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Article

Keywords: Global warming trend, Aerosol emissions, 1.5 °C warming threshold, CMIP7 emissions

Posted Date: October 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11306535/v1>

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Additional Declarations: There is **NO** Competing Interest.

Accelerated Early 21st-century Warming from Declining Aerosol Emissions and its Implications for Near-term Climate Change

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Abstract

Global aerosol emissions have declined rapidly since peaking around 2005, substantially weakening the aerosol-induced cooling effect on climate. Using updated historical emissions, we show that this decline, driven primarily by reduced sulphur emissions, enhanced trends in global-mean surface temperature and Earth's energy imbalance by approximately $0.07\text{ }^{\circ}\text{C decade}^{-1}$ and $0.09\text{ W m}^{-2}\text{decade}^{-1}$, respectively, equivalent to $0.14\text{ }^{\circ}\text{C}$ of additional warming over 2005–2025.

This rapid decline in aerosol emissions broadly aligned with the earlier strong-mitigation pathway, while greenhouse gas emissions remained close to the intermediate pathway. Analyses of newer emission scenarios indicate that, if these diverging aerosol and greenhouse gas emission trajectories persist, they could contribute an additional $0.1\text{ }^{\circ}\text{C}$ of warming by 2050, causing the $1.5\text{ }^{\circ}\text{C}$ and $2\text{ }^{\circ}\text{C}$ warming thresholds to be reached two to four years earlier. Therefore, limiting

warming to below 2 °C may require steeper greenhouse gas emission reductions if aerosol emissions continue to decline faster than projected in these new scenarios.

Keywords: Global warming trend, Aerosol emissions, 1.5 °C warming threshold, CMIP7 emissions

Main

Global-mean near-surface temperature (GMST), averaged over the last two decades, has exceeded pre-industrial levels by more than 1 °C, with a decadal mean anomaly of 1.26 °C during 2016 – 2025 [1]. More recently, the GMST anomaly temporarily surpassed the 1.5 °C threshold in 2023–2024 for the first time [2]. In addition to this long-term warming, the rate of temperature increase has accelerated in recent decades, reaching above 0.3 °C decade⁻¹ since the 2010s [3, 4, also see Fig. 1]. The global warming rate is influenced by multiple factors, including anthropogenic greenhouse gas (GHG) emissions, aerosol forcing, volcanic and solar forcing, climate feedbacks and internal climate variability [1]. However, the relative contributions of these factors to the observed warming remain uncertain.

While GHG forcing remains the dominant driver of the long-term global warming [5], studies have shown that reduction in aerosol forcing and decline in planetary albedo, primarily due to reduced low-cloud cover, have played a key role in recent planetary warming trends [2, 6, 7]. Aerosol and aerosol-precursor gas emissions, particular sulphur/sulphur dioxide (SO₂) emissions, have rapidly declined since 2005 due to adoption of stricter standards in China and other countries [8, 9]. Notably, SO₂ emissions had already been declining in Europe and North America since the 1980s; however, these reductions were largely offset by increasing emissions across Asia, resulting in a secondary peak in global SO₂ emissions around 2005 [8]. Subsequent aerosol emission declines in Asia, combined with continuing reductions in Europe and North America, led to a more rapid global decline thereafter.

Since aerosols increase the reflection of the incoming solar radiation through aerosol-cloud interactions and direct radiative effects, resulting in an overall cooling effect and partially mitigating GHG-induced warming (Fig. 1a), this post–2005 decline in aerosol emissions has led to an amplification in global warming [7, 10, 11]. Further studies have analysed the observed decline in low-cloud cover and cloud reflection over the past two decades and linked a substantial portion of these trends to the reducing influence of aerosol-cloud interactions over the oceans [12], although [6] attributed a larger role to cloud feedbacks and rapid adjustments associated with GHG-induced warming. On the other hand, while climate variability and the 2023/24 transition from a prolonged La Niña phase to an El Niño phase have contributed to further warming [13, 14], the increase in the GMST trend cannot be fully explained without considering the influence of anthropogenic emissions [15]. In particular, the sharp reduction in SO₂ emissions from international shipping since 2020 is likely to have had a significant, though highly uncertain, contribution to the decline in the aerosol forcing magnitude over oceans and the GMST surge during 2023 – 25 [16–20].

Several modelling studies, using both Earth system models and reduced-complexity climate models, have shown that reduction in SO_2 emissions leads to substantial warming in the Northern hemisphere and notable improvement in simulated sulphur concentrations in the atmosphere [11, 21, 22]. These climate simulations show that, aerosol reductions over 2005 – 2020 have lead to an increase in Earth’s energy imbalance (EEI) by about $0.1 - 0.2 \text{ W m}^{-2}\text{decade}^{-1}$ and an increase in the GMST trend by $0.03 - 0.05 \text{ }^\circ\text{C decade}^{-1}$ [7, 10, 11, 21, 23].

These findings suggest that the decline in emissions of aerosols and aerosol-precursor gases from anthropogenic sources may have caused a GMST increase by up to $0.1 \text{ }^\circ\text{C}$ over the past two decades. An additional warming of $0.04 - 0.06 \text{ }^\circ\text{C}$ and an increase in radiative forcing of $0.07 - 0.14 \text{ W m}^{-2}$ by 2023 – 2024 has also been suggested by modelling studies assessing the impact of the abrupt reduction in shipping SO_2 emissions ($\sim 7 - 8 \text{ Tg year}^{-1}$) due to the International Maritime Organization’s 2020 regulation [16–18, 20]. However, there remains large uncertainty and inter-model spread in these estimates, due to model biases and the large uncertainties in anthropogenic aerosol effective radiative forcing [24, 25].

The present study aims to quantify the contribution of aerosols to the increase in the GMST and EEI trends over the past two decades (2005–2025). We use Coupled Model Intercomparison Project Phase 6 (CMIP6) and Phase 7 (CMIP7) emissions datasets to generate historical and future GMST projections using the FaIR (Finite Amplitude Impulse Response) model, a reduced-complexity climate model [26]. A key novelty of this study is the use of CMIP7 forcing data, which captures the relatively rapid decline in aerosol emissions that was not fully represented in the CMIP6 forcing dataset [27]. In fact, SO_2 emissions since 2005 have remained somewhat below those assumed in the CMIP6 Shared Socioeconomic Pathway 1–2.6 (SSP126) scenario, while GHG emissions have closely followed the CMIP6 SSP245 pathway (Fig. 2). Given these divergent trajectories of aerosol and GHG emissions, Earth system models participating in CMIP6 may have underestimated the global-mean warming during the early decades of the SSP scenarios, as they did not fully account for the observed rapid decline in aerosol emissions and the associated reduction in the aerosol-induced cooling.

In this study, we seek to answer two key questions: (1) How much additional warming can be attributed to the rapid decline in aerosol emissions since 2005, and (2) How might future climate projections differ if aerosol and GHG emissions follow contrasting trajectories? To address these questions, we combine simulations from the FaIR model with analyses from comprehensive Earth system models. We employ multi-ensemble “flat-aerosol” perturbation experiments in FaIR to isolate and quantify the contribution of changes in emissions of non-methane short-lived climate forcers to observed temperature evolution, and compare these estimates with simulations from the Large-Ensemble Single-Forcing Experiment Intercomparison Project (LESFMIP) [28, 29]. We assess the contributions of aerosols and other non-methane short-lived climate forcers, including aerosols, aerosol-precursor gases, and reactive gases (SO_2 , black carbon, organic carbon, nitrogen oxides (NO_x), ammonia (NH_3), carbon monoxide (CO), and volatile organic compounds (VOCs)) [1], given their important roles in atmospheric oxidising capacity, secondary aerosol formation, and anthropogenic

aerosol forcing [30, 31]. This facilitates a direct comparison between FaIR-based analyses and LESFMIP simulations. We also quantify the individual contributions of these species to the observed GMST and EEI changes.

Furthermore, “low-aerosol” perturbation experiments in FaIR, and SSP370 climate simulations and SSP370 with low near-term climate-forcer emissions (SSP370-LowNTCF) climate simulations from the Aerosols and Chemistry Model Intercomparison Project (AerChemMIP) are used to evaluate the effects of continued aerosol emission reductions on projected warming by 2050 [32]. These analyses provide insights into how rapid reductions in aerosol emissions may alter the timing and likelihood of exceeding the 1.5 °C and 2 °C global warming thresholds.

Global-mean surface temperature trends and historical aerosol emissions

The observed GMST averaged over 2011–2020 was 1.08 °C relative to the 1850 – 1900 baseline. The FaIR model captures this warming reasonably well, with simulated GMST increases of approximately 1.10 °C and 1.09 °C when driven by the CMIP6 and CMIP7 forcings, respectively (Fig. 1a). Historical simulations from LESFMIP show a relatively lower warming of approximately 1.01 °C over the same period. Note that the CMIP6 FaIR and LESFMIP simulations are extended beyond 2014 using the SSP245 emissions pathway. LESFMIP GHG-only simulations indicate that GHG emissions contributed about 1.53 °C of warming, whereas aerosols exerted a net cooling effect, offsetting approximately 0.54 °C of this warming. This aerosol-induced cooling in LESFMIP simulations is generally consistent with the AR6 assessment [5], but is higher than other estimates that are close to 0.30 – 0.40 °C [1, 5, 7, 33]. Studies have shown that CMIP6 models exhibit high sensitivity to aerosol forcing and tend to simulate relatively strong negative aerosol effective radiative forcing (ERF) [33–35]. Consequently, LESFMIP simulations generally show less overall warming than observations, especially between the 1960s and 2000s (see Fig. 1a). However, these aerosol-driven temperature responses remain highly uncertain because of the difficulty in quantifying the aerosol ERF [24], which is estimated to range from -0.6 to -1.6 W m^{-2} (68% confidence interval) over 2005 – 2015 relative to the pre-industrial period [24, 36].

The observed GMST trend has also increased, from approximately $0.2 \text{ °C decade}^{-1}$ during 1970 – 2010 to nearly $0.35 \text{ °C decade}^{-1}$ after 2010 [Fig. 1b, also see 3]. While the GMST trend attributable to GHGs alone has remained relatively stable at around $0.2 \text{ °C decade}^{-1}$ since 1980, the trend associated with aerosols has undergone a notable shift, from approximately $-0.1 \text{ °C decade}^{-1}$ during 1960–1980 to slightly positive values of about $0.05 \text{ °C decade}^{-1}$ in recent years [also see 1]. Furthermore, the observed GMST trend fluctuates only weakly around $0.2 \text{ °C decade}^{-1}$ between 1970 and 2000, whereas both FaIR and LESFMIP exhibit substantially larger variability, with simulated GMST trends ranging from nearly 0 °C decade^{-1} to $0.4 \text{ °C decade}^{-1}$ (Fig. 1b). These large fluctuations in simulations are due to natural forcing, primarily volcanic

forcing [37], and are likely amplified by the tendency of climate models to underestimate decadal variability [38]. The larger variability in the FaIR simulations is also consistent with the absence of internally generated climate variability.

Globally-integrated SO_2 emissions have declined substantially since 2005, whereas magnitudes and trends in emissions of black carbon, organic carbon and other aerosol pre-cursor gases were smaller than earlier CMIP6 projections (Fig. 2). Notably, the observed decline in SO_2 emissions, i.e. CMIP7 historical dataset over 2005 – 2023, has been considerably faster than in the final years of the CMIP6 historical and the subsequent CMIP6 SSP245 projection, although the SSP126 pathway closely tracks the CMIP7 historical SO_2 emissions by 2023. On the other hand, the major GHG emissions have closely tracked the SSP245 pathway (Fig. 2i-j).

FaIR simulations forced with CMIP6 and CMIP7 forcings simulate aerosol ERF median values of -1.04 and -1.03 W m^{-2} in 2023 relative to 1750, respectively (Fig. 2f). This corresponds to a substantial reduction in the aerosol ERF magnitude from the 2005 median values of -1.29 and -1.38 W m^{-2} for CMIP6 and CMIP7 forcings, respectively. These estimates are in agreement with [1], who reported aerosol ERF close to -1.07 W m^{-2} in 2023 relative to 1750. The absolute change of $0.25 - 0.35 \text{ W m}^{-2}$ in the aerosol ERF is also consistent with previous studies that reported an increase in aerosol ERF by about $0.23 - 0.32 \text{ W m}^{-2}$ over 2000 – 2020 [9]. The aerosol ERF offsets a substantial fraction of the GHG ERF, which is close to 3.5 W m^{-2} [also see 1]. However, uncertainties in GHG forcing are considerably smaller than those associated with anthropogenic aerosols. Therefore, accurately quantifying aerosol ERF is crucial for future climate projections.

Contribution of aerosol decline to post-2005 warming

To quantify the aerosol’s contribution to the observed GMST trend, we compare GMST trends over 2005–2025 between the flat-aerosol perturbation experiments and the reference historical simulations from the FaIR model (Fig. 3-4). In flat-aerosol experiments, we maintain emissions of SO_2 , black carbon, organic carbon, NO_x , NH_3 , CO and VOC at year-2005 levels after 2005, while the remaining emissions and forcings are the same as in the reference historical simulations (see details in the Methods). To enable a comparison with LESFMIP simulations, we also assess trends over the period 2005–2020. The simulated median GMST trends from FaIR of $0.25 - 0.26 \text{ }^\circ\text{C decade}^{-1}$ over the 2005–2025 period are close to the observed GMST trend of $0.28 \text{ }^\circ\text{C decade}^{-1}$. Similar GMST trends are seen over 2005 – 2020. In contrast, the LESFMIP historical simulations exhibit a higher GMST mean-trend of $0.34 \text{ }^\circ\text{C decade}^{-1}$ over 2005 – 2020 and a substantial inter-model spread (Table 1).

In FaIR experiments, maintaining aerosol emissions at their 2005 peak levels (i.e., keeping emissions constant after 2005) reduces the 2005 – 2025 median warming rate from 0.26 to $0.19 \text{ }^\circ\text{C decade}^{-1}$ for CMIP7 emissions and from 0.25 to $0.20 \text{ }^\circ\text{C decade}^{-1}$ for CMIP6 emissions. These reductions account for approximately 27% and 20% of the total GMST trend, respectively (Table 1). The larger reduction of $0.07 \text{ }^\circ\text{C decade}^{-1}$ in CMIP7 simulations, compared with $0.05 \text{ }^\circ\text{C decade}^{-1}$ in CMIP6 simulations, indicates that the recent decline in aerosol emissions has had a notable impact on the GMST

trend and the associated weakening of aerosol-induced cooling was likely underestimated in earlier CMIP6 experiments. These estimates correspond to an additional 0.14 and 0.1 °C of global warming over 2005 – 2025 due to the decline in aerosol emissions in the CMIP7 and CMIP6 experiments, respectively (Fig. 4a).

The reduction in the GMST trend is larger for ensemble members with higher equilibrium climate sensitivity (ECS) and stronger aerosol ERF magnitudes (Fig. 3). This is expected, as aerosol ERF and ECS tend to be anti-correlated, which means that ensemble members with higher ECS generally require more negative aerosol ERF to reproduce the observed historical warming [39, 40]. Overall, these FaIR experiments show that the decline in aerosol emissions since 2005 has caused about 0.03 – 0.09 °C decade⁻¹ (68% confidence interval) increase in the mean GMST trend over 2005 – 2025.

This increase in the GMST trend is largely attributable to reductions in SO₂ emissions, which alone increased the GMST trend by 0.05 – 0.07 °C decade⁻¹ (Fig. 4c and Extended Data Table A1). Contributions from other climate forcings are at least an order of magnitude smaller. In particular, changes in black carbon, organic carbon, and NO_x emissions together increased the GMST trend by about 0.004 °C decade⁻¹, although there is substantial offsetting among their individual effects.

Comparison with the LESFMIP simulations shows that all models, except one, exhibit a reduction in the 2005 – 2020 GMST trend when historical aerosol emissions are fixed at pre-industrial levels (Table 1 and Fig. 3c). The LESFMIP multi-model-mean GMST trend reduces approximately by 0.1 °C decade⁻¹ (about 30%), from 0.34 °C decade⁻¹ in historical simulations to 0.24 °C decade⁻¹, when aerosol emissions are not included. This reduction in the GMST trend is nearly twice the magnitude simulated by FaIR, potentially due to the greater sensitivity of climate models to aerosol forcing [34]. The magnitude of reduction in the GMST trend varies significantly among LESFMIP models, ranging from approximately 0.22 °C decade⁻¹ for the NorESM2 model to -0.01 °C decade⁻¹ for the IPSL-CM6A-LR model. In comparison, the FaIR model, which is constrained using observations and historical climate simulations, produces a relatively narrower range in the GMST trend reduction helping better quantify the aerosols' contribution to the observed warming. Furthermore, unlike in the FaIR model, there is no clear dependence of changes in GMST trends on ECS in LESFMIP simulations (evident from the vertical separation between circles and triangles in Fig. 3c), although climate models with higher ECS exhibit larger GMST trends.

Decadal trends in Earth's energy imbalance

FaIR and LESFMIP historical simulations produce 2005 – 2014 time-mean EEI magnitudes of 0.7 – 0.8 W m⁻², which are close to the observed EEI of 0.67 W m⁻² (Fig. 4). However, both the FaIR and LESFMIP models significantly underestimate the EEI trend, producing magnitudes of 0.20 – 0.26 W m⁻²decade⁻¹ compared with the observed trend of 0.41 W m⁻²decade⁻¹ over 2005 – 2020 (Table 1). This underestimation of the EEI trend in climate models has been reported in previous studies [10, 41], and is related to model biases in simulating short-wave and long-wave radiative fluxes [42].

Nevertheless, the effect of aerosol emissions on EEI trends is evident in climate simulations. The 2005 – 2025 median EEI trend decreases by 0.09 [0.04, 0.15] $\text{W m}^{-2}\text{decade}^{-1}$ in CMIP7 and by 0.07 [0.04, 0.11] $\text{W m}^{-2}\text{decade}^{-1}$ in CMIP6 flat-aerosol FaIR experiments relative to the reference historical simulations (Fig. 4b and Table 1, 68% confidence interval is in square brackets). Similar to GMST trends, the change in the EEI trend is larger with CMIP7 forcings and is largely due to reduction in SO_2 emissions (Fig. 4d and Extended Data Table A1). CMIP7 FaIR analyses suggest that the post-2005 decline in aerosol emissions has caused an increase in EEI trend by about 0.09 $\text{W m}^{-2}\text{decade}^{-1}$ (about 35% of the simulated historical trend), or equivalently an increase by approximately 0.18 W m^{-2} in EEI over 20 years since 2005.

In comparison, the LESFMIP simulations exhibit a considerably larger aerosol contribution to the EEI trend, with a multi-model mean of approximately 0.17 ± 0.1 $\text{W m}^{-2}\text{decade}^{-1}$ over 2005 – 2020, which accounts for about 65% of the total simulated trend in historical simulations. These LESFMIP estimates are consistent with previous studies that have quantified the contribution of aerosols to EEI trends using Earth system models [10, 21, 41]. For example, [10] conducted coupled climate simulations with aerosol emissions fixed at their year-2000 levels (AERO2000) and reported an aerosol-driven increase in global-mean EEI of 0.15 – 0.28 $\text{W m}^{-2}\text{decade}^{-1}$ over 2000 – 2020. [21] and [41] used the atmospheric models CAM6-Chem and GFDL AM4, respectively, and found that decline in aerosol emissions caused an increase in the global EEI trend by 0.10 – 0.15 $\text{W m}^{-2}\text{decade}^{-1}$ over 2010 – 2020.

Implications for near-term climate change

We further explore a scenario in which aerosol emissions decline relatively rapidly, following the CMIP7 Low or CMIP6 SSP126 scenario, while GHG emissions and other forcings continue to follow the CMIP7 Medium or CMIP6 SSP245 pathway, which are most representative of present-day GHG emission trends (see [Methods](#)). The objective is to understand how a relatively rapid reduction in aerosol emissions, and the resulting atmospheric clean-up, would affect near-term climate projections (up to 2050) and the timing of crossing the 1.5 °C and 2 °C global warming thresholds.

These different trajectories of aerosol and GHG emissions lead to an additional warming of 0.08 °C and 0.15 °C by 2046 – 2055 in the FaIR CMIP7 and CMIP6 experiments, respectively (comparing the low-aerosol and reference simulations in Table 2). Due to this additional warming, the GMST reaches the 1.5 °C and 2 °C warming thresholds 2 – 4 and 4 – 7 years earlier, respectively, in low-aerosol simulations. In fact, this relatively rapid decline in aerosol emissions increases the probability of crossing 1.5 °C and 2 °C thresholds by 10% – 20% between 2030 and 2060 (Extended Data Fig. A1). For example, the probability of exceeding the 2 °C threshold in 2050 increases from approximately 34% in the reference CMIP6 simulation to nearly 56% in the low-aerosol CMIP6 simulation. These results highlight a significant challenge for countries’ GHG emissions reduction targets, climate mitigation plans, and efforts to limit global warming below 2 °C. Note that these effects are larger in CMIP6 FaIR experiments because aerosol emissions in the reference and low-aerosol scenarios begin to diverge after 2014, whereas the divergence in CMIP7 emissions starts only in 2024.

We compare these results against CMIP6 SSP370 and SSP370-LowNTCTCF outputs from Earth system models. In the SSP370-LowNTCF experiments, aerosol and non-methane ozone precursor emissions follow the CMIP6 SSP126 scenario, while all other forcings are retained from SSP370 [32]. Relative to SSP370, SSP370-LowNTCF simulations project an additional warming of approximately 0.2 °C by 2050 and thresholds of 1.5 °C and 2 °C are exceeded four and five years earlier, respectively, in multi-model-means (see Table 2). These results are consistent with the findings from the FaIR experiments. Since the gap between SSP370 and SSP126 aerosol emissions is larger than that between SSP245 and SSP126, the magnitude of the additional warming is greater than that simulated in the FaIR experiments.

Discussion

Emissions of anthropogenic aerosol and aerosol precursor gases have significantly declined since peaking around 2005 [8], leading to a substantial reduction in the strength of aerosol-induced negative radiative forcing. As a result, the cooling effect of aerosols that partially mitigates the warming induced by greenhouse gases (GHGs) has diminished, contributing to an increase in the global mean surface temperature (GMST) trend [9, 10]. In the present study, we quantified the impact of declining aerosol and other non-methane short-lived gas emissions on trends in the GMST and Earth’s energy imbalance (EEI) using the FaIR model [26], a reduced-complexity climate model, and LESFMIP single-forcing climate simulations [28]. Specifically, we used “flat-aerosol” perturbation experiments in FaIR, in which emissions of non-methane short-lived climate forcers (SO₂, black carbon, organic carbon, NO_x, CO, NH₃, volatile organic compounds) were maintained at their year-2005 levels after 2005 to isolate the contribution of the decline in aerosol emissions to changes in GMST and EEI trends.

Our findings show that the post-2005 reduction in aerosol emissions led to an increase in GMST and EEI trends by 0.07 °C decade⁻¹ (likely range of 0.04 – 0.11, 68% confidence interval) and 0.09 W m⁻²decade⁻¹ (likely range of 0.04–0.15), respectively, over the 2005 – 2025 period (Fig. 4). These are equivalent to an increase in the GMST by about 0.14 °C and an increase in EEI by about 0.18 W m⁻² over 20 years (2005 – 2025). These increases account for approximately 27% and 35% of the simulated historical GMST and EEI trends, respectively (Table 1). These increases are largely attributable to declining SO₂ emissions and the resulting reduction in the magnitude of aerosol radiative forcing. The contributions of other aerosol components to these decadal trends are at least an order of magnitude smaller. These estimates are based on CMIP7 historical emissions and forcings, providing the most updated analyses on this subject, and are consistent with analyses from FaIR experiments run with CMIP6 forcings, although indicate somewhat weaker aerosol-driven increases of 0.05 °C decade⁻¹ in GMST and 0.07 W m⁻²decade⁻¹ in EEI (see Table 1). The flat-aerosol FaIR experiments produce a much narrower uncertainty range in these trend estimates than LESFMIP models, which exhibit substantial inter-model spread and suggest aerosol-driven increases of approximately 0.10 °C decade⁻¹ in the GMST and 0.17 W m⁻² decade⁻¹ in EEI, magnitudes higher than estimated using the FaIR model.

As discussed earlier, aerosol forcing remains highly uncertain because of the complex relationships among emissions, particle and aerosol properties, and their interactions with clouds and radiation [24]. On the one hand, the cooling influence of aerosols during the 1960s–1990s, which was dominated by continental SO_2 emissions, appears to be overestimated in some Earth system models (Fig. 1a). On the other hand, evidence from [19] suggests that many recent global model studies may have underestimated the impact of declining shipping emissions since 2020. They link this discrepancy to assumptions on the size and abundance of fresh sulphate particles emitted in shipping exhaust plumes. Moreover, the efficacy of aerosol forcing per Tg of SO_2 emitted is likely very different between continental regions and marine environments with persistent low-cloud. These subtleties are not represented in our FaIR simulations; consequently, the aerosol influence on EEI and GMST trends during 2020–2025 may be stronger than the estimates presented in this study.

Near-term climate change, including the crossing of 1.5 °C and 2 °C warming thresholds, will be strongly influenced by the trajectories of aerosol and GHG emissions. To assess the impact of a relatively rapid future decline in aerosol emissions compared with GHG emissions, we performed “low-aerosol” perturbation experiments using the FaIR model. These simulations combined aerosol and other non-methane short-lived gas emissions from the CMIP7 Low scenario with all other forcings from the CMIP7 Medium scenario. Our analysis suggests an additional global warming of approximately 0.1 °C by 2050 (Table 2). Consequently, the 1.5 °C and 2 °C warming thresholds are crossed about two and four years earlier, respectively, than in the reference CMIP7 Medium projection. Analyses based on CMIP6 SSP370-lowNTCF climate simulations and FaIR simulations driven by CMIP6 forcings yield similar conclusions.

CMIP7 historical emissions show that post-2005 aerosol emissions declined more rapidly than projected in the CMIP6 SSP126-SSP245 scenarios, while GHG emissions remained close to the SSP245 trajectory (Fig. 2). If these diverging aerosol and GHG emission trajectories persist in the future, near-term global temperatures may increase more rapidly than projected in the CMIP7 future scenarios, increasing the likelihood of GMST exceeding or temporary overshooting the 1.5 °C and 2 °C warming thresholds. Such overshoots could amplify the intensity of climate extremes and the associated socioeconomic and biophysical losses [43]. Some of these, including biodiversity loss, ecosystem degradation, ice-sheet destabilization, and sea-level rise, may be irreversible or only partially reversible, even if global temperatures are subsequently reduced below these thresholds [44, 45].

While the post-2005 decline in aerosol emissions resulting from stricter air quality regulations has contributed to a temporary acceleration of global warming, this decline has also led to substantial improvements in air quality and decrease in air pollution, particularly surface concentration of particulate matter of less than 2.5 μm in diameter ($\text{PM}_{2.5}$) [46]. These measures are expected to yield significant public health benefits in the future [47]. For example, reductions in SO_2 emissions and $\text{PM}_{2.5}$ concentrations are expected to reduce air pollution-related mortality [48], given the strong association between short-term mortality risk and sulphate aerosol concentrations [49]. Overall, the health benefits associated with reduced air pollution are estimated to be three to six times greater than the health impacts associated with the increase in aerosol-driven

warming [50]. In addition, SO_2 and NO_x emissions contribute to acidic deposition and ecosystem damage, both of which have declined since the 1980s owing to the implementation of environmental regulations and clean-air policies [51].

These findings highlight important challenges for climate mitigation and adaptation policies, as well as for global efforts to limit warming to below 2 °C. Additional future scenario experiments that combine GHG emissions from the CMIP7 Medium-High scenarios with aerosol emissions from the Low or Very-Low scenarios could help quantify the climate impacts of a rapid decline in aerosol emissions. Several related experiments are planned as part of AerChemMIP2 [52], and we suggest conducting complementary experiments using reduced-complexity climate models, which can be run efficiently to examine a wide range of future scenarios. Such experiments would provide a more comprehensive assessment of the uncertainty associated with future aerosol emission pathways and their influence on climate change. Meeting long-term climate targets while minimizing temperature overshoots depends on the combined evolution of anthropogenic GHG and aerosol emissions, which together influence future warming, air quality, and associated health outcomes.

Methods

We use the FaIR model, a reduced-complexity climate model [26]. FaIR requires emissions of GHGs, aerosols and other gases, together with solar and volcanic forcing, as inputs. In this study, we use both CMIP6 and CMIP7 historical emissions and their corresponding future emissions scenarios from ScenarioMIP. For FaIR simulations driven by CMIP6 emissions, we use calibration parameters from fair-calibrate v1.4.0, which follows the calibration approach adopted for the IPCC Sixth Assessment Report (AR6) [5]. The fair-calibrate v1.4.0 parameter set is based on CMIP6 historical emissions and is constrained using the observed GMST, CO_2 concentrations, Earth’s energy uptake, and AR6 assessments of equilibrium climate sensitivity, transient climate response, and aerosol radiative forcing (total, aerosol-radiation and aerosol-cloud components) [53].

For FaIR simulations driven by CMIP7 emissions, we use the fair-calibrate v1.6.0 parameter set, which is calibrated using the CMIP7 ScenarioMIP historical emissions dataset and includes emissions of GHGs and short-lived climate forcers over the period 1750 – 2023. In addition, effective radiative forcing from land-use and land-cover change is derived from global irrigated area and historical albedo changes. These forcings are calculated offline and incorporated into the historical effective radiative forcing time series developed by the Indicators of Global Climate Change [IGCC; 1], which are used as inputs to FaIR. In contrast, land-use and land-cover change forcings are computed online in fair-calibrate 1.4.0 used for FaIR simulations run with CMIP6 forcings. Solar and volcanic forcings are also prescribed externally for both CMIP6 and CMIP7 FaIR simulations. Since the present study focuses on decadal temperature trends and quantifying the contribution of aerosols to these trends, we run FaIR without stochastic forcing, which is typically used to represent internal climate variability. We run the FaIR model with an ensemble of 841 members that is consistent with the applied constraints and fully samples the uncertainty in the assessed climate variable distributions.

Flat-Aerosol Experiments

To quantify the additional warming attributable to the decline in aerosol emissions since 2005, we performed aerosol perturbation experiments, termed as “flat-aerosol” simulations. In these experiments, emissions of aerosols and other non-methane short-lived gases (SO_2 , black carbon, organic carbon, NO_x , NH_3 , CO and VOC) were fixed at their year-2005 levels, while all other forcings followed the historical record and subsequent future scenario emissions (SSP245 for CMIP6 and Medium for CMIP7). Comparison of these simulations with the reference FaIR runs enables the isolation of the warming contribution from declining aerosol emissions and its effect on recent temperature and EEI trends. Note that NO_x also influences radiative forcing by modifying the atmospheric lifetime of methane and this effect is simulated in flat-aerosol experiments.

To complement analyses from the FaIR model, we utilize LESFMIP single-forcing climate simulations [28, 29], which follows the same experiment design as in the Detection and Attribution Model Intercomparison Project [54], but with an increase in ensemble size. The large ensemble size enables robust estimation of decadal trends in the GMST and EEI in the ensemble mean. From the LESFMIP dataset, we consider four experiments: (a) historical: run with all historical forcings (natural and anthropogenic), (b) hist-GHG: run with historical GHG forcings while all other forcings are fixed at pre-industrial levels, (c) hist-aer: run with historical aerosol forcings only, (d) hist-nat: run with natural forcings only. These simulations allow us to disentangle the contributions of aerosols and GHGs to historical climate change. We use output from seven models, each with multiple ensemble members (Extended Data Table A2), over the historical period (1850 – 2014), extended to 2020 using CMIP6 SSP245 forcings beyond 2014. To isolate the aerosol contribution, we compare the GMST and EEI trends from the sum of the hist-GHG and hist-nat simulations against those from the historical simulations. In general, the sum of GMST responses to individual forcings closely matches the historical simulation, indicating near-linearity of the climate response (not shown), although a small contribution from nonlinear interactions cannot be ruled out. To ensure consistency between the LESFMIP and FaIR experiments, GMST and EEI trends are analysed over the 2005 – 2020 period.

Low-Aerosol Experiments

To assess the future implications of a more rapid decline in aerosol emissions relative to GHG emissions, we conducted a set of idealized “low-aerosol” experiments. In these experiments, FaIR was driven by CMIP6 SSP245 or CMIP7 Medium emissions, while emissions of aerosols and other non-methane short-lived gases were replaced with those from the CMIP6 SSP126 or CMIP7 Low scenarios, respectively. These simulations were used to evaluate the impacts of accelerated aerosol reductions on 2050 temperatures and on the timing of GMST reaching the 1.5°C and 2°C warming thresholds.

In addition, we use output from CMIP6 SSP370 and SSP370-lowNTCF simulations from the Aerosols and Chemistry Model Intercomparison Project (AerChemMIP) [32]. In the SSP370-lowNTCF experiments, future aerosol and non-methane ozone precursor emissions were replaced with those from the SSP126 scenario, while GHG emissions

and other forcings followed the SSP370 pathway. The models considered in this study are CNRM-ESM2-1, MIROC6, GFDL-ESM4, BCC-ESM1, and CESM2-WACCM, with simulations running through 2055. These simulations allow us to investigate the influence of reduced aerosol emissions on future temperature projections. The models provide between one and three ensemble members, and some include interactive ozone chemistry, thereby capturing the effects of anthropogenic ozone changes. Nevertheless, the impact of ozone is expected to be small in comparison with the effects of aerosols and GHGs. Accordingly, we do not modify ozone concentrations in FaIR experiments.

Observational Datasets

Analyses from the FaIR and climate model simulations are compared against observations of the GMST [from 1] and EEI, measured as the net radiative flux at the top of the atmosphere, from CERES dataset [55].

Supplementary information. Not applicable

Acknowledgements. Not applicable

Declarations

The authors acknowledge funding from the Met Office Hadley Centre Climate Programme funded by DSIT.

Links to analysis scripts and post-processed data will be available upon acceptance of the manuscript. CMIP7 historical and future scenario emissions data, which were used to run FaIR simulations, are available at <https://doi.org/10.5281/zenodo.17845154> and <https://doi.org/10.5281/zenodo.19825038>. CMIP6 emissions and forcing datasets are available at <https://doi.org/10.5281/zenodo.4589756>. FaIR calibration parameters are available at <https://doi.org/10.5281/zenodo.7112539>. LESFMIP and other CMIP6 outputs used in this study are available on the Earth System Grid Federation (ESGF; <https://aims2.llnl.gov/search>). GMST observations are available on <https://doi.org/10.5281/zenodo.21494229> and EEI CERES observations are available on <https://ceres.larc.nasa.gov/data/>.

Authors declare no conflicts of interest.

References

- [1] Forster, P.M., Smith, C., Walsh, T., Lamb, W.F., Lamboll, R., Cassou, C., Hauser, M., Hausfather, Z., Lee, J.-Y., Palmer, M.D., *et al.*: Indicators of global climate change 2024: Annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data Discussions* **2025**, 1–72 (2025) <https://doi.org/10.5194/essd-17-2641-2025>
- [2] Goessling, H.F., Rackow, T., Jung, T.: Recent global temperature surge intensified by record-low planetary albedo. *Science* **387**(6729), 68–73 (2025) <https://doi.org/10.1126/science.adq7280>

- [3] Foster, G., Rahmstorf, S.: Global warming has accelerated significantly. *Geophysical Research Letters* **53**(5), 2025–118804 (2026) <https://doi.org/10.1029/2025GL118804>
- [4] Minière, A., Schuckmann, K., Sallée, J.-B., Vogt, L.: Robust acceleration of earth system heating observed over the past six decades. *Scientific Reports* **13**(1), 22975 (2023) <https://doi.org/10.1038/s41598-023-49353-1>
- [5] Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., *et al.*: Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change **2**(1), 2391 (2021)
- [6] Ceppi, P., Wilson Kemsley, S., Andersen, H., Andrews, T., Kramer, R.J., Nowack, P., Wall, C.J., Zelinka, M.D.: Emerging low-cloud feedback and adjustment in global satellite observations. *Atmospheric Chemistry and Physics* **26**(6), 4153–4171 (2026) <https://doi.org/10.5194/acp-26-4153-2026>
- [7] Jenkins, S., Povey, A., Gettelman, A., Grainger, R., Stier, P., Allen, M.: Is anthropogenic global warming accelerating? *Journal of Climate* **35**(24), 7873–7890 (2022) <https://doi.org/10.1175/JCLI-D-22-0081.1>
- [8] McDuffie, E.E., Smith, S.J., O’Rourke, P., Tibrewal, K., Venkataraman, C., Marais, E.A., Zheng, B., Crippa, M., Brauer, M., Martin, R.V.: A global anthropogenic emission inventory of atmospheric pollutants from sector-and fuel-specific sources (1970–2017): An application of the Community Emissions Data System (CEDS). *Earth System Science Data* **12**(4), 3413–3442 (2020) <https://doi.org/10.5194/essd-12-3413-2020>
- [9] Quaas, J., Jia, H., Smith, C., Albright, A.L., Aas, W., Bellouin, N., Boucher, O., Doutriaux-Boucher, M., Forster, P.M., Grosvenor, D., *et al.*: Robust evidence for reversal in the aerosol effective climate forcing trend. *Atmospheric Chemistry and Physics Discussions* **2022**, 1–25 (2022) <https://doi.org/10.5194/acp-22-12221-2022>
- [10] Hodnebrog, Ø., Myhre, G., Jouan, C., Andrews, T., Forster, P.M., Jia, H., Loeb, N.G., Olivié, D.J., Paynter, D., Quaas, J., *et al.*: Recent reductions in aerosol emissions have increased Earth’s energy imbalance. *Communications Earth & Environment* **5**(1), 166 (2024) <https://doi.org/10.1038/s43247-024-01324-8>
- [11] Samset, B.H., Wilcox, L.J., Allen, R.J., Stjern, C.W., Lund, M.T., Ahmadi, S., Ekman, A., Elling, M.T., Fraser-Leach, L., Griffiths, P., *et al.*: East asian aerosol cleanup has likely contributed to the recent acceleration in global warming. *Communications Earth & Environment* **6**(1), 543 (2025) <https://doi.org/10.1038/s43247-025-02527-3>

- [12] Von Salzen, K., Akingunola, A., Cole, J.N., Digby, R.A., Doherty, S.J., Fraser-Leach, L., Gryspeerdt, E., Sigmond, M., Wood, R.: Reduced aerosol pollution diminished cloud reflectivity over the North Atlantic and Northeast Pacific. *Nature Communications* **16**(1), 9433 (2025) <https://doi.org/10.1038/s41467-025-65127-x>
- [13] Jiang, N., Zhu, C., McPhaden, M.J., Hu, Z.-Z., Lian, T., Zhou, C., Chen, D.: Atypical warming pattern of strong 2023-24 El Niño boosts global temperatures to new 1.5 °C record. *Communications Earth & Environment* **6**(1), 1012 (2025) <https://doi.org/10.1038/s43247-025-02971-1>
- [14] Raghuraman, S.P., Soden, B., Clement, A., Vecchi, G., Menemenlis, S., Yang, W.: The 2023 global warming spike was driven by the El Niño–Southern Oscillation. *Atmospheric chemistry and physics* **24**(19), 11275–11283 (2024) <https://doi.org/10.5194/acp-24-11275-2024>
- [15] Merchant, C.J., Allan, R.P., Embury, O.: Quantifying the acceleration of multidecadal global sea surface warming driven by Earth’s energy imbalance. *Environmental Research Letters* **20**(2), 024037 (2025) <https://doi.org/10.1088/1748-9326/adaa8a>
- [16] Gettelman, A., Christensen, M., Diamond, M., Gryspeerdt, E., Manshausen, P., Stier, P., Watson-Parris, D., Yang, M., Yoshioka, M., Yuan, T.: Has reducing ship emissions brought forward global warming? *Geophysical Research Letters* **51**(15), 2024–109077 (2024) <https://doi.org/10.1029/2024GL109077>
- [17] Jordan, G., Henry, M.: IMO2020 regulations accelerate global warming by up to 3 years in UKESM1. *Earth’s Future* **12**(8), 2024–005011 (2024) <https://doi.org/10.1029/2024EF005011>
- [18] Skeie, R.B., Byrom, R., Hodnebrog, Ø., Jouan, C., Myhre, G.: Multi-model effective radiative forcing of the 2020 sulfur cap for shipping. *Atmospheric Chemistry and Physics* **24**(23), 13361–13370 (2024) <https://doi.org/10.5194/acp-24-13361-2024>
- [19] Smith, J., Henry, M., Yoshioka, M., Johnson, B., Haywood, J.: Recent modelling studies systematically underestimate the warming from IMO2020 shipping regulations. *EGUsphere* **2026**, 1–27 (2026) <https://doi.org/10.5194/egusphere-2026-2654>
- [20] Yoshioka, M., Grosvenor, D.P., Booth, B.B., Morice, C.P., Carslaw, K.S.: Warming effects of reduced sulfur emissions from shipping. *Atmospheric Chemistry and Physics* **24**(23), 13681–13692 (2024) <https://doi.org/10.5194/acp-24-13681-2024>
- [21] Smith, W.P., Tilmes, S., Gaubert, B., Granier, C., Zhu, Y., Eppers, O., Köllner, F., Brauner, P., Rollins, A., Waxman, E., *et al.*: Reduction of global sulfate aerosol concentration and corresponding radiative effects from recent chinese

- SO₂ emission reduction. *Geophysical Research Letters* **53**(3), 2025–118851 (2026) <https://doi.org/10.1029/2025GL118851>
- [22] Westervelt, D.M., Mascioli, N.R., Fiore, A.M., Conley, A.J., Lamarque, J.-F., Shindell, D.T., Faluvegi, G., Previdi, M., Correa, G., Horowitz, L.W.: Local and remote mean and extreme temperature response to regional aerosol emissions reductions. *Atmospheric Chemistry and Physics* **20**(5), 3009–3027 (2020) <https://doi.org/10.5194/acp-20-3009-2020>
 - [23] Zheng, Y., Zhang, Q., Tong, D., Davis, S.J., Caldeira, K.: Climate effects of China’s efforts to improve its air quality. *Environmental Research Letters* **15**(10), 104052 (2020) <https://doi.org/10.1088/1748-9326/ab9e21>
 - [24] Smith, C.J., Kramer, R.J., Myhre, G., Alterskjær, K., Collins, W., Sima, A., Boucher, O., Dufresne, J.-L., Nabat, P., Michou, M., *et al.*: Effective radiative forcing and adjustments in CMIP6 models. *Atmospheric Chemistry and Physics* **20**(16), 9591–9618 (2020) <https://doi.org/10.5194/acp-20-9591-2020>
 - [25] Wall, C.J., Norris, J.R., Possner, A., McCoy, D.T., McCoy, I.L., Lutsko, N.J.: Assessing effective radiative forcing from aerosol–cloud interactions over the global ocean. *Proceedings of the National Academy of Sciences* **119**(46), 2210481119 (2022) <https://doi.org/10.1073/pnas.2210481119>
 - [26] Leach, N.J., Jenkins, S., Nicholls, Z., Smith, C.J., Lynch, J., Cain, M., Walsh, T., Wu, B., Tsutsui, J., Allen, M.R.: FaIR v2.0.0: A generalized impulse response model for climate uncertainty and future scenario exploration. *Geoscientific Model Development* **14**(5), 3007–3036 (2021) <https://doi.org/10.5194/gmd-14-3007-2021>
 - [27] Paulot, F., Paynter, D., Ginoux, P., Naik, V., Horowitz, L.W.: Changes in the aerosol direct radiative forcing from 2001 to 2015: Observational constraints and regional mechanisms. *Atmospheric Chemistry and Physics* **18**(17), 13265–13281 (2018) <https://doi.org/10.5194/acp-18-13265-2018>
 - [28] Smith, D.M., Gillett, N.P., Simpson, I.R., Athanasiadis, P.J., Baehr, J., Bethke, I., Bilge, T.A., Bonnet, R., Boucher, O., Findell, K.L., *et al.*: Attribution of multi-annual to decadal changes in the climate system: The Large Ensemble Single Forcing Model Intercomparison Project (LESFMIP). *Frontiers in Climate* **4**, 955414 (2022) <https://doi.org/10.3389/fclim.2022.955414>
 - [29] Díaz, L.B., Butler, A.H., Avisar, D., Bischof, S., Boehm, C.L., Boschat, G., Dow, W.J., Garfinkel, C.I., Grise, K.M., Khatri, H., *et al.*: Disentangling anthropogenic effects on southern hemisphere circulation and surface climate: A multi-model large ensemble approach. *Journal of Geophysical Research: Atmospheres* **131**(16), 2025–046229 (2026) <https://doi.org/10.1029/2025JD046229>
 - [30] Karset, I.H.H., Berntsen, T.K., Storelvmo, T., Alterskjær, K., Grini, A., Olivie,

- D., Kirkevåg, A., Seland, Ø., Iversen, T., Schulz, M.: Strong impacts on aerosol indirect effects from historical oxidant changes. *Atmospheric Chemistry and Physics* **18**(10), 7669–7690 (2018) <https://doi.org/10.5194/acp-18-7669-2018>
- [31] O’Connor, F.M., Abraham, N.L., Dalvi, M., Folberth, G.A., Griffiths, P.T., Hardacre, C., Johnson, B.T., Kahana, R., Keeble, J., Kim, B., *et al.*: Assessment of pre-industrial to present-day anthropogenic climate forcing in ukesm1. *Atmospheric Chemistry and Physics* **21**(2), 1211–1243 (2021) <https://doi.org/10.5194/acp-21-1211-2021>
- [32] Collins, W.J., Lamarque, J.-F., Schulz, M., Boucher, O., Eyring, V., Hegglin, M.I., Maycock, A., Myhre, G., Prather, M., Shindell, D., *et al.*: Aerchemmip: Quantifying the effects of chemistry and aerosols in CMIP6. *Geoscientific Model Development* **10**(2), 585–607 (2017) <https://doi.org/10.5194/gmd-10-585-2017>
- [33] Gillett, N.P., Kirchmeier-Young, M., Ribes, A., Shiogama, H., Hegerl, G.C., Knutti, R., Gastineau, G., John, J.G., Li, L., Nazarenko, L., *et al.*: Constraining human contributions to observed warming since the pre-industrial period. *Nature Climate Change* **11**(3), 207–212 (2021) <https://doi.org/10.1038/s41558-020-00965-9>
- [34] Smith, C.J., Forster, P.M.: Suppressed late-20th century warming in CMIP6 models explained by forcing and feedbacks. *Geophysical Research Letters* **48**(19), 2021–094948 (2021) <https://doi.org/10.1029/2021GL094948>
- [35] Mulcahy, J.P., Jones, C.G., Rumbold, S.T., Kuhlbrodt, T., Dittus, A.J., Blockley, E.W., Yool, A., Walton, J., Hardacre, C., Andrews, T., *et al.*: UKESM1.1: Development and evaluation of an updated configuration of the UK Earth System Model. *Geoscientific Model Development* **16**(6), 1569–1600 (2023) <https://doi.org/10.5194/gmd-16-1569-2023>
- [36] Bellouin, N., Quaas, J., Gryspeerdt, E., Kinne, S., Stier, P., Watson-Parris, D., Boucher, O., Carslaw, K.S., Christensen, M., Daniau, A.-L., *et al.*: Bounding global aerosol radiative forcing of climate change. *Reviews of Geophysics* **58**(1), 2019–000660 (2020) <https://doi.org/10.1029/2019RG000660>
- [37] Aubry, T.J., Toohey, M., Khanal, S., Chim, M.M., Verkerk, M., Johnson, B., Schmidt, A., Kovilakam, M., Sigl, M., Nicholls, Z., *et al.*: Stratospheric aerosol forcing for CMIP7 – Part 1: Optical properties for pre-industrial, historical, and scenario simulations. *Geoscientific Model Development* **19**(9), 3725–3756 (2026) <https://doi.org/10.5194/gmd-19-3725-2026>
- [38] Kravtsov, S., Grimm, C., Gu, S.: Global-scale multidecadal variability missing in state-of-the-art climate models. *npj Climate and Atmospheric Science* **1**(1), 34 (2018) <https://doi.org/10.1038/s41612-018-0044-6>
- [39] Skeie, R.B., Aldrin, M., Berntsen, T.K., Holden, M., Huseby, R.B., Myhre, G.,

- Storelvmo, T.: The aerosol pathway is crucial for observationally constraining climate sensitivity and anthropogenic forcing. *Earth System Dynamics* **15**(6), 1435–1458 (2024) <https://doi.org/10.5194/esd-15-1435-2024>
- [40] Watson-Parris, D., Smith, C.J.: Large uncertainty in future warming due to aerosol forcing. *Nature Climate Change* **12**(12), 1111–1113 (2022) <https://doi.org/10.1038/s41558-022-01516-0>
- [41] Raghuraman, S.P., Paynter, D., Ramaswamy, V.: Anthropogenic forcing and response yield observed positive trend in Earth’s energy imbalance. *Nature communications* **12**(1), 4577 (2021) <https://doi.org/10.1038/s41467-021-24544-4>
- [42] Myhre, G., Hodnebrog, Ø., Loeb, N., Forster, P.M.: Observed trend in Earth energy imbalance may provide a constraint for low climate sensitivity models. *Science* **388**(6752), 1210–1213 (2025) <https://doi.org/10.1126/science.adt0647>
- [43] Reisinger, A., Fuglestad, J.S., Pirani, A., Geden, O., Jones, C.D., Maharaj, S., Poloczanska, E.S., Morelli, A., Johansen, T.G., Adler, C., *et al.*: Overshoot: A conceptual review of exceeding and returning to global warming of 1.5 °C. *Annual Review of Environment and Resources* **50**(1), 185–217 (2025) <https://doi.org/10.1146/annurev-environ-111523-102029>
- [44] Ritchie, P.D., Steinert, N.J., Abrams, J.F., Alkhayou, H., Arnscheidt, C.W., Bochow, N., Chapman, R.R., Clarke, J., Dennis, D.P., Donges, J.F., *et al.*: The implications of overshooting 1.5 °C on Earth system tipping elements – A review. *Environmental Research Letters* **21**(4), 043001 (2026) <https://doi.org/10.1088/1748-9326/ae3cad>
- [45] Meyer, A.L., Bentley, J., Odoulami, R.C., Pigot, A.L., Trisos, C.H.: Risks to biodiversity from temperature overshoot pathways. *Philosophical Transactions of the Royal Society B: Biological Sciences* **377**(1857), 20210394 (2022) <https://doi.org/10.1098/rstb.2021.0394>
- [46] Ma, Z., Liu, R., Liu, Y., Bi, J.: Effects of air pollution control policies on PM 2.5 pollution improvement in China from 2005 to 2017: A satellite-based perspective. *Atmospheric Chemistry and Physics* **19**(10), 6861–6877 (2019) <https://doi.org/10.5194/acp-19-6861-2019>
- [47] Schraufnagel, D.E., Balmes, J.R., De Matteis, S., Hoffman, B., Kim, W.J., Perez-Padilla, R., Rice, M., Sood, A., Vanker, A., Wuebbles, D.J.: Health benefits of air pollution reduction. *Annals of the American Thoracic Society* **16**(12), 1478–1487 (2019) <https://doi.org/10.1513/AnnalsATS.201907-538CME>
- [48] Li, Y., Peng, J., Ni, M., Bai, Y., Liu, Q., Li, C.: Air pollution control and carbon reduction policies: Assessing effectiveness in alleviating PM2.5-associated mortality in China. *Environment International* **188**, 108742 (2024) <https://doi.org/10.1016/j.envint.2024.108742>

- [49] O'Brien, E., Masselot, P., Sera, F., Roye, D., Breitner, S., Ng, C.F.S., Sousa Zanotti Stagliorio Coelho, M., Madureira, J., Tobias, A., Vicedo-Cabrera, A.M., *et al.*: Short-term association between sulfur dioxide and mortality: A multicountry analysis in 399 cities. *Environmental health perspectives* **131**(3), 037002 (2023) <https://doi.org/10.1289/EHP11112>
- [50] Xing, J., Wang, J., Mathur, R., Pleim, J., Wang, S., Hogrefe, C., Gan, C.-M., Wong, D.C., Hao, J.: Unexpected benefits of reducing aerosol cooling effects. *Environmental Science & Technology* **50**(14), 7527–7534 (2016) <https://doi.org/10.1021/acs.est.6b00767>
- [51] Stoddard, J.L., Jeffries, D., Lükewille, A., Clair, T., Dillon, P., Driscoll, C., Forsius, M., Johannessen, M., Kahl, J., Kellogg, J., *et al.*: Regional trends in aquatic recovery from acidification in north america and europe. *Nature* **401**(6753), 575–578 (1999) <https://doi.org/10.1038/44114>
- [52] Fiedler, S., O'Connor, F.M., Watson-Parris, D., Allen, R.J., Collins, W.J., Griffiths, P.T., Kasoar, M., Kikstra, J., Kok, J.F., Murray, L.T., *et al.*: AerChemMIP2 – Unraveling the role of reactive gases, aerosol particles, and land use for air quality and climate change in CMIP7. *Geoscientific Model Development* **19**(8), 3477–3508 (2026) <https://doi.org/10.5194/gmd-19-3477-2026>
- [53] Smith, C., Cummins, D.P., Fredriksen, H.-B., Nicholls, Z., Meinshausen, M., Allen, M., Jenkins, S., Leach, N., Mathison, C., Partanen, A.-I.: fair-calibrate v1.4.1: Calibration, constraining, and validation of the fair simple climate model for reliable future climate projections. *Geoscientific Model Development* **17**(23), 8569–8592 (2024) <https://doi.org/10.5194/gmd-17-8569-2024>
- [54] Gillett, N.P., Shiogama, H., Funke, B., Hegerl, G., Knutti, R., Matthes, K., Santer, B.D., Stone, D., Tebaldi, C.: The detection and attribution model intercomparison project (DAMIP v1.0) contribution to CMIP6. *Geoscientific Model Development* **9**(10), 3685–3697 (2016) <https://doi.org/10.5194/gmd-9-3685-2016>
- [55] Loeb, N.G., Doelling, D.R., Wang, H., Su, W., Nguyen, C., Corbett, J.G., Liang, L., Mitrescu, C., Rose, F.G., Kato, S.: Clouds and the Earth's radiant energy system (CERES) energy balanced and filled (EBAF) top-of-atmosphere (TOA) edition-4.0 data product. *Journal of climate* **31**(2), 895–918 (2018) <https://doi.org/10.1175/JCLI-D-17-0208.1>
- [56] Zelinka, M.D., Myers, T.A., McCoy, D.T., Po-Chedley, S., Caldwell, P.M., Ceppi, P., Klein, S.A., Taylor, K.E.: Causes of higher climate sensitivity in CMIP6 models. *Geophysical Research Letters* **47**(1), 2019–085782 (2020) <https://doi.org/10.1029/2019GL085782>

Table 1 Decadal trends in the GMST and EEI from observations, FaIR and LESFMIP simulations. For FaIR simulations and observations (computed over 2005 – 2025 and 2005 – 2020), the trend magnitudes are median from all ensemble members in FAIR and samples created from a bootstrapping method, respectively, and the likely range (17^{th} – 83^{rd} percentiles) is shown in square brackets. For LESFMIP models, trends (computed cover 2005 – 2020 only) are the ensemble-mean for each model and the multi-model-mean $\pm$ standard deviation are also included. The LESFMIP flat-aerosol trends correspond to trends computed from the sum of hist-GHG and hist-nat simulations, which were extended to 2020 following the SSP245 pathway.

Model	GMST trend ($^{\circ}\text{C decade}^{-1}$)		EEI trend ($\text{W m}^{-2}\text{decade}^{-1}$)	
	historical	flat-aerosol	historical	flat-aerosol
Observations (05 – 25)	0.28 [0.25, 0.30]	–	0.47 [0.40, 0.55]	–
Observations (05 – 20)	0.25 [0.23, 0.27]	–	0.41 [0.31, 0.50]	–
FaIR CMIP6 (05 – 25)	0.25 [0.20, 0.30]	0.20 [0.17, 0.23]	0.17 [0.12, 0.24]	0.11 [0.08, 0.15]
FaIR CMIP7 (05 – 25)	0.26 [0.20, 0.32]	0.19 [0.16, 0.22]	0.21 [0.15, 0.29]	0.12 [0.09, 0.16]
FaIR CMIP6 (05 – 20)	0.24 [0.19, 0.29]	0.20 [0.17, 0.23]	0.20 [0.15, 0.27]	0.13 [0.10, 0.17]
FaIR CMIP7 (05 – 20)	0.26 [0.21, 0.32]	0.19 [0.16, 0.22]	0.23 [0.16, 0.32]	0.12 [0.08, 0.15]
NorESM2-LM	0.38	0.16	0.32	0.16
MIROC6	0.20	0.15	0.16	0.08
MRI-ESM2-0	0.27	0.14	0.29	-0.05
ACCESS-ESM1-5	0.30	0.22	0.35	0.08
IPSL-CM6A-LR	0.35	0.36	0.18	0.05
HadGEM3-GC31-LL	0.39	0.31	0.28	0.20
CanESM5	0.46	0.37	0.26	0.12
LESFMIP model-mean	0.34 ± 0.08	0.24 ± 0.09	0.26 ± 0.06	0.09 ± 0.07

Table 2 2046 – 2055 time-mean GMST anomalies (relative to 1850 – 1900) and years of the crossing 1.5°C and 2°C warming thresholds in reference and low-aerosol perturbation experiments. For FaIR, values are median from all ensemble members and 17th – 83rd percentile range is shown in square brackets. For CMIP6 Earth system models, the ensemble-mean for each model is shown, and the multi-model-mean $\pm$ standard deviation are also included. Model-means of years are rounded to nearest integers and, for threshold of 2°C, model-means are computed for bottom three models for consistency.

Model	GMST (°C)		Year crossing 1.5°C		Year crossing 2°C	
	Ref	Low-aerosol	Ref	Low-aerosol	Ref	Low-aerosol
FaIR CMIP6 SSP245	1.90 [1.67 2.16]	2.05 [1.75 2.39]	2034 [2026-2041]	2030 [2025-2037]	2055 [2045-2069]	2048 [2038-2066]
FaIR CMIP7 Medium	1.91 [1.69 2.22]	1.99 [1.74, 2.33]	2034 [2025-2041]	2032 [2025-2039]	2055 [2044-2069]	2051 [2041-2066]
MIROC6	1.69	1.88	2045	2039	-	2052
GFDL-ESM4	1.74	1.93	2037	2032	-	2049
BCC-ESM1	1.85	2.11	2044	2037	2055	2048
CESM2-WACCM	2.32	2.54	2028	2026	2040	2035
CNRM-ESM2-1	2.05	2.20	2034	2036	2049	2045
Model-mean	1.93 $\pm$ 0.23	2.13 $\pm$ 0.23	2038 $\pm$ 6	2034 $\pm$ 5	2048 $\pm$ 6	2043 $\pm$ 6

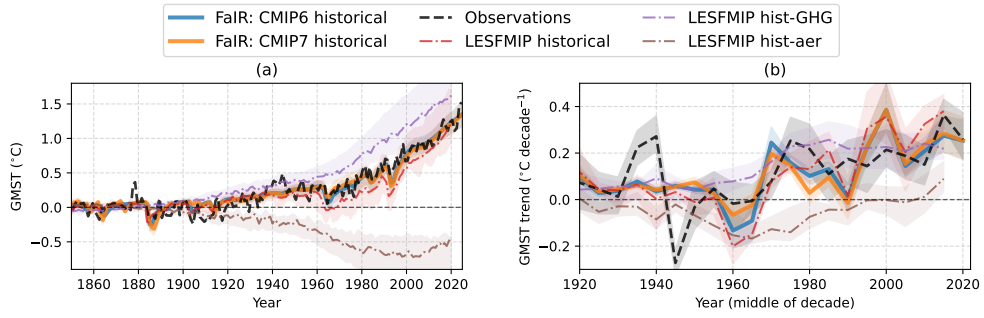


Fig. 1 (a) Global-mean near-surface air temperature (GMST) timeseries relative to 1850–1900; (b) decadal GMST trends derived from non-overlapping 10-year intervals. FaIR runs with CMIP6 forcing and LESFMIP runs are extended beyond 2014 following the SSP245 emission pathway. Lines represent the median values and the shading represents the spread between 10th and 90th percentile. In panel (b), significance intervals for observations are computed using a bootstrapping method involving random resampling with replacement.

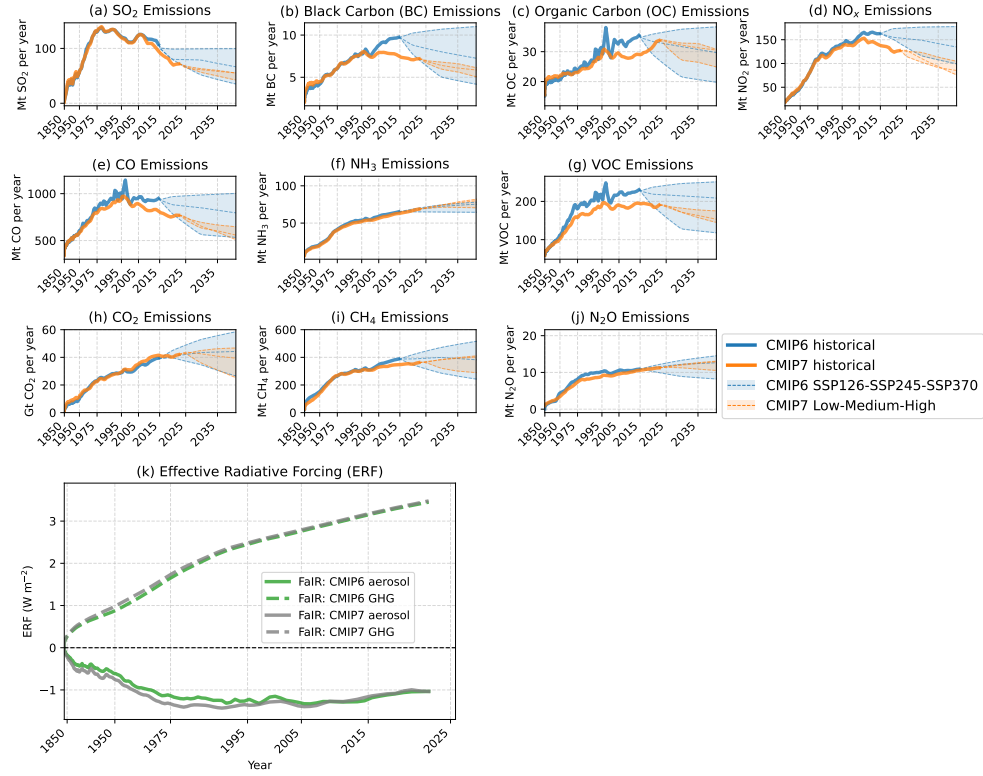


Fig. 2 (a-j) Timeseries of historical emissions of non-methane short-lived climate forcers (SO₂, black carbon and organic carbon, NO_x, CO, NH₃ and VOC) and GHGs (CO₂, CH₄ and N₂O) in CMIP6 and CMIP7. The dashed curves represent the spread between projected future emission scenarios in CMIP6 (SSP126, SSP245, SSP370) and CMIP7 (Low, Medium and High). (k) Timeseries of the median aerosol and GHG ERF from FaIR simulations. In panel (f), FaIR runs with CMIP6 forcing are extended beyond 2014 following the SSP245 emission pathway.

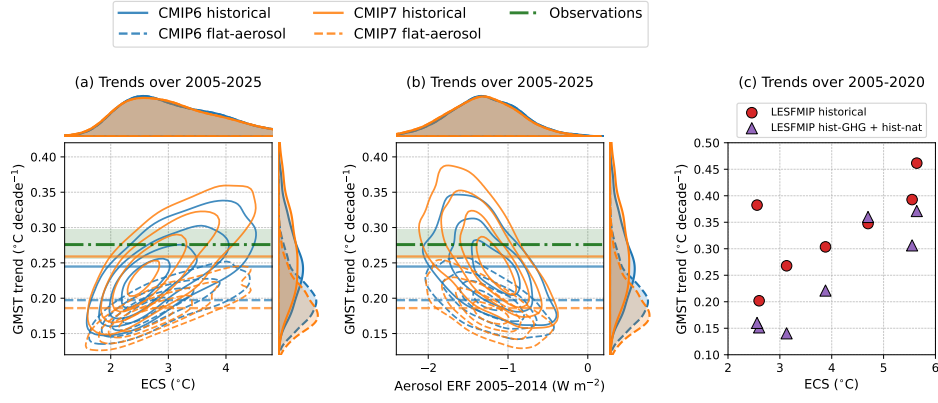


Fig. 3 GMST trends from (a,b) FaIR simulations (computed over 2005–2025), (c) LESFMIP climate simulations (computed over 2005 – 2020). For the FaIR simulations, contours of GMST trends from all ensemble members are shown against ECS or the 2005 – 2014 time-mean aerosol ERF relative to 1750. For LESFMIP models, ensemble-mean trends are plotted against models’ ECS from [56]. The significance intervals for observations are computed using a bootstrapping method involving random resampling with replacement and the shading represents the 17th – 83rd percentile range.

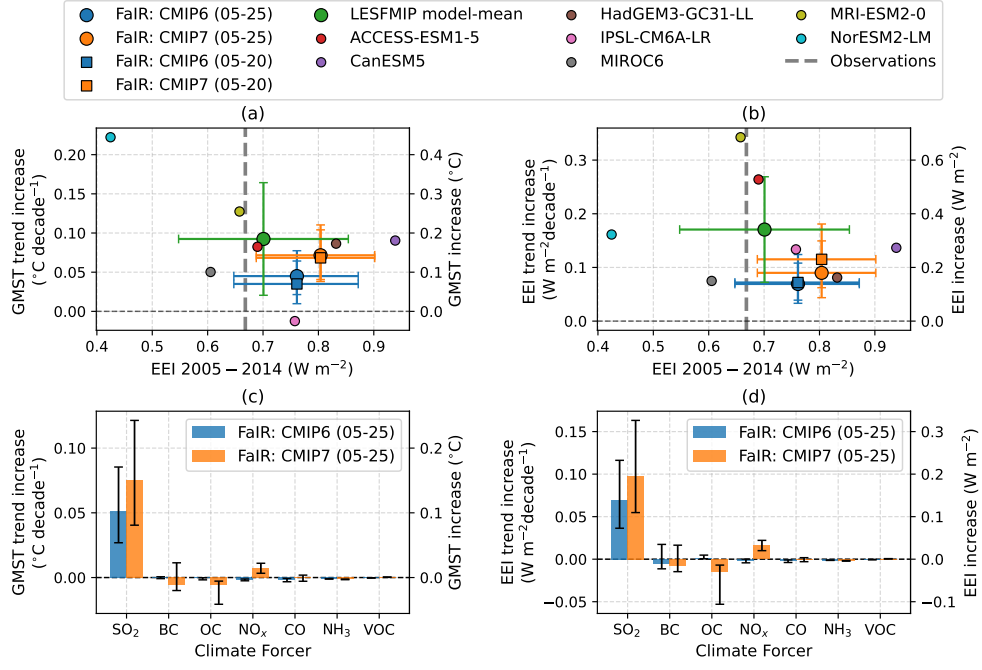


Fig. 4 Impact of the post-2005 decline in aerosol emissions: (a) Increase in GMST decadal trend and (b) Increase in EEI decadal trend from FaIR simulations and LESFMIP climate simulations against 2005 – 2014 time-mean EEI. For FaIR simulations, filled circles and squares show the median values and errorbars present the 17th – 83rd percentile range. For LESFMIP model-mean, filled circles and squares represent the multi-model-mean $\pm$ standard deviation. For FaIR simulations, GMST and EEI trends are computed over 2005 – 2025 and 2005 – 2020 periods, while LESFMIP results are for 2005 – 2020 only. Contributions from individual aerosols and aerosol-precursor gases to the (c) Increase in the 2005 – 2025 GMST trend and (d) Increase in the 2005 – 2025 EEI trend. On the right axes, the expected changes in GMST and EEI (estimated from decadal trends) due to decline in aerosol emissions are shown over a 20-year period (2005 – 2025).

Appendix A Extended Data

Table A1 Changes in GMST and EEI trends due to different climate forcers estimated from FaIR flat-aerosol and reference experiments, run with both CMIP6 and CMIP7 forcings. Decadal trends are over 2005 – 2025 and median values are shown.

Climate Forcer	GMST trend change ($^{\circ}\text{C decade}^{-1}$)		EEI trend change ($\text{W m}^{-2}\text{decade}^{-1}$)	
	CMIP6	CMIP7	CMIP6	CMIP7
SO ₂	0.05	0.07	0.07	0.10
Black Carbon	−0.0001	−0.005	−0.005	−0.008
Organic Carbon	−0.0003	−0.006	0.001	−0.01
NO _x	−0.002	0.007	−0.002	0.016
CO	−0.002	−0.0006	−0.002	−0.0006
NH ₃	−0.001	−0.001	−0.001	−0.002
VOC	−0.0003	0.0003	−0.0004	0.0004

Table A2 List of LESFMIP models used in this study. All historical simulations were extended to 2020, using CMIP6 SSP245 forcings beyond 2014.

Model	Number of Ensemble Members			
	historical	hist-GHG	hist-aer	hist-nat
ACCESS-ESM1-5	40	9	10	10
CanESM5	50	50	30	50
HadGEM3-GC31-LL	55	55	55	60
IPSL-CM6A-LR	11	10	10	10
MIROC6	50	50	10	50
MRI-ESM2-0	4	5	5	5
NorESM2-LM	3	23	23	23

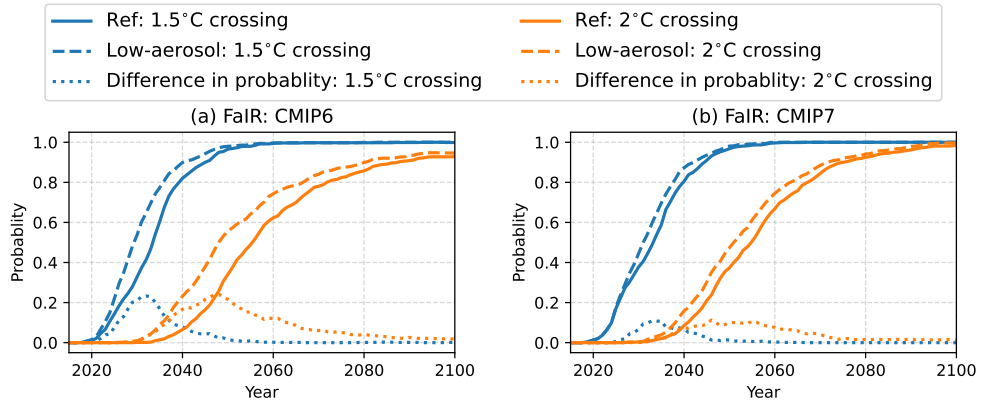


Fig. A1 Probability of the GMST (relative to 1850-1900) exceeding the 1.5°C and 2°C thresholds in the reference and low-aerosol FaIR experiments: (a) FaIR CMIP6 and (b) FaIR CMIP7. Probabilities are calculated as the fraction of ensemble members for which the GMST exceeds the specified threshold.