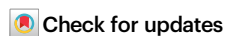


Strategizing emission cuts in China to mitigate short-term warming from clean air policies

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Aerosol-cloud interactions remain one of the largest sources of uncertainty in estimates of anthropogenic climate forcing. Reducing aerosols to achieve air quality improvement and climate goals can cause unintended warming due to the weakening of aerosol cooling. Here we investigate the climate impacts of spatially optimized sulfur dioxide (SO₂) emission reduction under a carbon-neutral pathway in China. We find that targeting reduction in highly polluted regions in China significantly suppresses the rise in effective radiative forcing due to aerosol-cloud interactions (ERF_{aci}) during 2020–2060. Owing to the nonlinear aerosol-cloud interaction, the optimized emission reduction strategy limits the regional average increase in ERF_{aci} of more than 0.89 W m⁻² to less than 0.13 W m⁻² in the short-term future during 2020–2040 and weakens the ERF_{aci} increase by two-thirds in 2060 over China. These findings demonstrate the critical role of targeted emission control in mitigating short-term climate risks while pursuing air quality goals.

Aerosols are tiny particles suspended in the atmosphere, playing a vital role in the Earth's climate system^{1,2}. They impact the climate mainly through two pathways, i.e., aerosol-radiation and aerosol-cloud interactions³. Aerosol-radiation interaction (ARI) refers to the scattering and absorbing of solar radiation due to aerosols, which directly alters the Earth's radiation balance and subsequently affects energy distribution and climate patterns^{4,5}. Aerosol-cloud interaction (ACI) denotes aerosols acting as cloud condensation nuclei (CCN) and ice-nucleating particles (INP), influencing cloud formation, microphysical properties, and cloud evolution, which affects critical processes such as precipitation, radiation, and the hydrological cycle^{6,7}. Through these mechanisms, aerosols significantly influence the global climate system and are key factors in driving climate variability and climate change.

Among the two pathways, ACI has been recognized as playing a central role in regulating the Earth's energy balance, which is also one

of the top components of uncertainty in the climate system⁸. The latest assessment report by the Intergovernmental Panel on Climate Change⁹ reported that the effective radiative forcing (ERF) due to ACI was −0.84 (−1.45 to −0.25) W m⁻² in 2019 relative to 1750, with a higher magnitude and larger uncertainty range than that of −0.22 (−0.47 to 0.04) W m⁻² contributed by ARI. Clouds have nonlinear responses to aerosol changes, adding complexity to the quantification of ACI. For example, Jia and Quaas¹⁰ explored the relationship between aerosols and cloud microphysical properties based on satellite data and found that the response of cloud droplet number concentration (N_d) to changes in aerosol index (AI) was smaller in polluted areas than clean regions due to the transition of ACI from aerosol-limited to updraft-limited regime, challenging the assumed log-linear lnAI–lnN_d relation as widely adopted in previous satellite-based studies¹¹ and modeling studies¹². Cloud droplet formation is governed by the equilibrium between two

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processes: the number of aerosol particles available as CCN, and the supply of supersaturation generated by vertical updrafts. When aerosol loading is low, available CCN are insufficient to fully consume the supersaturation produced by updrafts; thus, additional aerosols can be efficiently activated into droplets, with N_d increasing nearly proportionally, which represents the aerosol-limited state. As aerosol loading increases, the activation process consumes supersaturation more rapidly. Ultimately, the rate of supersaturation generated by the updraft becomes insufficient to activate all available CCN. At this point, supersaturation rather than aerosol concentration becomes the limiting factor for activation, which is the updraft-limited state.

Due to air quality legislation, aerosols have been steadily declining in North America and Europe since the 1980s. In contrast, East Asia and South Asia remain hotspots for anthropogenic aerosol emissions. Among these regions, China experienced severe aerosol pollution from anthropogenic activities in the early 2010s, driven by rapid industrialization and urbanization^{13–16}. With over one million premature deaths attributed to aerosol pollution annually, China faces critical public health challenges that require immediate attention and policy intervention^{17–19}. To address these health and environmental issues, China has taken a series of measures to curb emissions of aerosols and gas precursors. Notably, China has implemented stringent vehicle emission standards, resulting in significant reductions in black carbon emissions from the transportation sector and improvements in urban air quality^{20–22}. Additionally, after the Air Pollution Prevention and Control Action Plan promulgated in 2013, aerosol concentrations have significantly declined in China^{23–25}. To achieve the targets of Beautiful China and carbon neutrality, future aerosol emissions in China are projected to further decrease²⁶.

The interaction of aerosols with radiation and clouds introduces complex feedback mechanisms that can either amplify or diminish the effects of climate change. Specifically, scattering aerosols enhance planetary albedo and cool the surface, while absorbing aerosols heat the atmosphere and stabilize the boundary layer. These radiative perturbations alter cloud formation and precipitation by modifying temperature, humidity, and vertical motion profiles. Meanwhile, through aerosol-cloud interactions, increased CCN can raise N_d and reflectivity, suppress precipitation, and trigger rapid adjustments in cloud lifetime and liquid water path, collectively exerting either cooling or warming feedbacks depending on cloud type and region^{27–29}. Many studies have examined the climate impacts of reducing aerosol emissions, highlighting the dual nature of aerosols as both cooling agents and climate stressors. For instance, Yang et al.³⁰ employed the Community Earth System Model (CESM1) with future emission scenarios from the Dynamic Projection for Emissions in China (DPEC) framework, showing that projected aerosol reductions in China toward carbon neutrality during 2015–2060 could produce a large positive ERF at the top of the atmosphere (TOA) up to 1.0 W m^{-2} and a warming exceeding 0.5 K over eastern China. Similarly, Wang et al.³¹ focused on the impact of global aerosol emission reductions on climate based on CESM1 simulations. They revealed that the aerosol abatement toward carbon neutrality would lead to a significant temperature rise by up to 1.5°C at the regional scale in 2050 relative to 2020, overtaking the contemporaneous climate influence of greenhouse gases (GHGs) abatement under the Shared Socioeconomic Pathway (SSP) 1-1.9. Samset et al.³² showed that a 75% reduction in East Asian sulfate aerosols had partially unmasked GHGs-driven warming, leading to an annual mean warming of $0.07 \pm 0.05^\circ\text{C}$, sufficient to be a main driver of the uptick in global warming rate since 2010. This finding underscores the significant warming contribution of aerosol reductions, highlighting the urgent need for coordinated mitigation strategies. Aerosol emission reductions also increase the occurrence of extreme weather events (e.g., heatwaves, heavy rainfall)^{33,34}. As rapid clean-up of aerosol emissions, especially over Asia, the warm extremes are intensified, which further influences the Asian summer monsoon³³. The shift

toward fewer aerosol results in more frequent and intense heatwaves and changes in precipitation patterns, creating risks of heavy rainfall in some regions^{35,36}.

While improving air quality, China is also actively reducing emissions and pursuing carbon neutrality targets. This entails not only reducing GHG emissions but also cutting aerosol emissions, since aerosols share many of the same sources as GHGs. The weakened cooling effect of reducing aerosols can unmask the warming that is induced by the continuously increasing GHGs levels. The warming effect from aerosol emission reductions is estimated to emerge as early as 2025 in China¹⁰, highlighting the urgency of addressing the unintended climate consequences of such reductions. To effectively mitigate the temperature rise, Yang et al.³⁰ proposed that strictly controlling black carbon (BC) emissions from the residential sector and adopting clean technologies for the industry and transportation sectors are a potential way for the co-benefits of climate and air quality. Bellouin et al.²⁸ suggested, in order to avoid the short-term warming effect caused by the reduction of aerosol emissions, emission reductions should be applied to both GHGs and aerosols. This study aims to provide a method to mitigate potential future warming through optimizing the strategy of aerosol emissions reduction, building on established theories of aerosol-induced nonlinear responses in cloud microphysics, thereby achieving a balance between climate goals and air quality improvement.

Results

Potential warming due to aerosol reduction toward carbon neutrality

China's commitment to aerosol emission reductions as part of its carbon neutrality and clean air action framework has important implications not only for air quality improvement but also for broader climate consequences^{5,32,37,38}. The reduction of sulfur dioxide (SO_2) emissions, projected to decrease from 10.0 Tg in 2020 to 1.0 Tg in 2060 under the carbon neutrality scenario (Supplementary Fig. 1), aligns with China's decarbonization and pollution control objectives. However, this reduction introduces complex feedback mechanisms, particularly through its impact on radiative forcing. As SO_2 emissions decrease, reduced aerosols serving as CCN/INP, especially in the polluted eastern regions, lead to the decrease in N_d in China from 104.83 cm^{-2} in 2030 to 76.35 cm^{-2} in 2060 toward carbon neutrality, based on the empirically fitted sigmoid relationship between AI and N_d and the linear regression relationship between AI and SO_2 emission (see Methods).

As fewer cloud droplets reflect solar radiation, more solar energy reaches the Earth, thereby producing a positive change in aerosol-cloud interactions (ERF_{aci}) over the coming decades. Following the carbon neutrality pathway, China shows strong positive ERF_{aci} changes over central-eastern and northeastern China, with the largest changes more than 10 W m^{-2} by 2060 relative to 2020 (Fig. 1). Averaged over China, ERF_{aci} presents positive changes by 0.89 W m^{-2} in 2030 and 3.03 W m^{-2} in 2060 relative to 2020, exacerbating the warming induced by the continuous rising GHGs levels and further complicating the climate adaptation and mitigation efforts. Note that the responses in cloud microphysics and the associated ERF_{aci} to aerosol reduction are not linear. During 2020–2030, anthropogenic SO_2 emission in China decreased by 4.2 Tg , more than five times of the 0.8 Tg during 2050–2060. But the ERF_{aci} change is 0.89 W m^{-2} during 2020–2030, less than twice that of the 0.70 W m^{-2} during 2050–2060. It indicates a shift in cloud microphysical properties from the aerosol-updraft transition zone to the aerosol control zone, leading to the stronger forcing response to the aerosol change in the cleaner conditions¹⁰.

Mitigation strategy through optimizing emission reduction

While reducing aerosol emissions under carbon neutrality is essential for public health, the associated climate consequences need to be

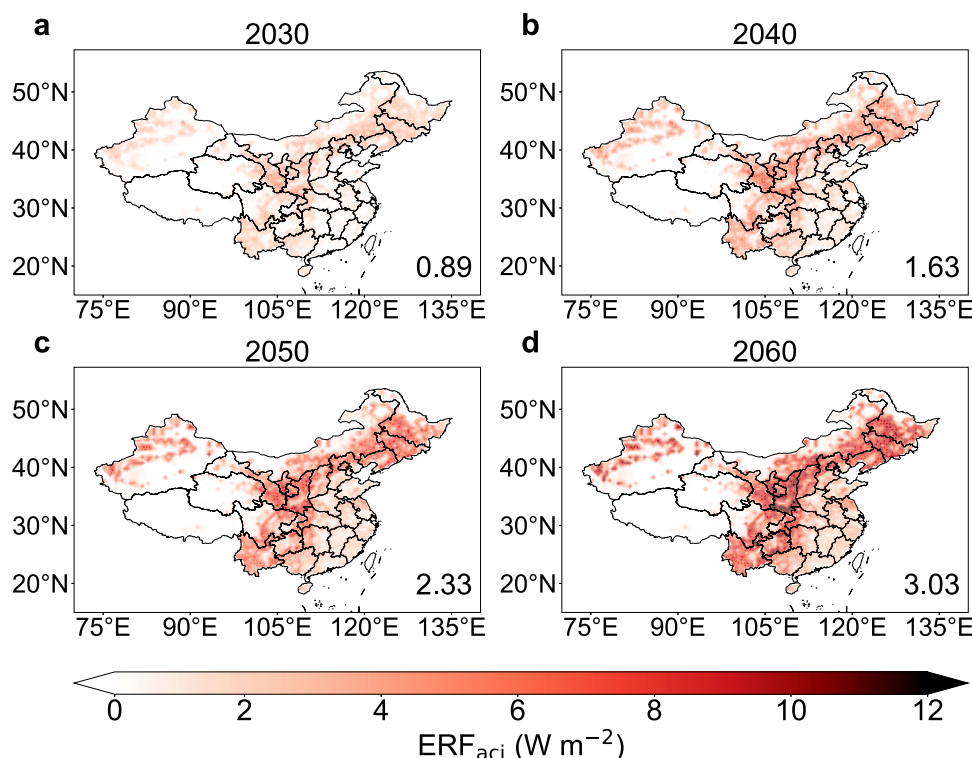


Fig. 1 | Effective radiative forcing due to aerosol-cloud interactions (ERF_{aci}) responses to SO₂ emission reductions in China. Spatial distribution of changes in ERF_{aci} (W m⁻²) in China in **a** 2030, **b** 2040, **c** 2050, and **d** 2060 under the carbon

neutral scenario relative to 2020. Regional averaged value over China is shown in bottom right of each panel.

managed carefully. This section evaluates the effectiveness of targeted emission reduction strategies in minimizing the unintended warming. Figure 2 compares the influences of original emission reduction of SO₂ and the emission reduction only over high SO₂-emitting areas in 2030. With the same total amount of emission reduction across China, different strategies produce completely different climate effects. The SO₂ emissions are projected to reduce across central-eastern China during 2020–2030 in the original scenario, while the testing case only reduces SO₂ emissions over high-emitting regions. Attributed to the non-linearity of the aerosol-cloud relation, the targeted emission reductions over high-emitting regions can significantly mitigate the warming effect due to aerosol emission reductions. The short-term regional average ERF_{aci} change between 2020 and 2030 can be limited from 0.89 W m⁻² for the original scenario to less than 0.10 W m⁻² for the targeted emission reduction scenario. In addition, reducing aerosol emissions from the most polluted areas (5% case, referring to the scenario of emission reduction for the top 5% SO₂ emission grid cells in China) produces less positive ERF_{aci} change than the moderately polluted areas (10% and 20% cases). This suggests that prioritizing emission reductions in highly polluted regions not only benefits environmental improvement in areas with the worst air quality but also reduces the risk of additional warming associated with future aerosol reductions in China.

The testing case for 2030 indicates that focusing on emission reductions in the most polluted regions can successfully mitigate the unintended warming. However, a specific percentage for the high emission area is not suitable for a large amount of emission reduction, because cloud microphysical properties would shift from the aerosol-updraft transition zone to the aerosol control zone and, therefore, the sensitivities of N_d and ERF_{aci} would increase with the sustained decrease in aerosol emissions. Here, we optimize the emission reduction strategy by introducing a dynamic emission reduction scheme based on a varying threshold for gridded emission rates,

aiming to reduce the same amount of regional total emissions while optimizing the distribution of reductions across high emission regions. This method effectively minimizes future warming effects arising from aerosol emission reductions under carbon-neutrality policies.

With the help of the dynamic emission reduction strategy, although the national emission of SO₂ is reduced by the same amount, N_d only decreases by 0.10 cm⁻² in 2030 and 16.32 cm⁻² in 2060 (Fig. 3), much lower than 8.34 cm⁻² in 2030 and 28.48 cm⁻² in 2060 with the original emission reduction strategy. Accordingly, the emission reduction would produce an ERF_{aci} change of 0.89–1.63 W m⁻² in China during 2020–2040 with the original emission scenario, while the dynamic emission reduction strategy could limit it to less than 0.13 W m⁻² in the short-term future (Fig. 4a). By the carbon neutral year 2060, the original ERF_{aci} change (3.03 W m⁻²) could be weakened by two-thirds, with a regional average of 1.09 W m⁻² for the dynamic emission reduction strategy focusing on high-emission regions. These results emphasize the importance of accounting for spatial differences in abatement policies. The dynamic emission reduction strategy not only reduces total emissions but also optimizes the geographical distribution of abatement, effectively mitigating the warming effect induced by future aerosol reduction.

Discussions

Reducing aerosol emissions can significantly improve air quality, but it also carries potential warming risks by weakening the cooling effect. Therefore, mitigation must be managed carefully along the carbon-neutrality pathway to avoid exacerbating climate change. This study reveals that the dynamic optimization strategy that prioritizes emission reductions in high-emission regions can substantially suppress the positive growth of short-term ERF_{aci}. This approach effectively mitigates warming from reduced aerosol levels while simultaneously improving air quality. The dynamic emission reduction strategy achieves similar reductions in the national PM_{2.5} concentrations as the

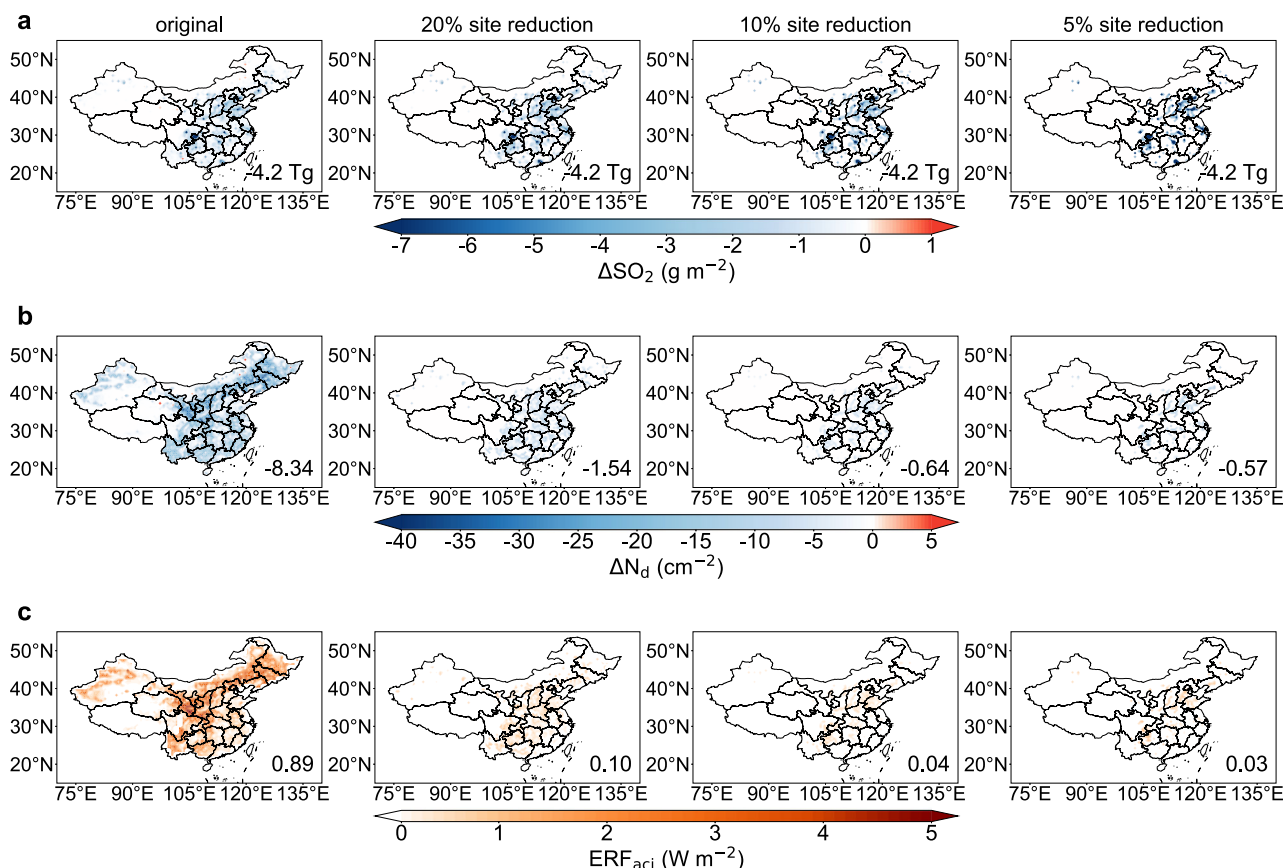


Fig. 2 | Changes in SO_2 emissions and associated cloud droplet number concentration (N_d) and effective radiative forcing due to aerosol-cloud interactions (ERF_{aci}) responses. Spatial distribution of changes in **a** anthropogenic SO_2 emissions (g m^{-2}), **b** N_d (cm^{-2}) and **c** ERF_{aci} (W m^{-2}) in China in 2030 relative to 2020

from the original emission scenario and the reduction scenarios targeting the top 20%, 10%, and 5% of high SO_2 -emitting areas. Regional average value over China is shown in bottom right of each panel.

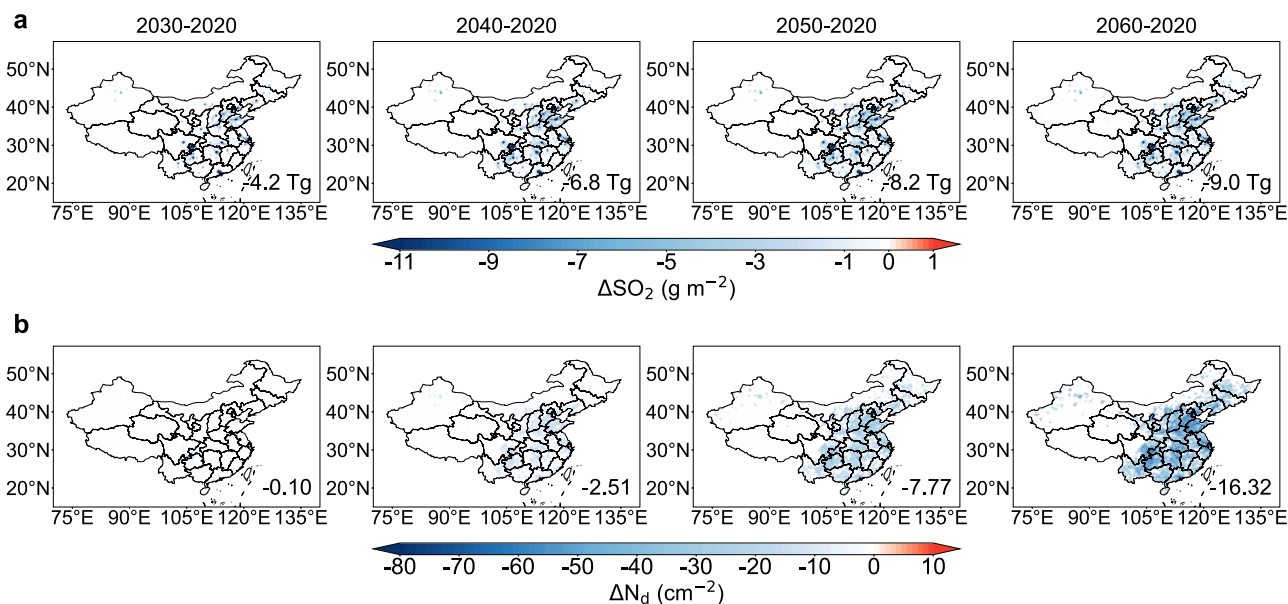


Fig. 3 | Changes in SO_2 emissions and cloud droplet number concentration (N_d) under dynamic emission reduction strategy. Spatial distribution of changes in **a** anthropogenic SO_2 emissions (g m^{-2}) and **b** N_d (cm^{-2}) in China in 2030, 2040, 2050,

and 2060 relative to 2020 from the dynamic emission reduction scenario. The regional average value for China is shown in the bottom-right corner of each panel.

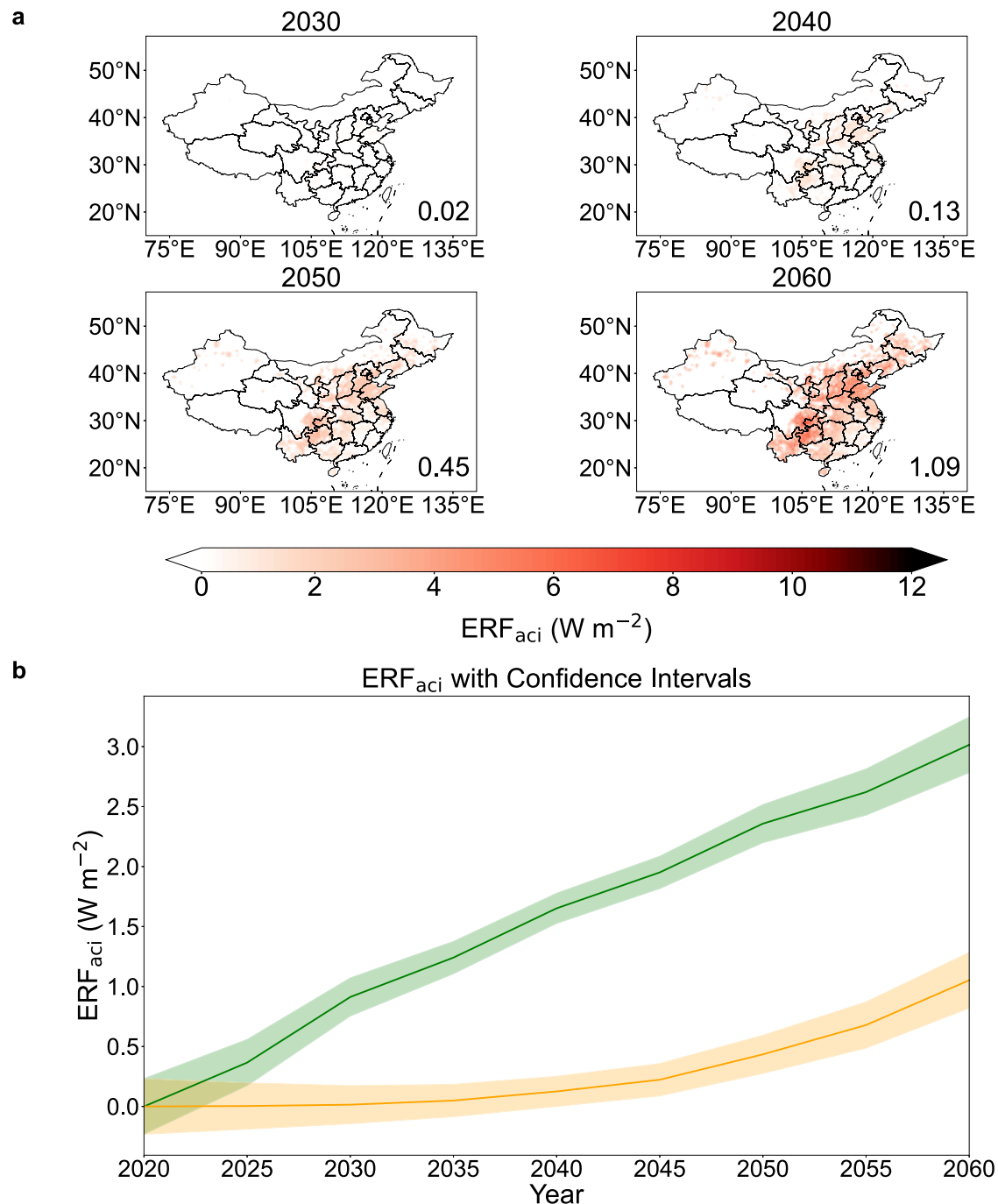


Fig. 4 | Spatial pattern and time series of effective radiative forcing due to aerosol-cloud interactions (ERF_{aci}) changes under dynamic emission reduction strategy. **a Spatial distribution of ERF_{aci} changes ($W m^{-2}$) in China in 2030, 2040, 2050, and 2060 relative to 2020 by adopting the dynamic emission reduction strategy. Regional average value over China is shown in the bottom right of each panel. **b** Projections of ERF_{aci} due to aerosol-cloud interactions with 95% confidence**

intervals. The green and orange lines represent the projected future changes in ERF_{aci} under original emission abatement and dynamical emission reduction, respectively. The shaded areas indicate the 95% confidence intervals, reflecting the uncertainty range of projections due to potential errors in estimating N_d and fitting the model.

original scenario, indicating that climate benefits due to the optimization framework do not come at the expense of compromising air quality improvements (Supplementary Fig. 2). Compared to the original emission scenario, the dynamic strategy significantly flattens the growth of positive ERF_{aci} change from 2030 to 2050 (Fig. 4a). However, its effectiveness declines in the second half of the 21st century. The sensitivities of N_d and ERF_{aci} continue to rise as aerosol decreases due to the nonlinear aerosol-cloud interaction. This underscores the

importance of integrating short-term aerosol-emission optimization into broader, long-term mitigation frameworks.

The changing aerosol emissions can also influence ERF via aerosol-radiation interaction. Here, the future changes in aerosol-radiation (ERF_{ari}) under the original emission scenario and the dynamic emission reduction scenario are simulated using the GEOS-Chem model. Both scenarios exhibit a progressively increasing positive changes in ERF_{ari} over time, especially in key emission-intensive

regions such as southeastern China and the Sichuan Basin (Supplementary Fig. 3). Despite differences in emission scenarios, the regional average ERF_{aci} changes during 2030–2060 relative to 2020 remain similar between the original and dynamic scenarios, indicating that aerosol-radiation coupling plays a secondary role in distinguishing the climate impacts of the two strategies. Decomposition of the radiative effects reveals that the climatic benefit of the optimized SO_2 reduction strategy arises primarily from changes in cloud microphysical properties rather than from direct aerosol scattering or absorption.

The dynamic emission reduction strategy has been proven to mitigate warming at the national scale. However, some regions could face stronger warming than expected. The optimizing method aims to shift emission-reduction actions from relatively clean and moderately polluted areas to highly polluted areas. Therefore, over the highly polluted regions, a stronger emission reduction can cause larger positive changes in ERF_{aci} , which is noteworthy. Moreover, the calculation of ERF_{aci} is based on estimates of N_d , which are derived through sigmoid fitting of observational data. This process introduces multiple sources of uncertainty. First, aerosol index (AI) is calculated from SO_2 emissions data, and the formula is fitted to data from 2001–2020, which could be changed due to future climate change. The estimation of N_d relies on AI retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite observations, which may suffer from aerosol retrieval biases over complex land surfaces³⁹ and sampling biases due to high cloud cover⁴⁰. In addition, since the relationship between AI and SO_2 is calculated based on regional averages without considering aerosol transport and mixing processes, the estimated AI shows a similar distribution but is lower in the national average than the satellite retrieval (Supplementary Fig. 4). Second, the nonlinearity of the sigmoid function introduces fitting errors, particularly with the extreme AI values. Third, the conversion from N_d to ERF_{aci} depends on empirical coefficients derived from previous studies, which are subject to uncertainties stemming from model assumptions and regional differences. Therefore, the uncertainty intervals shown in Fig. 4b reflect the combined effects of Sigmoid fitting errors, limitations of AI data, and the uncertainty of conversion coefficients, although it does not change the main conclusion of this study. Current climate models still exhibit substantial uncertainty in aerosol–cloud interactions. Satellite-based analyses indicate that CMIP6 models generally overestimate N_d sensitivity and cannot reproduce the nonlinear saturation behavior in polluted regions¹⁰. Multi-model constraints using volcanic eruption signals further show that existing models typically underestimate cloud-cover responses to aerosol perturbations, contributing to large uncertainties in aerosol-mediated cooling⁴¹. These limitations motivate our choice of an observation-constrained empirical framework for estimating ERF_{aci} in response to SO_2 emission changes, while fully coupled modeling simulations remain a key direction for validation and long-term assessment of climate responses beyond radiative forcing.

Although this study focuses on sulfate-driven ERF_{aci} , considering the comparable radiative forcing of other aerosols in China, we further examined the potential contribution of organic carbon (OC) using the same empirical framework (Supplementary Fig. 5). If the OC emission is applied as the indicator of AI, the calculated ERF_{aci} change will be higher than 2 W m^{-2} in the mid-21st century, similar to that calculated based on SO_2 emission. In addition, when the dynamic emission reduction strategy is adopted for OC emissions, the associated ERF_{aci} change will be substantially limited to 0.3 W m^{-2} in 2050. These results support our finding that optimized aerosol emission controls can mitigate short-term climate risks while advancing air quality goals.

Our findings indicate that while dynamic emission reduction strategies can effectively mitigate short-term warming, they impose disproportionately high reduction pressures on several industrialized provinces (Supplementary Fig. 6). For instance, SO_2 emissions in Shandong province are projected to drop from 0.88 Tg in 2020 to 0.03

Tg in 2060, compared to 0.11 Tg under the original scenario. Similar deeper emission cuts are observed in Chongqing, Hubei, and Hebei provinces. In these provinces, the industrial sector accounts for 62% to 94% of total anthropogenic SO_2 emissions in the year 2020. To enhance feasibility and regional equity, complementary policies are suggested, including dedicated fiscal support for clean technology upgrades, inter-provincial collaboration to gradually relocate high-emission production capacity, and implementation of workforce transition plans to cushion socioeconomic impacts. These measures will help translate conceptual strategies into more operational emission reduction frameworks while ensuring optimized climate benefits are not achieved at the expense of regionally imbalanced costs.

Methods

Observations and emission data

According to the nonlinearity between AI and N_d proposed by Jia and Quaas¹⁰, this study further incorporates future localized high-resolution emission scenarios under China's carbon neutrality targets to evaluate the impacts of aerosol reductions on ERF due to ERF_{ari} and ERF_{aci} based on satellite data, emission scenario and atmospheric chemistry model simulations.

Given that sulfate aerosol is the dominant contributor to long-term trends in aerosol optical depth (AOD), this study focuses primarily on SO_2 emissions as the main predictor for AI⁴². The anthropogenic emissions of SO_2 over China, spanning the period from 2001 to 2020, are sourced from the Multi-resolution Emission Inventory model for Climate and air pollution research (MEIC)²⁵. This emission dataset is specifically designed for studying air pollution in China, offering accurate regional representations and reflecting the dynamic nature of emission sources and control measures. The MEIC inventory provides monthly data across five major sectors, including power generation, industry, residential, transportation, and agriculture⁴³. Future anthropogenic emissions of SO_2 over 2020–2060 following the carbon-neutral pathway are provided by DPEC, which serves as an integrated tool for assessing the impacts of climate policies and pollution control measures under various socioeconomic development pathways⁴⁴. It offers a comprehensive framework for emissions dynamics across sectors with a resolution of 0.5° longitude $\times$ 0.5° latitude used in this study.

In addition to SO_2 emissions, this study employs satellite products from MODIS Collection 6.1 Level-3 daily products (MOD08), which offer essential aerosol and cloud properties such as aerosol optical depth (AOD), the Ångström exponent (AE), and liquid cloud cover (f_{liq}). Shortwave planetary albedo data for both all-sky (A_{all}) and clear-sky (A_{clr}) conditions, derived from the Clouds and the Earth's Radiant Energy System (CERES) SSF1deg Edition-4.2 Level-3 monthly product⁴⁵, are also used in this study to calculate cloud albedo. This combination of future emissions projections and radiative forcing data provides a nuanced understanding of the potential climate impacts of aerosol reductions under China's carbon neutrality goals.

Calculation of ERF_{aci} and the associated variables

In this study, AI is defined as $AI = AOD \times AE$, serving as a proxy for CCN. Unlike AOD, which indicates the total aerosol loading but does not differentiate between aerosols of varying particle sizes, the combination of AOD and AE enables a more accurate characterization of aerosols with small particle sizes. This is because AE provides information on the relative contribution of fine particles to the overall aerosol population^{46,47}. Using AI as a proxy enables a more detailed representation of aerosol microphysical properties, which are crucial for cloud formation.

A linear regression relationship is established between AI and SO_2 emissions for the period 2001–2020, which provides a robust fit for predicting AI based on SO_2 emission levels. The $\ln AI$ linearly increases

with the rising $\ln\text{SO}_2$, expressed as

$$\ln\text{AI} = 0.32 \ln\text{SO}_2 - 8.82 \quad (1)$$

The established regression model is then applied to estimate future AI values during 2020–2060 based on the DPEC-projected SO_2 emissions over China. Following the sigmoidal relationship between $\ln\text{AI}$ and $\ln\text{N}_d$ proposed by Jia and Quaas¹⁰, it further allows for the prediction of future N_d , expressed as:

$$\ln\text{Nd}(\ln\text{AI}) = \frac{1.15}{1 + e^{-3.41 \ln\text{AI} - 6.21}} + 4.07 \quad (2)$$

The corresponding future ERF change due to aerosol-cloud interactions (ERF_{aci}) relative to year 2020 can be calculated based on the cloud albedo derived from the Twomey formula⁴⁸:

$$\text{ERF}_{\text{aci}} = -F^\downarrow f_{\text{liq}} \cdot \frac{\alpha_{\text{cld}}(1 - \alpha_{\text{cld}})}{3} \cdot \Delta \ln \text{N}_d \quad (3)$$

where $F^\downarrow$ and α_{cld} are the mean incoming solar radiation flux and the cloud albedo, respectively, and f_{liq} is the liquid cloud fraction that can be obtained from the MODIS Level 3 product. Cloud albedo (α_{cld}) is calculated from the all-sky (α_{all}) and clear-sky (α_{clr}) shortwave planetary albedo data using the following equation⁴⁹:

$$\alpha_{\text{all}} = f_{\text{liq}} \cdot \alpha_{\text{cld}} + (1 - f_{\text{liq}}) \alpha_{\text{clr}} \quad (4)$$

Emission reduction strategy

This study aims to optimize spatial aerosol and precursor emission-reduction strategies in China to mitigate the associated positive ERF change. According to the sigmoidal relationship between AI and N_d , ERF_{aci} is insensitive to aerosol change over high polluted regions¹⁰ and, therefore, the emission reduction is preferred to emerge in the regions with high emissions, in order to reduce the aerosol reduction-induced positive ERF_{aci} change.

Firstly, the reduction strategies for testing target the top 20%, 10%, and 5% of high SO_2 -emitting areas identified based on the emissions in 2020. The total amount of SO_2 emission reduction across China in 2030, for example, from the original DPEC carbon-neutral pathway, is distributed separately to the top 20%, 10%, and 5% of high- SO_2 -emitting areas, while emissions in other regions of China are maintained at the 2020 level. This method keeps the total emission reduction unchanged but aims to weaken the aerosol-induced warming.

If the test cases effectively mitigate warming, then a dynamic emission reduction strategy can be implemented to maximize the effectiveness of warming mitigation by shifting emission abatement from relatively clean and moderately polluted areas to highly polluted areas. In the dynamic emission reduction strategy, the emission threshold for each target year is determined using an iterative bisection method based on two constraints: (1) the total national SO_2 emission reduction required for that year relative to the reference year (2020 in this study), and (2) the probability density distribution of grid-level SO_2 emissions in the reference year. The algorithm repeatedly adjusts the threshold by halving the search interval until the emission in each grid box below the threshold and the proposed total emission reduction based on this threshold exactly matches the prescribed national reduction target. Emission in each grid above the identified threshold is then reduced to that threshold level, while that below the threshold remains unchanged. This strategy dynamically searches for the threshold and limits emissions above it, thereby achieving targeted emission reductions for climate mitigation, offering new insights for targeted emission policies under the carbon neutrality framework.

GEOS-Chem model simulation

In addition to the ERF_{aci} , the ERF_{ari} change due to the aerosol emission reductions is also assessed by employing the global atmospheric chemistry model GEOS-Chem. The simulations are conducted every ten years during 2020–2060 at a horizontal resolution of $2^\circ \times 2.5^\circ$ over China, driven by present-day meteorological data from MERRA-2 and projected future SO_2 emissions under the carbon-neutrality scenario from the DPEC v1.2 dataset⁵⁰. Two sets of simulations are performed: a baseline case using the original emission reduction scenario and an optimized case using dynamic emission reduction.

Data availability

The MODIS cloud and aerosol products from MOD08 are available from the Atmosphere Archive and Distribution System Distributed Active Archive Center of the National Aeronautics and Space Administration (LAADS-DAAC, NASA) at <https://ladsweb.modaps.eosdis.nasa.gov>. The CERES SSF product is available from <https://ceres.larc.nasa.gov/data/>. The MEIC product is available from http://meicmodel.org.cn/?page_id=560. The DPEC product is available from http://meicmodel.org.cn/?page_id=1917.

Code availability

Code and results can be found at Zenodo⁵¹.

References

- Li, J. et al. Scattering and absorbing aerosols in the climate system. *Nat. Rev. Earth Environ.* **3**, 363–379 (2022).
- Chen, A., Zhao, C., Shen, L. & Fan, T. Influence of aerosol properties and surface albedo on radiative forcing efficiency of key aerosol types using global AERONET data. *Atmos. Res.* **282**, 106519 (2023).
- Forster, P. et al. in *Climate Change 2021: The Physical Science Basis* (eds. Masson-Delmotte, V., et al.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Loeb, N. G., Su, W., Bellouin, N. & Ming, Y. Changes in clear-sky shortwave aerosol direct radiative effects since 2002. *J. Geophys. Res. Atmos.* **126**, e2020JD034090 (2021).
- Chen, A., Zhao, C., Zhang, H., Yang, Y. & Li, J. Surface albedo regulates aerosol direct climate effect. *Nat. Commun.* **15**, 7816 (2024).
- Rosenfeld, D. et al. Global observations of aerosol-cloud-precipitation-climate interactions. *Rev. Geophys.* **52**, 750–808 (2014).
- Allen, R. J., Norris, J. R. & Storelvmo, T. Observationally constrained aerosol-cloud semi-direct effects. *NPJ Clim. Atmos. Sci.* **2**, 16 (2019).
- Su, T., Li, Z., Roldan Henao, N., Luan, Q. & Yu, F. Constraining effects of aerosol-cloud interaction by accounting for coupling between cloud and land surface. *Sci. Adv.* **10**, ead15044 (2024).
- Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge Univ. Press (2023).
- Jia, H. & Quaas, J. Nonlinearity of the cloud response postpones climate penalty of mitigating air pollution in polluted regions. *Nat. Clim. Chang.* **13**, 943–950 (2023).
- Hasekamp, O. P., Gryspeerdt, E. & Quaas, J. Analysis of polarimetric satellite measurements suggests stronger cooling due to aerosol-cloud interactions. *Nat. Commun.* **10**, 5405 (2019).
- McCoy, D. T. et al. The global aerosol-cloud first indirect effect estimated using MODIS, MERRA, and AeroCom. *Geophys. Res. Atmos.* **122**, 1779–1796 (2017).
- Zhou, H. et al. Recovery of ecosystem productivity in China due to the Clean Air Action plan. *Nat. Geosci.* **17**, 1233–1239 (2024).
- Shi, Y. et al. Representing anthropogenic dust in E3SMv1: Implementation, evaluation, and assessment of their radiative forcing.

- ESS Open Archive. <https://doi.org/10.22541/essoar.168988430.03348279/v1> (2023).
15. Xia, W. et al. Double trouble of air pollution by anthropogenic dust. *Environ. Sci. Technol.* **56**, 761–769 (2022).
 16. Zhang, X. Y. et al. Atmospheric aerosol compositions in China: spatial/temporal variability, chemical signature, regional haze distribution and comparisons with global aerosols. *Atmos. Chem. Phys.* **12**, 779–799 (2012).
 17. Hong, C. et al. Weakening aerosol direct radiative effects mitigate climate penalty on Chinese air quality. *Nat. Clim. Chang.* **10**, 845–850 (2020).
 18. Chen, S. et al. Fugitive road dust PM_{2.5} emissions and their potential health impacts. *Environ. Sci. Technol.* **53**, 8455–8465 (2019).
 19. Saikawa, E., Naik, V., Horowitz, L. W., Liu, J. & Mauzerall, D. L. Present and potential future contributions of sulfate, black and organic carbon aerosols from China to global air quality, premature mortality and radiative forcing. *Atmos. Environ.* **43**, 2814–2822 (2009).
 20. Zhang, J. et al. Vehicular non-exhaust particulate emissions in Chinese megacities: source profiles, real-world emission factors, and inventories. *Environ. Pollut.* **266**, 115268 (2020).
 21. Menon, S. et al. Aerosol climate effects and air quality impacts from 1980 to 2030. *Environ. Res. Lett.* **3**, 024004 (2008).
 22. Streets, D. G. Dissecting future aerosol emissions: warming tendencies and mitigation opportunities. *Clim. Change* **81**, 313–330 (2007).
 23. Gao, J. et al. Climate responses in China to domestic and foreign aerosol changes due to clean air actions during 2013–2019. *NPJ Clim. Atmos. Sci.* **6**, 160 (2023).
 24. Wang, W. et al. Is the key-treatment-in-key-areas approach in air pollution control policy effective? Evidence from the action plan for air pollution prevention and control in China. *Sci. Total Environ.* **843**, 156850 (2022).
 25. Zheng, B. et al. Trends in China's anthropogenic emissions since 2010 as the consequence of clean air actions. *Atmos. Chem. Phys.* **18**, 14095–14111 (2018).
 26. Cheng, J. et al. Pathways of China's PM_{2.5} air quality 2015–2060 in the context of carbon neutrality. *Natl. Sci. Rev.* **8**, nwab078 (2021).
 27. Nazarenko, L. et al. Interactive nature of climate change and aerosol forcing. *J. Geophys. Res. Atmos.* **122**, 3457–3480 (2017).
 28. Bellouin, N. et al. Bounding global aerosol radiative forcing of climate change. *Rev. Geophys.* **58**, e2019RG000660 (2020).
 29. Wang, X., Zhai, S. & Shen, L. Cooling from aerosol–radiation interaction of anthropogenic coarse particles in China. *NPJ Clim. Atmos. Sci.* **7**, 220 (2024).
 30. Yang, Y., Zeng, L., Wang, H., Wang, P. & Liao, H. Climate effects of future aerosol reductions for achieving carbon neutrality in China. *Sci. Bull.* **68**, 902–905 (2023).
 31. Wang, P. et al. Aerosols overtake greenhouse gases causing a warmer climate and more weather extremes toward carbon neutrality. *Nat. Commun.* **14**, 7257 (2023).
 32. Samset, B. H. et al. East Asian aerosol cleanup has likely contributed to the recent acceleration in global warming. *Commun. Earth Environ.* **6**, 543 (2025).
 33. Iles, C. E. et al. Strong regional trends in extreme weather over the next two decades under high- and low-emissions pathways. *Nat. Geosci.* **17**, 845–850 (2024).
 34. Zou, A., Yang, Y., Wang, H., Wang, P. & Liao, H. Aerosol decline accelerates the increasing extreme precipitation in China. *Geophys. Res. Lett.* **52**, e2024GL113887 (2025).
 35. Yang, Y. et al. Abrupt emissions reductions during COVID-19 contributed to record summer rainfall in China. *Nat. Commun.* **13**, 959 (2022).
 36. Liu, Z. et al. Contribution of local and remote anthropogenic aerosols to a record-breaking torrential rainfall event in Guangdong Province, China. *Atmos. Chem. Phys.* **20**, 223–241 (2020).
 37. Gao, J. et al. Fast climate responses to emission reductions in aerosol and ozone precursors in China during 2013–2017. *Atmos. Chem. Phys.* **22**, 7131–7142 (2022).
 38. Jia, R. et al. Direct radiative effects of dust aerosols over Northwest China revealed by satellite-derived aerosol three-dimensional distribution. *J. Meteorol. Res.* **36**, 767–778 (2022).
 39. Levy, R. C. et al. The Collection 6 MODIS aerosol products over land and ocean. *Atmos. Meas. Tech.* **6**, 2989–3034 (2013).
 40. Jia, H., Ma, X., Yu, F. & Quaas, J. Significant underestimation of radiative forcing by aerosol–cloud interactions derived from satellite-based methods. *Nat. Commun.* **12**, 3649 (2021).
 41. Wang, Y. et al. Challenges in global climate models to represent cloud response to aerosols: insights from volcanic eruptions. *Nat. Commun.* **16**, 1234 (2025).
 42. Frey, L., Bender, F. A.-M. & Svensson, G. Cloud albedo changes in response to anthropogenic sulfate and non-sulfate aerosol forcings in CMIP5 models. *Atmos. Chem. Phys.* **17**, 9145–9162 (2017).
 43. Fan, T. et al. Emission or atmospheric processes? An attempt to attribute the source of large bias of aerosols in eastern China simulated by global climate models. *Atmos. Chem. Phys.* **18**, 1395–1417 (2018).
 44. Tong, D. et al. Dynamic projection of anthropogenic emissions in China: methodology and 2015–2050 emission pathways under a range of socio-economic, climate policy, and pollution control scenarios. *Atmos. Chem. Phys.* **20**, 5729–5757 (2020).
 45. Zhang, T., Stackhouse, P. W., Cox, S. J., Mikovitz, J. C. & Long, C. N. Clear-sky shortwave downward flux at the Earth's surface: ground-based data vs. satellite-based data. *Quant. Spectrosc. Radiat. Transf.* **224**, 247–260 (2019).
 46. Stier, P. Limitations of passive remote sensing to constrain global cloud condensation nuclei. *Atmos. Chem. Phys.* **16**, 6595–6607 (2016).
 47. Nakajima, T., Higurashi, A., Kawamoto, K. & Penner, J. E. A possible correlation between satellite-derived cloud and aerosol microphysical parameters. *Geophys. Res. Lett.* **28**, 1171–1174 (2001).
 48. Twomey, S. Aerosols, clouds and radiation. *Atmos. Environ.* **25**, 2435–2442 (1991).
 49. Jia, H., Hasekamp, O. & Quaas, J. Revisiting aerosol–cloud interactions from weekly cycles. *Geophys. Res. Lett.* **51**, e2024GL108266 (2024).
 50. Qin, Y. et al. Amplified positive effects on air quality, health, and renewable energy under China's carbon-neutral target. *Nat. Geosci.* **17**, 411–418 (2024).
 51. Yang, Y. Data for significant relief of unintended warming associated with aerosol decline through optimizing emission reduction strategy. Zenodo. <https://doi.org/10.5281/zenodo.16731166> (2025).

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Author contributions

Y.Y. designed the research. Y.Z. performed the analysis and simulations. All authors, including Y.Z., H.J., H.L., H.W., P.W., H.Liao, and Y.Y., discussed the results and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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