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The harmonized climate and air quality benefits of a realistic phase out of fossil fuels

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Fossil fuel combustion produces emissions of the long-lived greenhouse gas carbon dioxide and short-lived pollutants, including sulphur dioxide, that contribute to atmospheric aerosol formation[1]. Atmospheric aerosol can cool the climate, masking some of the warming effect resulting from greenhouse gases emissions[1]. Aerosol particulates are highly toxic when inhaled, however, leading to millions of premature deaths per year[2, 3]. Phasing out unabated fossil fuel combustion will thus provide health benefits but will also reduce aerosol masking of greenhouse gas-induced warming. Given the much more rapid response of aerosols to emissions changes relative to carbon dioxide, there are large near-term increases in the magnitude and rate of climate warming in many idealized studies that typically assume an instantaneous removal of all anthropogenic or fossil fuel-related emissions[1, 4, 5, 6, 7, 8, 9]. Here we show that more realistic modelling scenarios do not produce a substantial near-term increase in either the magnitude or rate of warming, and in fact can lead to a decrease in warming rates within two decades of the start of the fossil fuel phaseout. Accounting for the time required to transform power generation, industry and transportation leads to gradually increasing and largely offsetting climate impacts of carbon dioxide and sulphur dioxide, with the rate of warming further slowed by fossil methane emission reductions. Our results indicate that even the most aggressive plausible transition to a clean energy society provides benefits for climate change mitigation and air quality at essentially all decadal to centennial timescales.

There is a substantial body of literature pointing out that air quality policies, under which cooling aerosol particles are reduced, can be beneficial for human health but lead to 'disbenefits' for climate change[1, 4, 5, 6, 7, 8, 9]. Such trade-offs clearly exist for some air quality policies, such as flue gas desulfurization of coal-fired power plants, and studies have suggested the alarming possibility that warming rates could accelerate from their current levels of about 0.2°C per decade to 0.4 to 0.8°C were aerosols alone to be rapidly removed[5, 10, 11, 12, 13]. The presence of such trade-offs in response to climate policies is less clear, however. The scientific community has long known that due to the shorter lifetime (days to weeks) of cooling aerosols relative to long-lived greenhouse gases such as carbon dioxide (CO_2, decades to centuries), cessation of emissions would lead to a near-term pulse of warming. This was illustrated most clearly by the Intergovernmental Panel on Climate Change (IPCC) in the Frequently Asked Questions to the Working Group I contribution to the Fifth Assessment Report (AR5)[14], which showed that ceasing anthropogenic emissions would lead to a spike in warming of about half a degree within a few years, followed by a slow cooling that would require nearly a century to recover to current temperatures. Many studies over the past two decades have found a similar near-term warming due to removal of anthropogenic aerosols when all aerosol or all anthropogenic emissions cease[4, 9, 15, 16, 17, 18].

Though authors have often framed their work at least in part as an examination of the geophysical commitment to past emissions, such results have also been widely assumed to provide an indication of future behavior were there to be dramatic anthropogenic emission cuts. This has driven a fairly common perception that the broad phasing out of unabated fossil fuel usage required to meet ambitious climate change mitigation targets such as the Paris Climate Agreement also leads to trade-offs, with a near-term increase in both the magnitude and rate of warming as a 'climate penalty' (e.g. https://nationalpost.com/news/world/scrubbing-aerosol-particles-from-the-atmosphere-a-faustian-bargain-study-finds, ref. [3, 7]). Such a view may come from incomplete understanding of scientific studies, or from news and social media reaction from which some may have incorrectly inferred that aerosol removal inevitably leads to accelerated warming regardless of co-emitted greenhouse gases. This perception has led to contentious debates in the policy arena, for example during the approval process for the Summary for Policy Makers of the IPCC Special Report on 1.5°C (hereafter SR1.5) about the role of non-CO_2 emissions reductions. Specifically, some countries with high air pollution burdens pushed for an equal emphasis on the near-term acceleration of warming that would result if they were to shift away from fossil fuels alongside the Report's presentation of the public health benefits.

We have studied the pathways included in the recently released SR1.5 (ref. [19]) to investigate whether such a climate penalty exists in realistic scenarios of the transition to clean energy as well as in the idealized 'zero emissions' studies. We include 42 pathways classified by the SR1.5 as consistent with 1.5°C with no or limited (<0.1°C) temporary overshoot of the target (see Methods). These scenarios are least-cost pathways generated by models of the energy-economy-land system and include a rapid phaseout of unabated fossil fuel usage with a median decrease of ~60% by 2050 and 85% by 2100 for all primary energy and a >90% reduction in usage of fossil fuels for electricity generation by

2050. The speed at which fossil fuels usage is reduced in these models is based on feasibility assessments of rates of capital turnover, technology switching, socio-economic limits to technological and behavioral shifts, and the requisite financial flows. Rates of change in individual sectors are typically at the high end of those in historical precedents, whereas the scale of the transitions envisioned is substantially larger than any historical precedent for similar rates of change[20]. In other words, although energy-economy-land models have sometimes underpredicted the rates of uptake of specific new technologies[21], the overall rates of the societal transformation away from fossil fuels in the 1.5°C pathways are likely at the upper end of what could be achieved under very ambitious policies. Hence these are likely as close to the 'zero emissions' case as is practically possible. These shifts result in rapid and deep cuts in both CO_2 and non-CO_2 emissions, with CO_2 from fossil sources and sulphur dioxide (SO_2, that is largely co-emitted) decreasing by around 75-85% by 2050 in most scenarios (Figure 1). Some emissions with large non-fossil sources, such as methane (CH_4), do not necessarily decline by such a large fraction, but typically decrease sharply in the near-term as their fossil portion is eliminated (Extended Data Fig. 1).

We evaluate the global mean surface temperature response to these emissions changes using the FaIR model that incorporates reduced complexity (relative to Earth System Models) representations of the carbon cycle and the climate system[22, 23] (see Methods). Carbon dioxide removal technologies are excluded to highlight the role of emissions reductions, and some scenarios hence do not stay below 1.5°C. Unlike the response to idealized, instantaneous emissions removals, global mean temperatures in realistic pathways do not show a near-term spike in warming (Figure 2). Temperatures continue to increase for at least a decade, and near-term rates of change are highly scenario dependent, but none exhibit an acceleration of warming to 0.3°C decade^{-1} or higher, and all show a rapid decline in warming rates starting in the 2020s with rates by 2040 ranging from negative (cooling) to less than half the current value (Figure 2).

We unravel the contributions of individual fossil-related emission decreases to projected temperatures by recalculating changes when holding the fossil portion of individual pollutant emissions constant at 2018 levels while allowing other emissions to follow their specified 1.5°C pathways (see Methods). The results show the gradual evolution of temperature responses, with the largest impacts coming from fossil CO_2, SO_2 and CH_4 emissions changes (Figure 3). The pace of change is influenced by the inertia in both the physical climate system and in the socio-economic systems in which fossil fuels are used. For CO_2, concentrations adjust slowly to emissions changes, leading to a response that is substantially extended in time in comparison with the response to SO_2 given that both are largely phased out in the first half of the century (Figure 1). However, the response to CO_2 is also clearly visible in the near-term. For SO_2, the temperature response is limited only by the response of the climate system, but the emissions changes are gradual as the models include the reality that it takes substantial time to transform energy, transportation and industrial systems under least-cost pathways. Hence roughly 2-3 decades are required to reach 2/3 of the 2100 temperature response to SO_2 changes under these scenarios despite their assumption of systemic rates of change that are faster and broader than any historical precedent[20]. This gradual response to aerosol changes in plausible 1.5°C scenarios is consistent with findings using an intermediate complexity model[18].

These results differ greatly from the idealized picture of a near-instantaneous response to the removal of aerosol cooling followed by a slow transition to dominance by the effects of CO_2. In these more plausible cases, the temperature effects of CO_2, SO_2 and CH_4 reductions roughly balance one another through about 2040, after which the cooling effects of reduced CO_2 continue to grow whereas the SO_2 reduction-induced warming and CH_4 reduction-induced cooling effects taper off so that CO_2 reduction-induced cooling dominates (Figure 3). Examining the impact of CO_2 and SO_2 alone (Figure 3d), the faster response of SO_2 means that the net effect of these two pollutants would indeed be a short-term warming, but a very small one of between 0.02 and 0.10°C in the ensemble mean temperature response (up to 0.30°C for the 95th percentile across pathways). Accounting for all fossil-related emissions (Figure 3e), any brief 'climate penalty' decreases to no more than 0.05°C (0.19°C at the 95th percentile), with the smaller value largely due to the additional near-term cooling from methane reductions. Nearly all the warming in the 2020s and 2030s (Figure 2) is thus attributable to the impact of the residual emissions (mainly of CO_2) during the gradual fossil phase out as well as response to historical emissions[17].

What explains the difference in our results in comparison with perception of a climate penalty due to the rapid removal of aerosol cooling? In large part, the difference between the response times of aerosols and CO_2 is smoothed out when both emissions are reduced gradually compared with idealized zero emissions simulations. Note also that aerosol-cloud interactions are highly non-linear, with a substantial fraction of the forcing remaining even at low aerosol precursor emissions. In addition, the perception of a climate penalty may also reflect results from earlier work on transitioning away from fossil fuels suggesting that the effects of sulfate could substantially outweigh those of CO_2. That was likely true in the past, as the ratio of SO_2 to CO_2 emissions (in tonnes of S/C) was ~1/100 in 1980, roughly double the ~1/200 value in 2019 (using SR1.5 scenario data). This stems from an increase in CO_2 emissions of ~70% along with a reduction in SO_2 emissions of ~20% due to air pollution controls in many regions. Hence over the past 40 years, the world's success in curbing SO_2 emissions along with its failure to curb CO_2 emissions have led the world to a state where aerosols mask a substantially smaller portion of the effect of CO_2, greatly diminishing any 'climate penalty' resulting from simultaneously phasing out emissions of both pollutants. Prominent analyses showing that aerosol reductions owing to clean air policies have likely led to observed increases in warming[24, 25] and could cause rapid acceleration in future warming[5, 10, 11, 12, 13] may have also left such a strong impression that the same is presumed to be the impact of any future reductions in SO_2, even when accompanied by CO_2 reductions. Finally, studies have shown that complete cessation of CO_2 emissions leads to fairly constant global temperatures[15], which has implied to some that CO_2 reductions can be neglected in determining the climate impact of a fossil-fuel phaseout[7]. On the contrary, when compared to continued present-day emissions, the phaseout of CO_2 is more important than concurrent air pollution reductions for climate over the long term, and no less important in the short term (Figure 3). Hence the misperception may stem from misapplication of idealized cases, failure to account for recent emissions trends, misconstruing the climate impacts of air quality policies alone to be a good proxy for phasing out fossil fuels, or a combination of these.

It is important to point out that our conclusions do not result from different model physics relative to prior studies. Indeed, an instantaneous removal of SO_2 as in prior idealized studies also leads to a near-term acceleration in warming in our modeling. Extended Data Fig. 2 shows the temperature difference from zeroed SO_2 compared to the original scenarios where SO_2 emissions follow the trajectories in Figure 1b. The magnitude can vary depending upon the assumed climate sensitivity and aerosol forcing, but only the latter could affect our conclusions markedly as changes in the climate sensitivity would similarly impact the response to other emissions[17]. Based on an analysis of geophysical uncertainties associated with both aerosol forcing and climate sensitivity, we find that any climate penalty associated with the rapid phaseout of fossil fuel usage envisioned in the SR1.5 pathways is likely to be at most 0.29°C. Such a large penalty can happen if both climate sensitivity and present-day aerosol forcing are at the 95th percentile of their AR5-assessed uncertainty ranges, and is also pathway dependent (Extended Data Fig. 3). This is a somewhat extreme case, implying very rapid present-day and near-future warming (though consistent with historical observations; see Extended Data Fig. 4).

Overall, we find that the success of air quality controls implemented over the past few decades in reducing SO_2 emissions at the global scale along with the continued growth in CO_2 emissions has substantially changed the balance between the effects of present-day emissions of these two pollutants on climate in the near-term. Therefore, gradually phasing out the unabated fossil fuel combustion that is the primary source of these two emissions in a very ambitious but plausible manner leads to relatively minimal change in the near future warming. A slower phaseout of fossil fuel use would allow more time for CO_2 concentrations to adjust to CO_2 emissions reductions at a given level of reduced aerosol masking, thus shifting the net impact even further away from accelerated warming in the near-term, but with a higher level of eventual peak warming[17]. A 'climate penalty' could occur were air pollution controls to be put in place while greenhouse gas emissions were allowed to continue to increase, as many studies have shown[5, 10, 11, 12, 13]. The apparent success of ongoing efforts to reduce air pollution in places such as China[26] thus adds to the urgency to phase out fossil fuel usage.

It is well-established that the reduction of SO_2 and other short-lived pollutants accompanying a shift to clean energy leads to enormous public health benefits, saving millions of lives per year[3, 19, 27, 28] and providing health and productivity gains leading to overall welfare benefits valued in the trillions of dollars annually[29, 30]. Given those health improvements, and that the net climate impact is a reduction in warming rates beginning in the 2030s (Figure 3) and is thus also beneficial, we suggest that there is no evidence for a conflict between climate and air quality goals in the case of a worldwide transition to clean energy.

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Code and data availability: All data used in this study is available at the Integrated Assessment Modeling Consortium’s 1.5°C Scenario Explorer hosted by IIASA at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/. FaIR v1.3.6 is available from https://doi.org/10.5281/zenodo.1549342. Code used in this study is available from https://doi.org/10.5281/zenodoXXXXXXX.

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Author contributions: DS conceived the study, CS analyzed the scenarios, both authors designed the analyses and wrote the paper.

Figure Legends

Figure 1. Anthropogenic emissions in 1.5°C pathways with low or no overshoot considered in SR1.5. (a) Fossil-related emissions are shown for CO_2 (along with a minimal non-fossil industrial source) to separate those from other sources (primarily land-use) and from carbon dioxide removal technologies, whereas emissions from all sources are shown for (b) SO_2 and (c) CH_4 to highlight how the fractional reduction depends upon whether emissions are heavily dominated by fossil fuel use (SO_2) or have substantial non-fossil sources (CH_4). The legend for all figures is presented in Extended Data Fig. 9.

Figure 2. Global mean surface temperatures and warming rates in the 1.5°C pathways with low or no overshoot. (a) Global mean surface temperatures (relative to preindustrial) are shown accounting for all changes except carbon dioxide removal technologies and (b) annual rates of warming in those pathways as computed with the FaIR climate model emulator. Each line represents the ensemble mean result for a specific 1.5°C pathway.

Figure 3. Global mean surface temperature response to changes in fossil fuel-related emissions. Response are shown for (a) CO_2 only, (b) SO_2 only, (c) CH_4 only, (d) both CO_2 and SO_2 and (e) all pollutants relative to 2019 in the 1.5°C pathways with low or no overshoot (other emissions lead to changes of less than 0.07°C by 2100, so are not shown individually). Solid lines show ensemble means; shaded regions show 5th to 95th percentile temperature responses across the ensemble in each scenario.

Methods

Emissions

The starting point of our analysis is the 42 scenarios from the "below 1.5°C" and "1.5°C low overshoot" categories from Chapter 2 in SR1.5 (ref. [19]) and also available on the IAMC Scenario Explorer[31, 32]. This set of pathways results from screening all 53 potential pathways to include those that also reported Kyoto greenhouse gas emissions in 2010, the last year the scenarios are intended to capture historical emissions, within the range determined to be valid based on prior IPCC evaluation[33]. All scenarios provide separate energy and land-use related CO_2 emissions. For CO_2, the scenarios report total emissions from energy and industrial processes. Negative emissions associated with BECCS and enhanced weathering have been removed to highlight the role of fossil fuel emissions cuts. Non-fossil contributions within industry are <4% of the total[34], so we use this to represent fossil-related emissions. From the 42 pathways, 17 provide information on the proportion of emissions of non-CO_2 fossil-related forcers that relate to agriculture, forestry and other land use (AFOLU) which are not fossil emissions. Some scenarios also provide an "other" category for emissions that are non-fossil and non-AFOLU, but there is little consistency in the proportion of these emissions to the total, so they have been treated as fossil emissions, with the exception of methane. Results are insensitive to this categorization choice for non-CO_2 emissions. For methane, the 17 models provide energy sector emissions and we use these rather than the difference of total and AFOLU, noting that there are substantial sources of methane that are non-fossil and non-AFOLU (e.g. waste). This treatment of methane is a conservative assumption as it decreases the difference between the fossil-fuel phase out and constant-emissions scenarios. The time-varying fossil fuel fraction is calculated from the scenarios containing this data (Extended Data Fig. 1). The mean of these scenario fractions is applied to all scenarios to generate an assumed fossil fuel fraction for emissions other than CO_2. Applying the scenario specific values, were those available for all 42 scenarios, would have minimal effect as either the fossil fraction varies little across scenarios (e.g. SO_2) or the impacts are small (e.g. organic carbon (OC)), except for methane in which case the uncertainty range would be larger.

There are additional indirect emissions changes due to substitution of other fuels to replace fossil fuels. In particular, extensive use of biofuels leads to increased N_2O in a few scenarios, but only late in the century and only in those with the greatest usage of biofuel energy with carbon capture and storage. In most pathways, fossil fuel demand is substituted for renewables, efficiency and demand management, with increased use of nuclear power in some scenarios, all of which do not lead to indirect emissions. Hence any influence of indirect emissions is expected to be very small.

For scenarios where we assess constant 2018 emissions into the future, we apply the constant emissions assumption to the fossil component of the emissions only, allowing the non-fossil component to vary based on the scenario-mean non-fossil fraction of total emissions from the base scenario. We examine the impacts of future changes (post-2018) rather than changes throughout the entire scenario (post-2010) to provide more relevant information to inform policy making.

Modeling Climate Response

Our scenario pathways are run in the Finite Amplitude Impulse Response (FaIR) simple climate model (v1.3.6; refs. [22, 23]) using a 1000 member perturbed parameter ensemble. FaIR converts emissions of greenhouse gases and short-lived climate forcers into an effective radiative forcing (ERF; see Extended Data Fig. 5), and from this to a temperature anomaly, via an intermediate concentration step for greenhouse gases and simplified carbon cycle representation for CO_2. The atmospheric concentrations of CO_2 are determined using the four time-constant impulse response model in AR5 with an adjustment to the time constants of CO_2 uptake for cumulative emissions and temperature. The recent trend in airborne fraction of CO_2 and simulated atmospheric CO_2 concentrations in FaIR agree very well with observations (Extended Data Fig. 6). For completeness, in addition to the influence of the fossil fuel phaseout relative to constant fossil emissions shown in Figures 3 and Extended Data Fig. 5, the behavior of CO_2 and temperature response to CO_2 relative to present-day values is also presented (Extended Data Fig. 7; ERF follows concentrations). In this study, we do not consider natural forcing for projections, consistent with both SR1.5 and prior FaIR modeling[17]. The base scenarios in this paper are the FaIR results presented in SR1.5 (ref. [19]).

The perturbed parameter ensemble samples the uncertainty in equilibrium climate sensitivity (ECS), transient climate response (TCR), strength of the ERF for 11 groups of anthropogenic forcing agents, pre-industrial airborne fraction of a pulse emission of CO_2, and the strength of carbon cycle feedbacks due to temperature and cumulative carbon emissions. ECS and TCR distributions are informed by CMIP5 model results from abrupt $4xCO_2$ and 1% per year CO_2 experiments[35]. ERF uncertainty is applied by using the AR5 assessed distributions for each forcing category (well mixed greenhouse gases, aerosols, tropospheric ozone, and several other minor anthropogenic forcings)[1] except for methane for which the uncertainty in forcing has recently been revised[36]. Aerosol forcing is comprised of both direct and indirect effects. The direct effect scales linearly with emissions of aerosol precursor species, with the coefficients based on radiative efficiencies from the Aerocom project[37]. The indirect component is calculated from a logarithmic relationship of forcing to emissions of SO_2, BC and OC, that is fit to an emulation of the Community Atmosphere Model (CAM5)[38]. The direct and indirect effects are scaled to the best estimate of ERF from aerosol-radiation interactions (ERFari) and aerosol-cloud interactions (ERFaci) respectively, from AR5 (scaling is applied uniformly across aerosol species). The carbon cycle is represented using a simple fit to the behavior of earth system models of full and intermediate complexity[39] with a state-dependent increase in airborne fraction based on cumulative CO_2 emissions and temperature anomaly since pre-industrial[23]. In FaIR, this is represented by scaling the four time constants of atmospheric CO_2 decay.

The 1000 member ensemble for each scenario is constrained based on whether individual ensemble members replicate the gradient of observed warming, including observational uncertainty and accounting for the autocorrelation from internal variability[40], from the mean of the HadCRUT4, GISTEMP and NOAA observational datasets from 1880 to 2014, of 0.90 ± 0.19°C (refs. [41, 42, 43]). In applying the historical constraint we use the same parameter draws but do include historical solar and volcanic forcing, as in SR1.5. 2014 is used as the end date for the historical constraining as the CMIP6 historical volcanic time series ends in 2014. This procedure retains between 323 and 325 ensemble members depending on the scenario. The differences are a result of slightly different emissions pathways from 2010 in each scenario.

In Figure 2a we show the ensemble mean temperature projections from FaIR, which are substantially lower than those projected from the more established Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC; ref. [44]) for the same scenarios. The temperature projections from MAGICC define the scenario classifications in SR1.5. Much of the differences between the models can be explained by the parameter setups, with MAGICC having a higher mean TCR and stronger near-present day aerosol forcing than FaIR[19], and higher airborne fraction of CO_2, leading to a greater rate of warming in the present and in the near future in MAGICC compared to FaIR[45]. Extended Data Fig. 4 shows that a much greater rate of near-term temperature change in FaIR that is still consistent with historical observations can be projected with a high TCR and stronger present-day aerosol forcing.

To assess the geophysical uncertainty we use the 5th percentile and 95th percentile of the temperatures output from the constrained ensemble for each scenario. In each case the 95th (or 5th) percentile of the constant fossil fuel emissions run is subtracted from the 95th or 5th percentile of the original scenario (because the same geophysical conditions would apply in both the constant emission and base SR1.5 scenario pathways). In Extended Data Figs. 3 and 4 we also analyse a situation where we run one ensemble member per scenario with a TCR, ECS and aerosol forcing that approximately corresponds to the 95th percentile of these values from AR5 (2.7°C, 6.0°C and -1.9 W/m^2 respectively) with all other geophysical variables left at their default values. The 95th percentiles were not defined in terms of a distribution for ECS and TCR in AR5. The "likely" range (> 66%) for TCR of 1.0 to 2.5°C implies at least a 17th to 83rd percentile range, with a TCR exceeding 3.0°C deemed to be "extremely unlikely" (< 5%). Hence the 95th percentile of TCR is constrained to lie at or below 3.0°C and is probably above 2.5°C. We choose 2.7°C for consistency with the upper ranges of the observed historical temperature change (Extended Data Fig. 3). The ECS is only "unlikely" (< 10%) to exceed 6.0°C, but we choose 6.0°C to give a TCR/ECS ratio of 0.45. Using a higher ECS gives a smaller TCR/ECS ratio, and 0.45 is towards the lower end of the range of CMIP5 models[46]. It should be stressed that TCR is more important for historical and near-future climate change than ECS[47] and our results are insensitive to any sensible choice of ECS. Such a configuration, while extreme, does produce results consistent with historical temperature observations, however (Extended Data Fig. 4). In these 95th percentile runs, we observe a climate penalty of between 0.07 and 0.29°C, depending on the scenario (Extended Data Fig. 3).

We note that although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources, including fluorinated gases and both methane and nitrous oxide from agriculture, along with biofuels that are a large source of warming BC, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil fuel phaseout on temperature is minimal during the first 20 years (Figure 3), reducing those other pollutants is the only plausible way to decrease warming during that period.

This study examines the effects of a global phaseout of fossil fuel use. If the transition is not global but regional, the effects could differ although such scenarios would not be able to achieve the 1.5°C target. In the most extreme case, were just one region to undertake a phaseout of fossil fuel use, that region could indeed experience larger local disbenefits for climate as nearly all the positive reduction in SO_2 forcing would be localized there whereas the negative CO_2 forcing would be spread out globally. This type of result has been seen in detailed modeling with general circulation models (GCMs) (e.g. [48]). Such effects would be ameliorated by action to phase out fossil fuels in multiple regions, however.

More generally, it is difficult to compare our results with those from GCMs as the latter have not yet explored the effects of 1.5°C scenarios relative to baseline emissions. The closest analogue from a GCM are results using the GISS-E2R climate model examining a faster phase out of fossil fuel usage to achieve 1.5°C rather than 2°C. Those found that negative radiative forcing due to reduced CO_2 and reduced ozone (owing to decreases in emissions of precursors such as NO_x and CO) largely offset positive forcing due to reductions in cooling aerosols and a slight increase in methane, so that net forcing was less than 0.03 W m^{-2} through 2060 in their simulations[28]. Those results differ in their impact of methane (increasing in those scenarios whereas decreasing in the scenarios examined here) as the 2°C reference scenario used in that study already incorporated all the methane reductions included in the 1.5°C scenarios, hence the only additional impact was a small chemical response in which methane's lifetime increased due to reductions in NO_x emissions. The overall finding of a minimal climate penalty in those GCM simulations seems to be qualitatively consistent with the results from the simple climate model (FaIR) used in this work.

Radiative Forcing and Methane

As noted previously, FaIR converts emissions of greenhouse gases and short-lived climate forcers into an effective radiative forcing (ERF). The ERF values in FaIR are consistent with those in the IPCC AR5, other than for methane (see next paragraph), and the perturbed parameter ensemble accounts for the full range of uncertainty in each forcing component as evaluated in AR5. Differences in forcing trajectories due to fossil fuel related emissions are shown in Extended Data Fig. 5.

For methane, this study uses a recently published update to the radiative efficiency[34]. The update incorporated revisions to spectroscopic databases since the 1998 parameterization that was the basis for the AR5 relationship, and most importantly included shortwave absorption of methane which was previously not included. This leads to an increase in the total radiative forcing of methane by about 25%. However, as this increase is applied consistently to both historical and future methane, it has negligible impact on the conclusions reported here (e.g. 2040 temperatures would differ by ~0.01°C; Extended Data Fig. 8).

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Extended Data Fig. 1. **Fraction of total emissions due to fossil fuels.** Emissions are shown for each of the 17 scenarios where data were provided (grey lines) along with the scenario mean (thick black line) values used in this study for the indicated components.

Extended Data Fig. 2. **Temperature responses for zero anthropogenic SO_2 emissions from 2019 minus the original scenarios**. Differences between ensemble means from each scenario (solid lines) and 5th to 95th percentile regions spanning all scenarios (shaded area) are shown. This thus presents the impact of an instantaneous removal relative to the gradual removal in the 1.5°C scenarios rather than relative to constant present-day emissions.

Extended Data Fig. 3. **95th percentile sensitivity calculations of global mean surface temperature response to changes in all fossil fuel-related emissions**. Values are as in Figure 3e but for FaIR calculations using the 95th percentile of ECS, TCR and aerosol forcing simultaneously. Lines show ensemble means for 1.5°C scenarios minus constant 2018 fossil fuel emissions.

Extended Data Fig. 4. **Sensitivity of historical and projected surface temperatures to geophysical uncertainties.** Global mean surface temperature response to historical and projected emissions are shown using both ensemble mean (dashed lines) and the 95th percentile geophysical setup for ECS, TCR and aerosol forcing simultaneously (solid lines). The historical observations from Cowtan & Way[49], HadCRUT4[39], GISS (GISTEMP)[40], NOAA[41] and Berkeley Earth[50] are shown for comparison.

Extended Data Fig. 5. **Global mean effective radiative forcing due to changes in fossil fuel-related emissions.** Global mean annual average effective radiative forcing differences between the mitigation and constant emissions scenarios shown in Figure 3 are presented.

Extended Data Fig. 6. **Instantaneous airborne fraction of CO_2.** Values derived from observations and in the FaIR model are shown.

Extended Data Fig. 7. **Impact of projected changes in CO_2.** (a) Global mean surface temperature response to changes in CO_2 relative to the present-day and (b) the associated ERF.

Extended Data Fig. 8. **Sensitivity to updated radiative forcing from methane**. Global mean surface temperature response to changes in fossil fuel-related methane emissions and in all fossil fuel-related emissions as in Figures 3c and 3e (top) but comparing against sensitivity calculations using the AR5 estimate of methane forcing (bottom) rather than the updated radiative efficiency accounting for shortwave absorption[33] used throughout the rest of this study.

Extended Data Fig. 9. **Caption for all scenarios shown in other figures**. Colors go from dark to light in ascending order of peak temperature.

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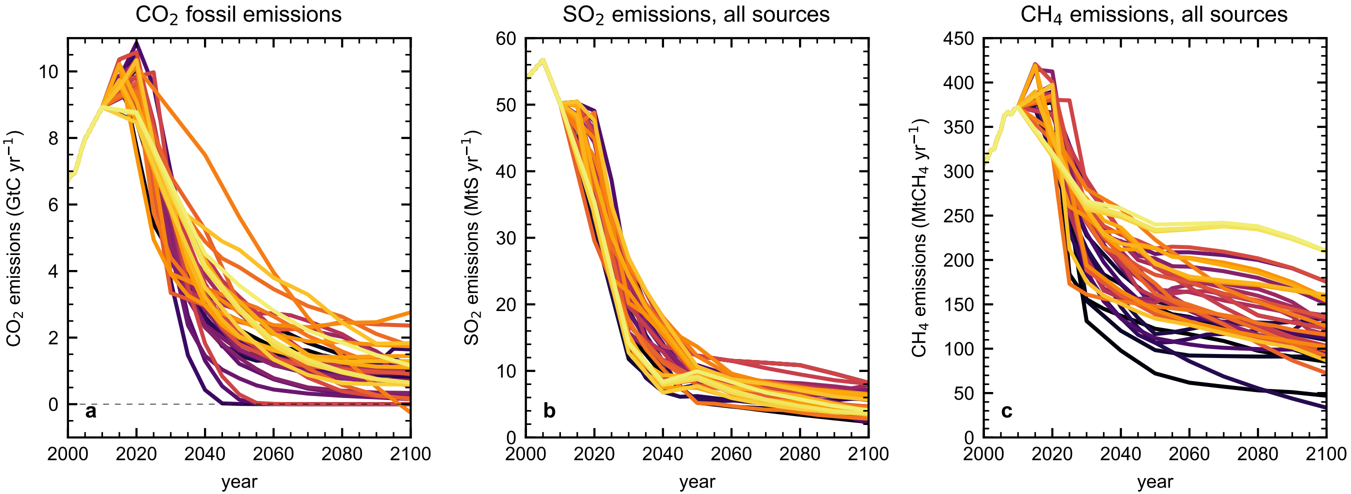
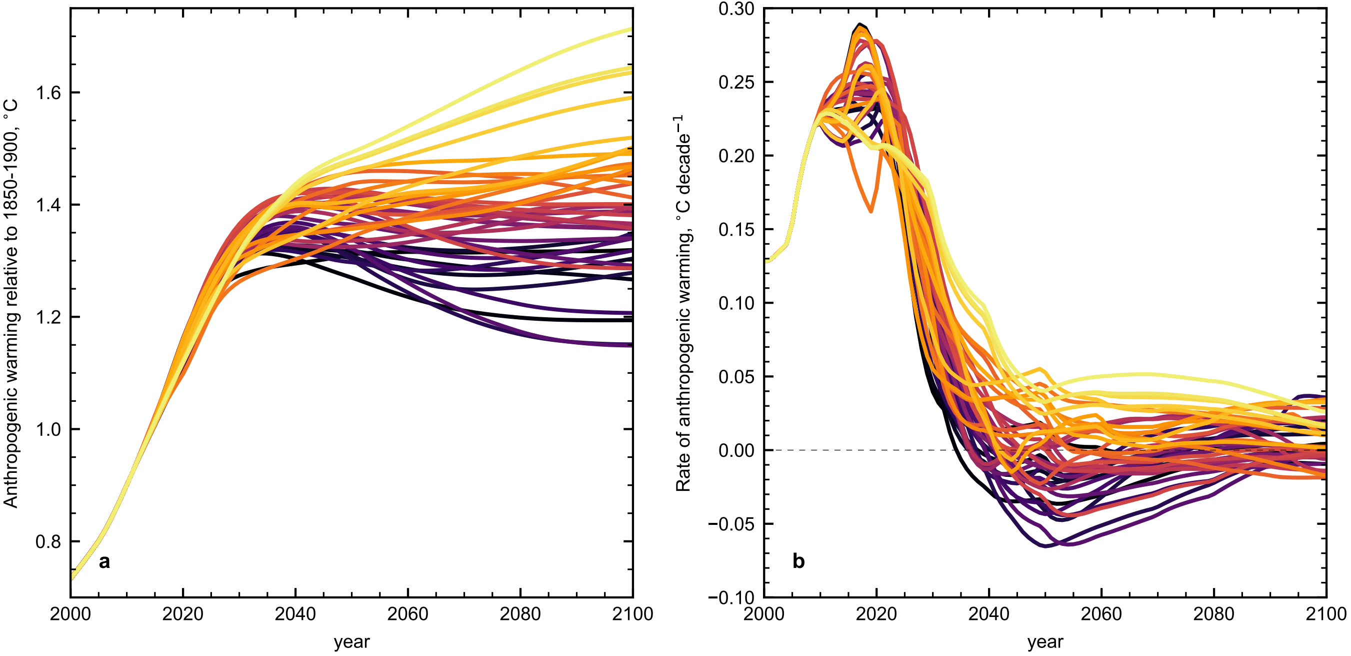
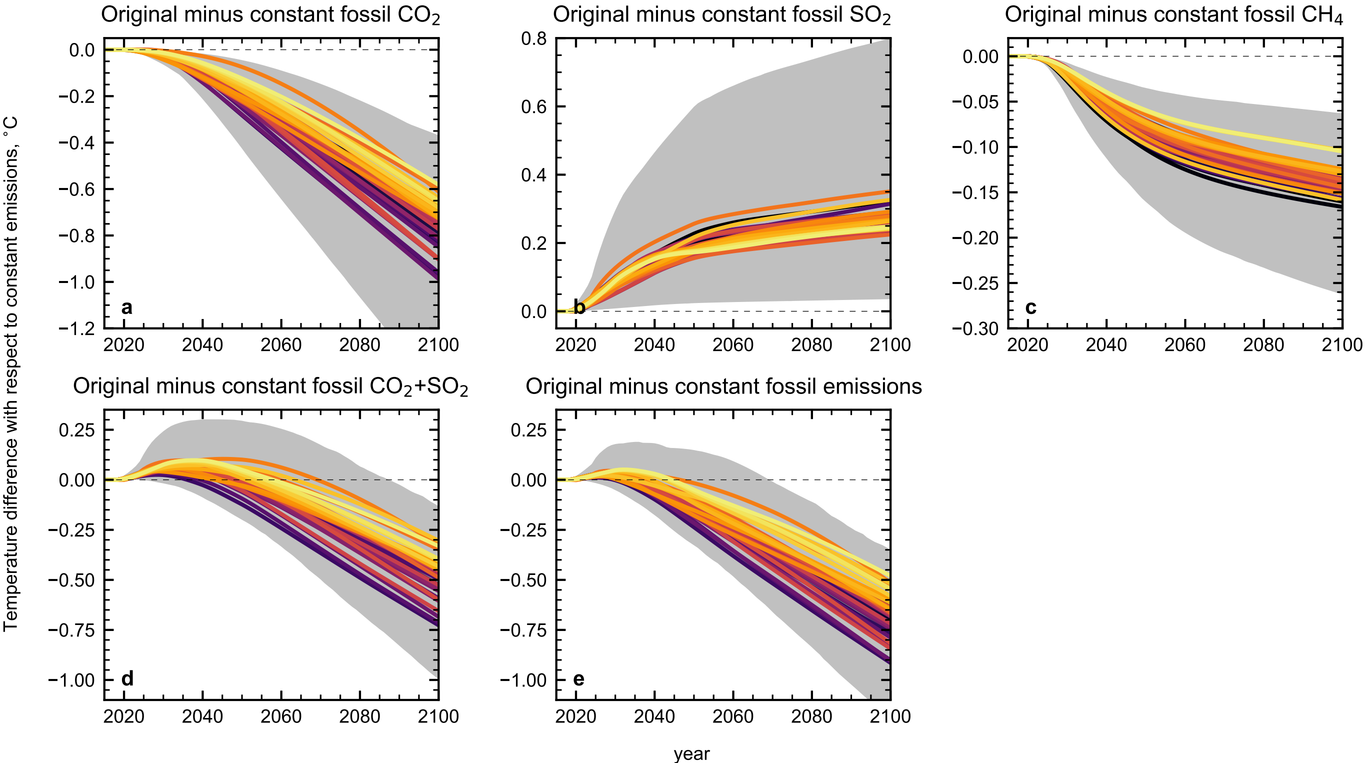

CO$_2$ fossil emissions
SO$_2$ emissions, all sources
CH$_4$ emissions, all sources
CO$_2$ emissions (GtC yr^{-1})
SO$_2$ emissions (MtS yr^{-1})
CH$_4$ emissions (MtCH$_4$ yr^{-1})
0
2
4
6
8
10
10
20
30
40
50
60
50
100
150
200
250
300
350
400
450
2000
2020
2040
2060
2080
2100
year
a
b
c



Anthropogenic warming relative to 1850-1900, °C
0.8
1.0
1.2
1.4
1.6
a
2000
2020
2040
2060
2080
2100
year
Rate of anthropogenic warming, °C decade^{-1}
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
b
2000
2020
2040
2060
2080
2100
year


Original minus constant fossil CO_2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
a
2020
2040
2060
2080
2100
Original minus constant fossil SO_2
0.8
0.6
0.4
0.2
0.0
b
2020
2040
2060
2080
2100
Original minus constant fossil CH_4
0.00
−0.05
−0.10
−0.15
−0.20
−0.25
−0.30
c
2020
2040
2060
2080
2100
Original minus constant fossil CO_2+SO_2
0.25
0.00
−0.25
−0.50
−0.75
−1.00
d
2020
2040
2060
2080
2100
Original minus constant fossil emissions
0.25
0.00
−0.25
−0.50
−0.75
−1.00
e
2020
2040
2060
2080
2100
Temperature difference with respect to constant emissions, °C
year