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## LETTER

# Climate effects of China's efforts to improve its air quality

#### Yixuan Zheng<sup>1,2</sup>, Qiang Zhang<sup>3</sup>, Dan Tong<sup>4</sup>, Steven J Davis<sup>4</sup>, and Ken Caldeira<sup>2</sup>

- <sup>1</sup> Center of Air Quality Simulation and System Analysis, Chinese Academy of Environmental Planning, Beijing 100012, People's Republic of China
- <sup>2</sup> Department of Global Ecology, Carnegie Institution for Science, Stanford, CA 94305, United States of America
- <sup>3</sup> Department of Earth System Science, Tsinghua University, Beijing 100084, People's Republic of China
- <sup>4</sup> Department of Earth System Science, University of California, Irvine, Irvine, CA 92697, United States of America

E-mail: kcaldeira@carnegiescience.edu

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Facing severe air pollution issues, China has implemented a series of clean air policies aimed to improve the country's air quality. These policies largely focused on reducing emissions of major air pollutants such as sulfur dioxide (SO<sub>2</sub>) and primary aerosols. However, changes in such pollution also affect radiative forcing. To understand the climate consequences of these clean air actions in China, we evaluate the near-equilibrium climate response to sustained changes in aerosol (and precursors) emission rates equivalent to those that occurred in China between 2006 and 2017. During this period, China's SO<sub>2</sub> emissions declined by ~70%, and black carbon emissions declined by ~30%. Climate simulations that used a fully coupled ocean and atmosphere climate model indicate that China's reductions in aerosol emission rates from 2006 to 2017 may exert a net increase in global radiative forcing of  $0.09 \pm 0.03$  W m<sup>-2</sup> and a mean warming of  $0.12 \pm 0.01$  °C in the Northern Hemisphere; and may also affect the precipitation rates in East Asia and in more distant regions. The success of Chinese policies to further reduce aerosol emissions may bring additional net warming, and this 'unmasked' warming would in turn compound the challenge and urgency of international climate mitigation efforts.

## 1. Introduction

Economic growth and industrialization in China over recent decades have been supported by increasing consumption of energy from coal; in turn, this consumption has made China the world's largest emitter of major air pollutants such as sulfur dioxide (SO<sub>2</sub>) and black carbon (BC) for a long time [1]. For example, in 2010 China accounted for one-fourth of global SO<sub>2</sub> emissions [1]. These air pollutant emissions severely deteriorated Chinese air quality and adversely affected public health [2], with an estimated 2.5 million premature deaths related to air pollution in 2015 [3]. Air pollution in China has thus become a prominent social and public health concern [4].

To tackle the severe air pollution issues, the Chinese government has over the past decades implemented a series of clean air policies, with those after 2005 becoming increasingly stringent [5]. For example, in the 11th five year plan, China set a target to reduce national SO<sub>2</sub> emissions by 10% in 2010

sions, and a 10% reduction in NO<sub>x</sub> emissions, for 2015 relative to 2010 levels [7]. In 2013, the State Council of China announced the strictest plan to date, the *Air Pollution Prevention and Control Action Plan*. This action plan demanded reductions, by year 2017 relative to 2013, in annual mean concentrations of  $PM_{2.5}$  (fine particulate matter with aerodynamic diameter less than 2.5  $\mu$ m) between 15% and 25% in key regions (e.g. Beijing and its surrounding regions) [8]. During the past decades, efforts have been expended to meet these targets and success has been

relative to 2005 [6]. In the following five year plan, the goal was an additional 8% reduction in  $SO_2$  emis-

ded to meet these targets, and success has been achieved [9–11]. Driven by clean air actions, aerosol pollution in China was substantially alleviated after 2013 and notable public health benefits ensued [11–13]. During 2013–2017, the national annual population-weighted mean PM<sub>2.5</sub> concentration has been estimated to have reduced by 32%, from 67.4 to 45.5  $\mu$ g m<sup>-3</sup>, leading to a 14% reduction in premature deaths due to long-term  $PM_{2.5}$  exposure, and a 61% reduction in premature deaths associated with acute  $PM_{2.5}$  exposure [13].

Yet the same aerosols that impact public health also affect the climate [14, 15]. Aerosols scatter and absorb incoming solar radiation and interact with clouds [16, 17], thereby affecting regional and global climate. According to the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5), anthropogenic aerosols are estimated to exert a -0.9 W m<sup>-2</sup> (95% CI: -1.5 to -0.4) global mean radiative forcing since pre-industrial time [18]. This forcing from aerosols temporarily offsets (or 'masks') up to one-third of the positive radiative forcing from the increased concentrations of well-mixed greenhouse gases since preindustrial, estimated as 2.8 W m<sup>-2</sup> (95% CI: 2.3 to 3.4) [18]. On one hand, of the different aerosol species, sulfate aerosol is the dominant cooling agent in the atmosphere [19]. Indeed, anthropogenic sulfate aerosol is estimated to cool the globe on average by 0.55  $\pm$  0.02 °C in 2010, equivalent to 76% of all temperature change due to all anthropogenic aerosols [20]. On the other hand, BC absorbs heat in the atmosphere and warms the Earth. Since preindustrial, BC from anthropogenic fossil and biofuel emissions is estimated to exert a +0.40 W m<sup>-2</sup> (95%) CI: +0.05 to +0.80) global mean radiative forcing via aerosol-radiation interaction [18]. East Asia, specifically, is a region where climate variations have been substantially modulated by anthropogenic aerosol emissions [21, 22].

Given the impacts of aerosols on climate, actions that reduce atmospheric aerosol concentrations inevitably affect the climate system. Previous studies demonstrated that clean air actions in North America and Europe during the past decades had exerted local and global impacts [23-26]. For example, U.S. air quality regulation, mainly via reducing SO<sub>2</sub> emissions, is estimated to exert a direct radiative forcing by 0.8 W m<sup>-2</sup> and a positive indirect radiative forcing by  $1.0 \text{ W} \text{ m}^{-2}$  over the eastern U.S. between 1990 and 2010 [23]. This air quality regulation has been estimated to have resulted in a 0.35 °C annual mean warming in the eastern U.S. from 1980 to 2010 [24]. Similarly, air quality regulation in Europe has been estimated to have increased European mean surface temperatures by 0.45  $\pm$  0.11 °C between 1970 and 2010 [25]. Climate modeling further shows that controls on SO<sub>2</sub> emissions in Europe since 1980 may have exacerbated warming in the Arctic region [26]. Future aerosol emission reductions are likely to further warm the Earth [27]. In addition to the effects on temperature, anthropogenic aerosol has also been identified as one of the key drivers of historical global and regional precipitation changes [28, 29]. Furthermore, future policies that would reduce aerosol emissions would tend to increase global and Asian summer monsoon precipitation [22].

According to the Multi-resolution Emission Inventory for China (MEIC) [10, 30], China's SO<sub>2</sub> emissions (i.e. precursor of sulfate aerosol) decoupled from the country's fast-growing economy and peaked around 2006 [30], driven by the nationwide installation of flue gas desulfurization devices (FGD) on coal-fired power plants [6, 31, 32]. Clean air actions that targeted coal-fired power plants and emissionintensive industrial sectors after 2010 further reduced SO<sub>2</sub> emissions in China [10, 11]. Consequently, India is now the largest SO<sub>2</sub> emitter globally [33]. As estimated by MEIC, SO<sub>2</sub> emissions in China have been reduced by 23.5 Tg (a  $\sim$ 70% reduction) between 2006 and 2017, a decrease similar to the SO<sub>2</sub> reductions obtained by air quality regulations in Europe and the U.S. over the past several decades. Emissions of BC and organic carbon (OC) were also at high levels in China in 2006. Upgrades on dust removal devices in emission-intensive industrial sectors (e.g. the cement industry) and promotion of advanced stoves and clean fuels for residential households reduced emissions of BC and OC by 0.5 Tg (29%) and 1.4 Tg (41%), respectively, from 2006 to 2017 [10, 30, 34]. These reductions in aerosol (and their precursors) emissions in China would be expected to have local and global climate consequences as has been demonstrated for emission reductions in Europe and the U.S.

Impacts of China's recent clean air actions on air quality and the associated public health benefits have been extensively investigated [12, 13, 35-39]. Yet the climate effects of reduced aerosol concentrations in China have been the subject of only a few studies [40–42]. By using a regional chemical transport model, Dang et al (2019) [40] studied changes in regional radiative forcing as a consequence of the clean air actions from 2012 to 2017, and found a 1.18 W m<sup>-2</sup> positive forcing from reduced PM<sub>2.5</sub> pollution over eastern China. The global temperature and precipitation responses of a complete removal of China's anthropogenic aerosol emissions have also been evaluated using global climate models [41, 42]. These studies found that removing China's SO<sub>2</sub> emissions tends to exert a net warming effect and increase precipitation globally [41, 42]. However, the global climate implications of China's air pollution control policies, especially the significant reductions in aerosol (and precursors) emissions since 2006, have not previously been systematically investigated.

To provide a better understanding of the full range of impacts of China's clean air actions, based on the newly updated aerosol emission inventory [10, 30], we analyzed near-equilibrium climate responses to the clean air actions in China from 2006 to 2017 using the Community Earth System Model version 1.2.2 (CESM 1.2.2) [43]. That is, we analyzed the climate effects of these reductions under the assumption that they continue into the future and the climate system is linear enough that the climate effects of the aerosol emission changes can be considered as additional to the climate effects of other forcing.

# 2. Materials and methods

#### 2.1. Emission scenarios

To investigate the climate impacts of emission reductions in China from 2006 to 2017, we considered two aerosol emission scenarios based on the year 2000 levels of greenhouse gases (i.e. CO<sub>2</sub> concentration is set to 367 ppm) and aerosol forcing [44, 45]. Emissions of aerosols and their precursors for the year 2000 were obtained from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) [45]. The 2006 China aerosol emission scenario ('CN06') and the 2017 China aerosol emission scenario ('CN17') replaced anthropogenic aerosol emissions over China with those from the years 2006 and 2017, respectively, as obtained from the MEIC model [30]. Sectoral gridded SO<sub>2</sub> (including primary sulfate), BC, and OC emissions (i.e. the aerosol emissions considered in the CESM v1.2.2) for the year 2006 and 2017 were obtained from the MEIC model and used to substitute anthropogenic aerosol emissions from energy, industry, domestic, and transportation sectors for the two scenarios. Emissions from agricultural waste burning and waste treatment, which are not provided in the MEIC model, were fixed to the ACCMIP 2000 values in these two scenarios. Thus, comparison between scenarios CN06 and CN17 shows the climate impacts of emission reductions in China from 2006 to 2017.

Because China has committed to continue its efforts to combat air pollution, future emission reductions in China can be expected [46]. We therefore designed a China aerosol emission removal scenario ('noCN') to investigate the potential climate impacts of future emission reductions. The noCN scenario is identical to CN17, but it removes all anthropogenic aerosol emissions over China from the six sectors mentioned above. Thus, comparison between CN17 and noCN quantifies the potential climate impacts of removing all aerosol emissions in China after 2017.

To isolate the climate effect of aerosol emissions from China, all other forcing agents were held constant in our simulations. The three scenarios differ only in China's anthropogenic aerosol emissions. Anthropogenic aerosol emissions outside of China (including emissions from international shipping), as well as global aerosol emissions from natural sources, were fixed to their respective year 2000 levels in all three scenarios. Emissions over China for the three scenarios are shown in the supplementary materials figure S1 (available online at stacks.iop.org/ERL/15/104052/mmedia).

#### 2.2. Model configuration

In this study, we performed simulations using the CESM v1.2.2 with the Community Atmosphere Model version 5 (CAM5) [43, 44]. The CAM5 atmosphere model provides a fully interactive aerosol module, which incorporates the emission, transportation, scavenging, and chemical processes of aerosols [44], with consideration of the aerosol direct and semidirect radiative effects, and full aerosol indirect radiative effects within stratus clouds [44, 47]. We applied CAM5 with the three mode version of the modal aerosol module (i.e. Aitken, accumulation, and coarse modes of aerosols are considered; MAM3), which predicts internal mixtures of sulfate, BC, and OC with other aerosol species [44]. The precipitation feedback on temperature is considered in the CAM5 model [47]. In this study, the CAM5 atmosphere model was configured with a horizontal resolution of 1.9° latitude by 2.5° longitude and with 30 vertical layers.

Two types of time-slice experiments were conducted for each scenario: one uses prescribed sea surface temperatures (SSTs) and another uses a coupled atmosphere-ocean configuration. The prescribed SST simulations investigate the effective radiative forcing (ERF) of changes in aerosol emissions [48], and the coupled atmosphere-ocean simulations provide the near-equilibrium climate responses (e.g. changes in surface air temperature). In this study, the configuration for the prescribed SSTs simulation follows the F\_2000\_CAM5 component set, and the configuration for the coupled atmosphere-ocean simulations follows the B\_2000\_CAM5\_CN component set.

In the prescribed SST simulations, a repeating annual cycle of observed year 2000 SSTs was used. These simulations were run for 60 years, with the final 40 years used in our analysis. For the prescribed SST simulations, we refer to this 40 year period as 'near-equilibrium'. Based on the prescribed SST simulations, the ERF of changes in aerosol emissions was calculated and decomposed into contributions from clean-sky shortwave cloud radiative effect, longwave cloud radiative effect, direct radiative effect, and surface albedo radiative effect [48, 49]. 'Clean-sky' refers to a hypothetical case that neglects scattering and absorption of solar radiation by all of the aerosol, but includes the effect of clouds [48, 49]. This is in contrast to 'clear-sky', a hypothetical case with cloud-free atmosphere that includes the effects of aerosol scattering and absorption.

In our coupled atmosphere-ocean configuration, the CAM5 model was coupled with the Parallel Ocean Program version 2 (POP2) model, which gives phase 5 of the Coupled Model Intercomparison Project (CMIP5) configuration of CESM1.2. The POP2 ocean model applies a Greenland dipole grid system with a horizontal resolution of  $\sim 1^{\circ}$  and with 60 vertical layers. Simulations of each scenario were branched into a 3-member ensemble with slightly



**Figure 1.** Near-equilibrium changes in effective radiative forcing induced by decreased aerosol emissions in China from 2006 to 2017. (a) Global map of the changes in effective radiative forcing. (b) Changes in effective radiative forcing over East Asia (70–155° E, 0–55° N), the area bounded by red solid lines in panel (a). Stippling indicates regions where changes in effective radiative forcing are statistically significant at the 95% confidence level via one-sample t-test with an effective sample size adjusted for autocorrelation [51]. The domain-wide area-weighted mean difference is shown at the upper right margin of each panel. All results were derived as the difference between scenarios CN17 and CN06.

different perturbations in initial atmospheric states to test the statistical significance of our signal amid the noise of internal variability. Each scenario was thus presented by a 3-member ensemble, and the presented results for temperature and precipitation were derived based on the ensemble mean values. Each ensemble member was run for 150 years, with the last 100 years used in our analysis. When discussing results from the coupled atmosphere-ocean simulations, we referred to this 100 year mean as 'nearequilibrium' results, reflecting equilibration among atmosphere, land, and upper ocean. Equilibration with the deep-ocean can take thousands of years [50]. The 100 year results from the three members of each ensembles were pooled together for the significance testing, which was based on the one-sample t-test with an effective sample size adjusted for autocorrelation [51].

# 3. Results

# 3.1. Radiative effects of China's emission reductions 2006-2017

Figure 1 illustrates the near-equilibrium changes in annual mean ERF introduced by emission reductions between 2006 and 2017 over China. Overall, these emission reductions are estimated to exert a small but statistically significant radiative forcing globally, estimated to be 0.09  $\pm$  0.03 W m<sup>-2</sup> (figure 1(a)). Globally, the net radiative effect of aerosol reductions is dominated by shortwave cloud radiative effect, which contributes a  $0.21 \pm 0.03 \text{ W m}^{-2}$  net ERF (supplementary materials figure S2). The global impacts of longwave cloud radiative effect, direct radiative effect, and surface albedo radiative effect are relative minor, with estimated global mean values of  $-0.08 \pm 0.02$ ,  $0.01 \pm 0.00$ , and  $-0.05 \pm 0.02$  W m<sup>-2</sup>, respectively (supplementary materials figure S2).

The positive radiative effects concentrate over central and eastern China as well as downwind regions, where substantial aerosol reductions occurred (supplementary materials figure S3). Over East Asia (defined as 70–155° E, 0–55° N; figure 1(b)), the net ERF is estimated to be  $0.48 \pm 0.11$  W m<sup>-2</sup>. Similarly, the shortwave and longwave cloud radiative effect and direct radiative effect of reduced aerosol concentrations are strongest over central and eastern China and its downwind regions (supplementary materials figures S2).

# 3.2. Changes in surface temperature induced by China's emission reductions 2006-2017

Figure 2 shows the near-equilibrium changes in annual mean surface air temperature over the Northern Hemisphere induced by reductions in aerosol emissions in China from 2006 to 2017. The temperature response to aerosol reductions is less localized than the reductions in aerosols themselves (supplementary materials figure S3) due to atmospheric and oceanic heat transport. These temperature responses display interhemispheric asymmetry and polar amplification. According to our simulations, reduced aerosol emissions over China between 2006 and 2017 may warm large part of the middle and high latitudes in the Northern Hemisphere while exerting smaller impacts in the Southern Hemisphere (supplementary materials figure S4).

China's emissions reductions are estimated to cause near-equilibrium global annual mean surface temperature to increase by  $0.06 \pm 0.01$  °C, and the Northern Hemisphere mean temperature to increase by  $0.12 \pm 0.01$  °C. The interhemispheric asymmetry in the temperature response may be attributed to several reasons. These reasons include: the interhemispheric asymmetry in the net radiative effect of reduced emissions solely in the Northern Hemisphere (figure 1 and supplementary materials figure S3) and the larger percentage of ocean in the Southern



Figure 2. Near-equilibrium changes in annual mean surface air temperature over the Northern Hemisphere induced by decreased aerosol emissions in China from 2006 to 2017. (a) Map of changes in temperature over the Northern Hemisphere. (b) Changes in temperature over East Asia (70–155° E, 0–55° N), the area bounded by red solid lines in panel (a). Stippling indicates regions where changes in temperature are statistically significant at the 95% confidence level via one-sample t-test with an effective sample size adjusted for autocorrelation [51]. The domain-wide area-weighted mean difference is shown at the upper left margin of each panel. Latitude lines in panel (a) from the inside out are 80° N, 75° N, 60° N, 45° N, 30° N, 15° N, and 0°, respectively. All results were derived as the difference between scenarios CN17 and CN06.

Hemisphere, which has greater effective heat capacity than land [52–54]. The high latitude amplification of temperature responses to China's emission reductions resembles the high amplification of global warming that has occurred during the past decades [55].

Emission reductions in China from 2006 to 2017 would lead to measurable temperature changes over East Asia, especially over central and eastern China (figure 2(b)). Near-equilibrium mean surface air temperature over East Asia is estimated to increase by  $0.12 \pm 0.02$  °C, which is similar to the mean warming over the whole Northern Hemisphere. This similarity further indicates the widespread temperature impacts of regional aerosol emission reductions. Over East Asia, our results show that winter warms more than summer (supplementary materials figure S5), a phenomenon similar in character to human-induced warming seen in historical observations [56].

# 3.3. Responses of precipitation to China's emission reductions 2006-2017

Figure 3 shows the near-equilibrium changes in annual total precipitation rate as a result of aerosol reductions in China from 2006 to 2017. The global mean annual total precipitation rate is estimated to increase by  $2.34 \pm 0.55$  mm yr<sup>-1</sup>, primarily driven by unmasked greenhouse gases-induced warming from reduced aerosol emissions, which at a global scale increased the evaporation [57]. In response to China's aerosol reductions, precipitation changes both locally over East Asia and remotely. In our simulations with aerosol emission reductions, the total precipitation rate over East Asia is  $21.07 \pm 7.60$  mm yr<sup>-1</sup>

greater than in the simulations without emission reductions. Statistically significant enhancements are observed over large areas in central and eastern China, where most of the aerosol emission reductions were occurring. The local enhancement may be attributed to microscopical factors, especially an increased autoconversion rate (rate of cloud droplet coalescence into raindrops) due to decreased aerosol, as assumed in the model formulation, where aerosols increase the number of cloud condensation nuclei (CCN) and can therefore suppress the formation of larger cloud droplets, which have a higher tendency to coalescence into raindrops [58]. It is noteworthy that this result is derived from a single model simulation. Whether this result is representative of what happened in the real world is subject to high uncertainties regarding how the model parameterized the aerosol-cloud-precipitation interactions. Seasonally, the enhancement in precipitation over East Asia is greater in summer than in winter (supplementary materials figure S5), which may be partially due to the higher precipitation rate in summer due to the East Asian summer monsoon. The interhemispheric asymmetry in the temperature response (i.e. greater warming in the Northern versus Southern Hemisphere) is expected to result in a northward shift of the Intertropical Convergence Zone (ITCZ). This shift would be expected to enhance precipitation over the Northern Hemisphere tropics and suppress precipitation over the Southern Hemisphere (figure 3). While there is some indication that this may be happening in our simulations (figure 3(a)), few regions distant from China show statistically significant local precipitation changes.



**Figure 3.** Near-equilibrium changes in annual total precipitation rate induced by decreased aerosol emissions in China from 2006 to 2017. (a) Global map of the changes in precipitation rate. (b) Changes in precipitation rate over East Asia (70–155° E, 0–55° N), the area bounded by red solid lines in panel (a). Stippling indicates regions where changes in precipitation rate are statistically significant at the 95% confidence level via one-sample t-test with an effective sample size adjusted for autocorrelation [51]. The domain-wide area-weighted mean difference is shown at the upper right margin of each panel. All results were derived as the difference between scenarios CN17 and CN06.

#### 3.4. Impact of further emission removal in China

In addition to the emission reductions in China from 2006 to 2017, future emission control in China could be expected [11, 46], which would further impact climate. Figure 4 shows the potential near-equilibrium radiative and climate effects of removing all anthropogenic aerosol emissions over China after 2017, relative to a world in which 2017 emissions persisted. In general, the spatial patterns of radiative and climate effects of aerosol emission removal after 2017 are similar to those exerted by the emission reductions during 2006 and 2017, but greater in magnitude. Similar seasonal patterns in temperature and precipitation responses are also obtained (supplementary materials figure S5).

Removing all anthropogenic aerosol emissions over China after 2017 is estimated to exert an additional 0.14  $\pm$  0.03 W m<sup>-2</sup> net ERF globally in the near-equilibrium state (figure 4(a)), ~56% higher than that exerted by 2006-2017 emission reductions (figure 1(a)). The global net radiative effect is dominated by the shortwave cloud radiative effect, which contributes a 0.21  $\pm$  0.03 W m<sup>-2</sup> net ERF globally (supplementary materials figure S6(a)). Substantial positive radiative effects could be observed over central and eastern China, and as a consequence, a 1.26  $\pm$  0.11 W m<sup>-2</sup> net ERF is estimated over East Asia (figure 4(b)), equivalent to  $\sim$ 260% of that exerted by 2006-2017 emission reductions (figure 1(b)). The positive shortwave cloud radiative effect is greatest over central and eastern China, contributing to a 1.61  $\pm$  0.20 W m<sup>-2</sup> net ERF over East Asia (supplementary materials figure S6(b)). Note that removing all anthropogenic aerosol emissions over China after 2017 exerts a negative direct radiative effect over China (supplementary materials figure S6(f)), which is opposite to that induced by emission reductions between 2006 and 2017 (supplementary materials figure S2(f)). This difference is related to a

much higher reduction in BC emissions but a relative lower reduction in  $SO_2$  emissions by the complete removal of China's anthropogenic aerosol emissions after 2017 (noCN—CN2017; supplementary materials figures S1 and S3).

Similar to effects induced by aerosol reductions between 2006 and 2017, further aerosol removal after 2017 would lead to additional global warming, which shows interhemispheric asymmetry (figure 4(c); also see supplementary materials figure S7 for a polar view of temperature changes over the Northern Hemisphere for a direct comparison with figure 2(a)). The near-equilibrium global annual mean surface air temperature is estimated to increase by an additional  $0.09 \pm 0.01$  °C (i.e. 50% higher than that increased by 2006-2017 emission reductions), and the Northern Hemisphere mean temperature is estimated to increase by 0.12  $\pm$  0.01 °C (i.e. similar to that induced by 2006–2017 emission reductions). Strong warming could be observed over China, where aerosol removal occurs, contributing to an additional 0.19  $\pm$  0.02 °C increment in mean surface air temperature over East Asia (i.e. ~60% higher than that increased by 2006-2017 emission reductions; figure **4**(d)).

The removal of China's year 2017 anthropogenic aerosol may further increase global precipitation by 2.49  $\pm$  0.53 mm yr<sup>-1</sup> (i.e. 6% higher than the increase induced by 2006–2017 emission reductions), partially resulting from global warming induced by aerosol reductions (figure 4(e)) [57]. These aerosol reductions are estimated to enhance annual total precipitation over East Asia by 39.76  $\pm$  7.43 mm yr<sup>-1</sup> (figure 4(f); i.e. ~90% higher than that enhanced by 2006–2017 emission reductions). When other forcings such as those from greenhouse gases are specified at their year 2000 levels, total elimination of China's anthropogenic aerosol emissions leads to a greater local enhancement in precipitation than that



**Figure 4.** Near-equilibrium radiative effect and climate impacts of removing all anthropogenic aerosol emissions over China after 2017. (a) and (b) Changes in effective radiative forcing globally and over East Asia (70–155° E, 0–55° N). (c) and (d) Changes in annual mean surface air temperature globally and over East Asia. (e) and (f) Changes in annual total precipitation rate globally and over East Asia. Stippling indicates regions where changes are statistically significant at the 95% confidence level via one-sample t-test with an effective sample size adjusted for autocorrelation [51]. The domain-wide area-weighted mean difference is shown at the upper right margin of each panel. The domain-wide maximum difference for (b), (d), and (f) is shown at the upper left margin of each panel. All results were derived as the difference between scenarios noCN and CN17. Map of changes in temperature over the Northern Hemisphere is shown in supplementary materials figure S7.

induced by aerosol reductions between 2006 and 2017, which could be partially due to the nonlinearity in the response of clouds to aerosols [59]. The greater precipitation response induced by the complete removal of aerosols after 2017 indicates that cloud responses in the model used are sensitive to fractional changes in aerosol abundance (e.g.  $SO_2$  emissions are reduced by ~65% between scenarios CN17 and CN06 and are reduced by ~99% between scenarios noCN and CN17; see supplementary materials figure S1).

## 4. Discussion

China's air pollution control policies since 2005 led to a drop-off from peak SO2 emissions around 2006, and also drove notable declines in the country's emissions of BC and OC afterward. This study quantified the near-equilibrium radiative and climate effects of China's reductions in aerosol (and precursors) emissions from 2006 to 2017 as simulated in a global climate model. Overall the model suggests that these reductions in China's aerosol emissions would exert a positive climate forcing globally, warm large parts of the Northern Hemisphere with evident polar amplification, and enhance global mean precipitation.

Our study is subject to a number of limitations. First, we note that local and global scale responses to aerosol emission changes investigated here likely exhibit sensitivity to the background state, choice of model and model configuration, and other factors. Therefore, our results (and perhaps all results of a single climate model) should be interpreted as estimates of the likely scale of effects, understanding that the precise climate effect of Chinese aerosol emission reductions are likely to manifest themselves somewhat differently as climate changes in the real world. Second, the effects of changes in nitrogen emissions (precursor of nitrate aerosol) are not considered in this study as it is not available in CESM 1. However, according to the MEIC model [10, 30], from 2006 to 2017 changes in nitrogen emissions were small ( $\sim$ 3% increment), likely exerting a relatively marginal climate effect. As China's clean air actions proceeded, nitrate aerosols have been increasingly important [60, 61], suggesting the importance of investigating the climate effects of changes in nitrate aerosols in future studies. Third, changes in aerosol emissions outside of China is not considered in this study. However, these changes in aerosol emissions might affect China's climate. For example, studies have shown that changes in South Asian aerosol emissions might affect temperature and precipitation over China in a non-linear way [22, 62]. Future studies could consider investigating the climate effects of China's clean air policies based on scenarios with varying emissions outside of China.

Our study indicates the potential climate effects of China's air pollution control policies-policies enacted between 2006 and 2017-are expected to result in >0.1 °C warming over the nNorthern Hemisphere. The emission reductions in China exert warming effects not only locally but also remotely. From 2006 to 2017, the country's CO<sub>2</sub> emissions surged by  $\sim$ 54% [63], along with a  $\sim$ 70% reductions in SO<sub>2</sub> emissions, a  $\sim$  30% reduction in BC emissions, and a ~40% reduction in OC emissions. The decoupling of CO<sub>2</sub> and aerosol (and precursors) emissions can be attributed to the major reductions of aerosol emissions by end-of-pipe control policies which contribute nothing to CO2 reductions. This decoupling is likely to further exacerbate the already-severe global warming effects caused by CO<sub>2</sub> emissions from China.

Although aerosol emissions have been substantially reduced in China during the past decade, air pollution in China remains a serious problem. For example, until 2017, 64% of prefecture-level cities in China failed to meet the national annual standard for  $PM_{2.5}$  [11]. Therefore, tougher emission control policies can be expected in China to further improve air quality and thereby protect public health.

In one policy example from 2018, China announced the *Three-Year Action Plan for Winning the Blue Sky Defense Battle.* This plan gives priority to a considerable reduction in the emissions of major air pollutants and aerosol concentrations [64]. It can therefore be expected that aerosol emissions in China will continue to decrease [46], exerting further global warming effects as suggested by our China aerosol emission removal scenario (i.e. comparison between noCN and CN17). In accordance with our result, the removal of China's year 2017 anthropogenic aerosol emissions would exert an additional >0.1 °C mean warming over the Northern Hemisphere. This unmasked warming may require more efforts to mitigate climate change. To this end, adding to, or as alternatives to, aerosol pollution control measures that have little impact on carbon emissions (e.g. installing sulfur scrubbers), policymakers could consider implementing measures that simultaneously help to reduce emissions of air pollutants and greenhouse gases. For example, future policies in China could facilitate the introduction of more renewable energy to the country's coal-dominated energy system.

Health and environmental goals are often well aligned. Simultaneously removing aerosol and greenhouse gas emissions from our economy would produce substantial health and environmental benefits. But anti-pollution measures taken to achieve health objectives can trade off with climate goals, which in turn have an important health dimension. In such cases, when immediate public health considerations take precedence over climate change considerations—as may have happened, for example, with past Chinese policies aimed at reducing aerosol emissions—then effects such as the warming unmasked by such reductions, as illustrated in this study, may represent an additional challenge for national and international climate mitigation efforts.

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#### Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## **ORCID** iDs

Yixuan Zheng b https://orcid.org/0000-0002-3429-5754

Steven J Davis bhttps://orcid.org/0000-0002-9338-0844

Ken Caldeira () https://orcid.org/0000-0002-4591-643X

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