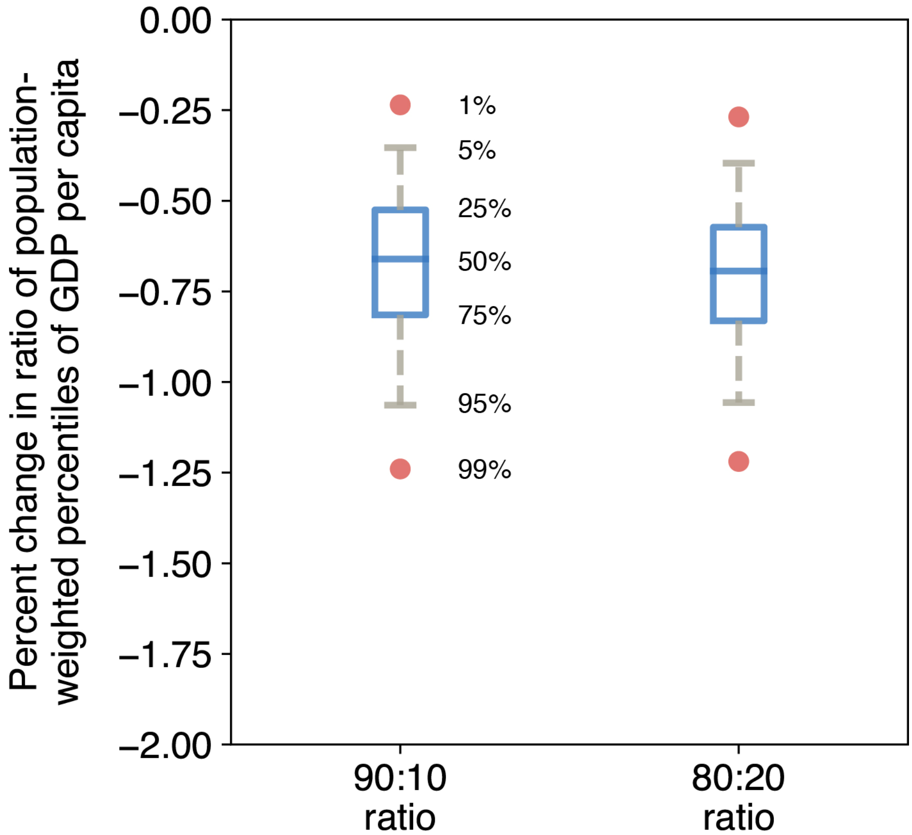
Extended Data Fig. 7 | Country-level percentage changes in GDP associated with anthropogenic aerosol-induced cooling. Countries are sorted by percentage change in GDP attributable to aerosol-induced cooling from the lowest on the left to the highest on the right. The x axis shows the share of global GDP for each country. The area of each bar represents the country-specific fraction of aerosol-induced cooling GDP changes out of global GDP in 2010. Bars are shaded by the country-level GDP per capita in 2010 (2010 US $). Countries that have large GDP increases from aerosol-induced cooling tend to have low per capita GDP, whereas countries that have large GDP decreases tend to have high per capita GDP. Error bars show the 90% CI (see Methods), which are plotted for countries with global GDP share larger than 0.5%.



Extended Data Fig. 8 | GDP increment introduced by aerosol-induced cooling among the G20 nations. (**a**) Median estimates (of ~8,000 realizations, see Methods) on changes in GDP in 2010 introduced by anthropogenic aerosols; (**b**) median estimates (of ~8,000 realizations, see Methods) on percentage changes in GDP in 2010 introduced by anthropogenic aerosols. Positive values indicate net benefits in GDP induced by the cooling effects of anthropogenic aerosols. Bars are shaded by the year 2010 population-weighted temperature of each country (derived from the ERA-Interim Reanalysis dataset, see Methods).



Extended Data Fig. 9 | Impact of aerosol-induced cooling on country-level economic inequality. Changes in global economic inequality were calculated as the percentage changes in the ratio of per capita GDP between the top and bottom population-weighted deciles (that is, 90:10 ratio) and quintiles (that is, 80:20 ratio) relative to the counterfactual world without anthropogenic aerosols. For example, the 50% line in the left box means that half of the ~8,000 combinations of response function parameters and model simulation ensemble members have >1% reduction in the ratio of country-level per-capita-GDP of the (population-weighted) 10% richest to 10% poorest countries – indicating that aerosol-induced cooling tend to reduce global inequality.



Extended Data Fig. 10 | Impact of sulfate-induced cooling on country-level economic inequality. Changes in global economic inequality were calculated as the percentage changes in the ratio of per capita GDP between the top and bottom population-weighted deciles (that is, 90:10 ratio) and quintiles (that is, 80:20 ratio) relative to the counterfactual world without anthropogenic sulfate aerosols. For example, the 50% line in the left box means that half of the ~8,000 combinations of response function parameters and model simulation ensemble members have >0.5% reduction in the ratio of country-level per-capita-GDP of the (population-weighted) 10% richest to 10% poorest countries – indicating that sulfate-induced cooling tend to reduce global inequality.