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Short Communication

Climate effects of future aerosol reductions for achieving carbon neutrality in China

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To limit the global warming to 1.5 °C above pre-industrial levels, beyond which the most dangerous impacts of climate change will occur, achieving carbon neutrality by the mid-21st century is essential [1]. As the largest developing country and a significant contributor to carbon dioxide (CO_2) emissions, China has announced its ambitious climate commitment to pass carbon peak before 2030 and to achieve carbon neutrality by 2060 [2]. Both climate policies and regional clean air actions have been implemented for reductions in fossil fuel emissions, including the emissions of short-lived aerosols and precursors [3]. In the context of pursuing carbon neutrality in China, aerosol reductions due to clean air actions and pollution control policies are very likely to have a great impact on climate [4–6].

In this study, climate effects of aerosol reductions due to China's clean air actions under localized future emission scenarios are investigated using the Community Earth System Model version 1 (CESM1) [7]. Fully coupled and atmosphere-only experiments in years of carbon peak (2030) and carbon neutrality (2060) are performed with anthropogenic emissions of aerosols and precursors under "Current-goals" (Current) and "Carbon-Neutral" (Neutral) scenarios from the Dynamic Projection for Emissions in China (DPEC) model that consider socioeconomic development, climate policy, and pollution control actions [8,9] (Figs. S1–S4 online). In addition, a present-day emissions simulation (PD) is conducted as the reference case (Supplementary materials online). Another sensitivity simulation is also conducted, with black carbon (BC) emissions set to follow the Neutral experiment but other emissions kept at the present-day levels (Neutral_BC), to quantify the relative roles of reducing strongly absorbing BC and other aerosols on future climate towards carbon neutrality. Greenhouse gases concentrations are kept at the 2015 levels in all simulations (Text S1 online).

Annual mean near-surface $PM_{2.5}$ concentrations are projected to decrease over China and the downwind areas in the future in the Neutral experiment compared to 2015 (Figs. S5 and S6 online). Averaged over East Asia (10°–55°N, 90°–155°E), the annual mean near-surface $PM_{2.5}$ concentrations are projected to decrease by 17% in 2030 and by 26% in 2060 relative to 2015 under the carbon neutrality scenario. Changes in column burden of $PM_{2.5}$ agree with those of near-surface concentrations (Figs. S7 and S8 online), with a decrease in burden by 16% in 2030 and by 24% in 2060 relative to 2015 over East Asia. Meanwhile, in line with the changes in emissions and concentrations, annual mean aerosol optical depth (AOD) is projected to decrease by 0.02–0.03 over East Asia in 2030 and 2060 relative to 2015 in the Neutral experiment, with maximum reductions exceeding 0.1 (Fig. S9 online). If China pursues carbon neutrality also following the WHO $PM_{2.5}$ guideline, the aerosol reduction would be more than that follows the current climate and air quality target of 5% in 2030 and 12% in 2060 for near-surface $PM_{2.5}$ concentrations.

Aerosols can perturb Earth's radiation balance and influence climate through interacting with radiation and clouds [10]. Changes in effective radiative forcing (ERF) of anthropogenic aerosols at the top of the atmosphere (TOA), estimated as the difference in net radiative fluxes between the atmosphere-only experiments with rapid adjustments included [11] are shown in Fig. S10 (online). The decreases in anthropogenic emissions of aerosols and precursor gases lead to a large positive ERF of aerosols at TOA over eastern China and the northern Pacific Ocean in the Neutral experiment relative to PD, with local values higher than 1.0 W m^{-2}. The regional averaged ERF at TOA over East Asia is 0.30 W m^{-2} in 2030

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and 0.63 W m^{-2} in 2060 relative to PD. The stricter pollution control policies are enforced, the higher positive ERF will be. The Neutral scenario will induce a higher ERF by 0.17 W m^{-2} in 2030 and 0.33 W m^{-2} in 2060 than that in the Current scenario. ERF at the surface is similar in spatial pattern but much higher in magnitude than that at TOA (Fig. S11 online).

Fig. 1 presents changes in annual mean surface air temperature in 2030 and 2060 that are attributed to aerosol reductions due to China's clean air actions under the carbon neutrality scenario relative to the current-goal scenario in the same time periods and in 2015. In the near-term future, aerosol reductions will cause 0.2–0.5 K of temperature increase over eastern China in 2030 in the Neutral experiment. In the long-term future, air temperature in 2060 will increase over 0.5 K in Neutral relative to 2015 over eastern China due to the future clean air actions. Under the carbon neutrality scenario, surface air warming in 2060 spreads across the whole northern Pacific Ocean, in accordance with the positive ERF over the oceans due to less aerosols transported from eastern China to this region. The maximum of surface warming related to future aerosol reductions locates around 30°N over mid-latitude regions (Fig. S12 online).

Averaged over East Asia, the future aerosol reductions due to clean air actions under the carbon neutrality scenario will induce a temperature increase by 0.20 ± 0.06 K in the carbon neutral year 2060 relative to 2015. Although aerosol reductions in the near-term future under carbon neutrality scenario would not lead to a significant increase in air temperature over East Asia in 2030 (0.01 ± 0.03 K), the long-term future reductions in aerosols under carbon neutrality can cause a strong warming by 0.23 ± 0.04 K in 2060 relative to that following the current-goal pathway.

Accompanied by the increase in temperature and the decrease in aerosols, annual mean precipitation will be enhanced over southern China and the downwind northwestern Pacific with maximum increases of 0.2–0.3 mm d^{-1} in 2030 and exceeding 0.3 mm d^{-1} in 2060 due to clean air actions in China under the carbon neutrality scenario compared to 2015 (Fig. 2). Averaged over East Asia, annual mean precipitation will increase by 0.04 ± 0.02 mm d^{-1} in 2030 and 0.05 ± 0.01 mm d^{-1} in 2060 under carbon neutrality compared to 2015. The stricter pollution control policies in the Neutral experiment will lead to a stronger precipitation enhancement than that in Current. The finding is consistent with Yang et al. [12], in which aerosol emission reductions during COVID-19 pandemic were revealed to contribute to summer extreme precipitation in China.

Although the reduction in greenhouse gases under carbon neutrality directly benefits the climate change mitigation [4], the cut down of aerosol and precursor emissions due to future clean air actions in China could partly offset the relative cooling of CO_2 emission reduction. Therefore, it is crucial to explore the potential co-benefit policy for both air quality and climate.

As shown in Fig. S13 (online), the reduction in absorbing aerosol (i.e., BC) emissions in China under the carbon neutrality scenario

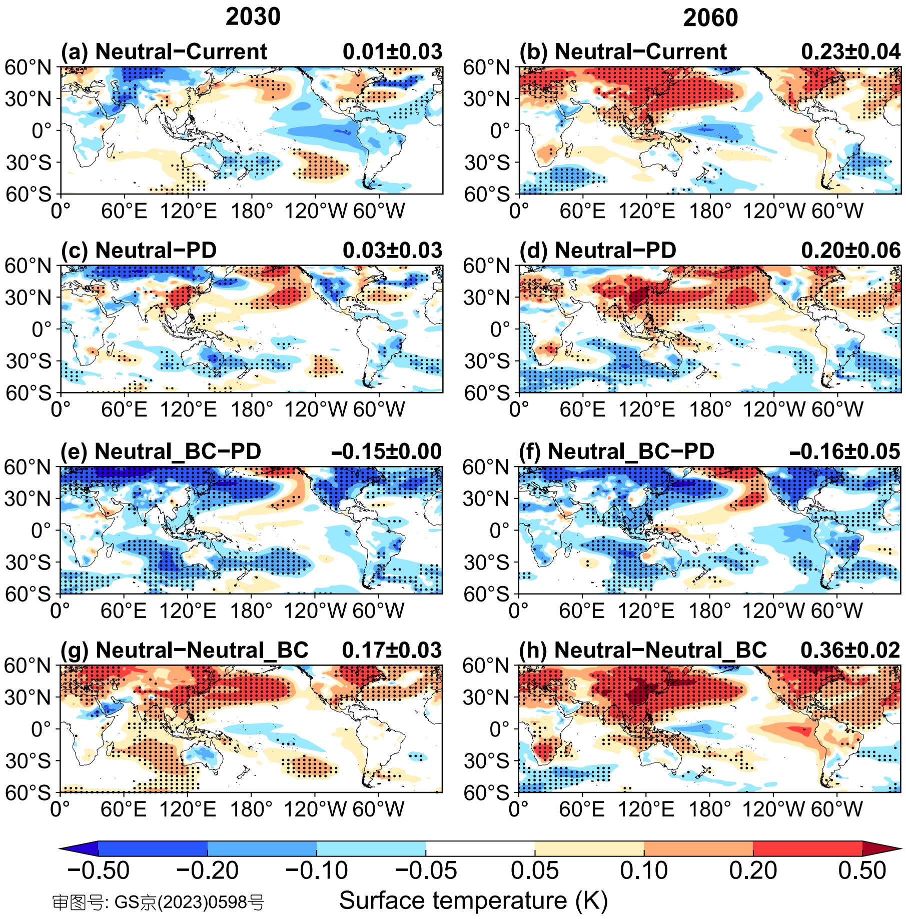

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Fig. 1. Spatial distribution of changes in annual mean surface air temperature (K) in 2030 and 2060 for Neutral compared to Current (a, b) and for Neutral compared to PD in 2015 (c, d), and changes in annual mean surface air temperature due to changes in absorbing (Neutral_BC–PD) and scattering (Neutral–Neutral_BC) aerosols, respectively, in 2030 (e, g) and 2060 (f, h) under the carbon neutrality scenario in China compared to the present-day condition. Stippled areas indicate statistical significance with 95% confidence from a two-tailed Student's *t* test. Regional averaged change over East Asia (10°–55°N, 90°–155°E) and the 1σ for ensemble members are shown at the top right of each panel.

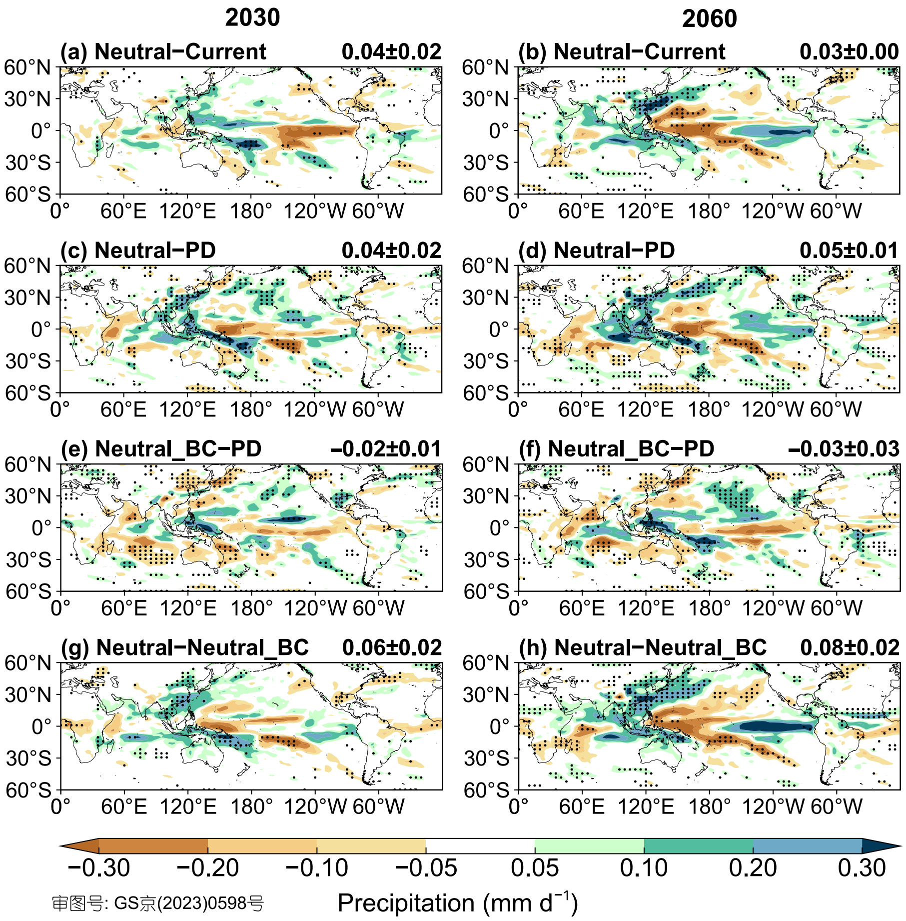

Fig. 2. Spatial distribution of changes in annual mean precipitation rate (mm d^{-1}) in 2030 and 2060 for Neutral compared to Current (a, b) and for Neutral compared to PD in 2015 (c, d), and changes in annual mean surface air temperature due to changes in absorbing (Neutral_BC–PD) and scattering (Neutral–Neutral_BC) aerosols, respectively, in 2030 (e, g) and 2060 (f, h) under the carbon neutrality scenario in China compared to the present-day condition. Stippled areas indicate statistical significance with 95% confidence from a two-tailed Student's *t* test. Regional averaged change over East Asia (10°–55°N, 90°–155°E) and the 1σ for ensemble members are shown at the top right of each panel.

will result in a negative ERF at the TOA over eastern China in both 2030 and 2060 relative to 2015, while the reduction in scattering aerosols will induce positive ERF over eastern China and the downwind oceanic areas. Averaged over East Asia, the decrease in scattering aerosols in China produces an ERF of 0.85 W m^{-2} in 2030 and 1.42 W m^{-2} in 2060 relative to 2015, largely neutralized by -0.55 W m^{-2} in 2030 and -0.79 W m^{-2} in 2060 from the reduction in BC emissions under the carbon neutrality scenario.

BC absorbs sunlight in the atmosphere with a warming or cooling effect on the surface air that depends on its vertical location [13]. The reduction in BC emissions in China will cool the higher latitude regions and the downwind oceans but has a negligible effect on surface air temperature in eastern China, as simulated in CESM1 (Fig. 1e, f). On the contrary, the reduction in scattering aerosol and precursor gas emissions in China is projected to warm the surface air across the whole mid-latitude regions (Fig. 1g, h). In the carbon peak year (2030) in China, the cooling and warming at the surface caused by the decreases in BC and other scattering aerosol emissions almost offset each other in East Asia. In the carbon neutral year (2060), the significant decrease in scattering aerosol emissions in China will lead to an average temperature increase of 0.36 ± 0.02 K in East Asia, half of which could be dampened by the reduction in BC emissions in China under the carbon neutrality scenario.

The damping effect of BC reduction is stronger as the altitude increases in the lower and middle troposphere, considering that BC absorbs top-down incoming solar radiation and sometimes upward reflection from low-level clouds. In 2030, the effect of BC reduction in China will surpass that of reduction in other scattering aerosols at 850 hPa (Fig. S14 online) and 500 hPa (Fig. S15 online) over East Asia in the carbon neutrality scenario, leading to a net atmospheric cooling due to clean air actions. In 2060, BC reduction in China can offset 45% of the East Asian surface warming caused by reductions in scattering aerosols, and this value increases to 67% at 850 hPa and 70% at 500 hPa, indicating a significant role of the BC reduction in climate mitigation.

Changes in precipitation due to the decrease in absorbing and scattering aerosols in China follow their induced temperature changes. The reduction in scattering aerosols in China will enhance precipitation over southern China by a maximum of 0.2–0.3 mm d^{-1} in 2030 (Fig. 2g) and over 0.3 mm d^{-1} in 2060 (Fig. 2h), whereas the reduction in BC will suppress precipitation over northern China by 0.1–0.2 mm d^{-1} in both 2030 and 2060 (Fig. 2g, h) due to the associated cooling effect.

Therefore, although BC only accounts for a small fraction of total aerosol burden in China, as the most important light-absorbing aerosol, BC reduction due to future clean air policies is beneficial to curbing climate warming from the reduction in other scattering aerosols under carbon neutrality.

Unlike the majority of emissions from industry and energy sectors for many scattering aerosols (e.g., sulfate), currently half of BC is emitted from the residential sector, including combustion for heating and cooking needs, followed by 30% from industry and 19% from transportation sectors (Fig. S16 online). Under the carbon neutrality scenario in China, the residential burning will be thoroughly switched to clean energy sources and the portion of BC emission from the residential sector will decrease from 51% in 2015 to 24% in 2030 and 7% in 2060. On the contrary, the fraction of BC emission from industry sector will increase from 30% in 2015 to 51% in 2030 and 74% in 2060 under the carbon neutrality scenario. Additionally, related to the less efficient emission reductions from long-distance freight and off-road diesel machinery, the contribution from transportation sector will be almost unchanged in 2060 relative to 2015. In the future, in addition to continuing the tight control of BC emissions from residential sector associated with combustion for heating and cooking, adopting stricter policies and new clean technologies with less BC emissions for industry and transportation sectors is a possible way for the co-benefits of climate and air quality in China.

This study indicates that, when China pursues the carbon neutrality goal and the long-term air quality target, aerosol reductions will cause temperature increase over eastern China, as also indicated in previous studies (Text S2 online), accompanied by enhanced precipitation over southern China. The net cooling from reduction in BC emissions under the carbon neutrality scenario can offset half of the warming induced by the decrease in scattering aerosols, suggesting a crucial role of BC reduction in climate change mitigation. Although BC only accounts for a small fraction of aerosols in China, future clean air actions of reducing BC emissions are potentially favorable to achieving the co-benefits for air quality and climate mitigation under carbon neutrality.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Yang Yang conceived the research and performed model simulations. Liangying Zeng prepared figures. All authors discussed the results and wrote the paper.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2023.03.048.

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