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Impacts of Aerosol Reduction in China on East Asian Summer Monsoon and Weather Extremes Following a Localized Carbon Neutral Emission Pathway

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Key Points:

- Aerosol reductions in China toward carbon neutrality intensify land-sea temperature difference and strengthen East Asian summer monsoon
- Future clean air actions present a potential side effect of intensifying the summertime extreme temperatures and precipitation in China
- Localized strong aerosol reductions exert a significant influence on regional climate and weather extremes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

To achieve the goal of carbon neutrality, China is projected to significantly reduce anthropogenic aerosols in addition to greenhouse gases. Here, the future changes in East Asian summer monsoon (EASM) and weather extremes responding to the idealized local emission reductions of anthropogenic aerosols (AA) in China are investigated based on time-slice simulations in an aerosol-climate model together with a localized carbon neutral emission scenario, while greenhouse gases and other anthropogenic climate forcers are kept at the present-day (2015) levels. The AA reduction in China leads to a positive change in June–July–August (JJA) mean effective radiative forcing over eastern China in 2030 and 2060s, along with a 0.2°C–0.4°C warming, respectively. It intensifies the temperature difference between land and ocean, and increases the precipitation over eastern China. Multiple EASM indices show that EASM intensity in JJA is estimated to be strengthened in the future, because of the AA decline in China. The AA emissions reduction toward carbon neutrality in China also presents a potential side effect of intensifying the summertime extreme temperatures and precipitation in China. This study reveals the important role of reductions of AA emissions in influencing EASM and weather extremes, which warrants careful assessment in the emission policymaking process prior to the implementation of mitigation strategies.

Plain Language Summary

To reach carbon neutrality, China plans to cut not only greenhouse gases but also particulate matter (aerosol) caused by human activities. This study looks at how reducing these air pollutants might affect East Asian summer monsoon (EASM) and extreme weather. Based on a climate model and emissions reduction scenario for China, we show that cutting these pollutants can make eastern China slightly warmer in summer, by 0.2–0.4°C in 2030 and 2060s, compared to the present-day (2015) condition. This happens because the air becomes clearer, allowing more sunlight to reach the ground. This change strengthens the temperature differences between land and sea surface, boosting summer rainfall in eastern China. The EASM could be strengthened in the future. Reducing these pollutants may also enhance heatwaves and heavy rain during summer. The study indicates that while reducing air pollution is important for the clean air following the carbon neutral pathway, the side effects on weather and climate should be considered when making policies.

1. Introduction

Aerosols can reduce atmospheric visibility and harm public health (Cohen et al., 2017). They also reflect solar radiation and modify cloud microphysical properties, dimming the surface, while solar absorbing aerosols also warm the atmosphere. Changes in the atmospheric and surface energy budget further influence climate and extreme events (Gao et al., 2023; Yang et al., 2017, 2019, 2020, 2022; Wang et al., 2023).

As one of the most complex and significant monsoon systems, the East Asian summer monsoon (EASM), which is driven by the large difference in temperature between the Asiatic land and its neighboring oceans, affects the climate in most regions of China (Ding & Chan, 2005). The EASM rainfall influences one-fifth of the world's population (Lei et al., 2011). Grasping the characteristics of the EASM change is crucial for Asian infrastructure, agriculture productivity, and the availability of water resources (Ding & Chan, 2005). In recent years, the rising frequency, intensity and duration of weather extremes become the distinctive feature of climate change, posing a particularly severe climate challenge to address (Song et al., 2022). The weather extremes have detrimental impacts on society, economy and ecosystems (Perkins, 2015; Xu et al., 2016). Therefore, quantifying roles of factors affecting future EASM changes and associated weather extremes is of vital importance (Wilcox et al., 2020).

Numerous prior studies have reported the impact of anthropogenic aerosols (AA) on historical variations in Asian summer monsoon system (e.g., Chen et al., 2016; He et al., 2022; Herbert et al., 2021; Jiang et al., 2013; Lang et al., 2025; Li et al., 2018, 2024; Liu et al., 2009; Liu et al., 2018; Mu & Wang, 2020; Persad et al., 2017; Wang et al., 2017; Xie et al., 2016). Using multiple model simulations, Li et al. (2018) reported that AA weakens Asian summer monsoon rainfall and circulation, primarily attributed to rapid atmospheric adjustments over land, largely driven by aerosol-cloud interactions. Jiang et al. (2013) utilized the Community Atmospheric Model version 5 (CAM5) to investigate the impact on EASM by the AA changes from 1850 to 2000 and found that the increased AA weakened the land–sea temperature difference and decreased/increased rainfall in northern/southern China. Based on the COVID-MIP multi-model simulations, He et al. (2022) found that the EASM was enhanced in terms of precipitation and southerly wind at lower troposphere in response to reduced aerosols over Asian continent during COVID-19. Liu et al. (2018) found that the 10 times of Asian sulfate and BC aerosol concentrations would decrease annual precipitation over China through the PDRMIP multi-model simulations. Using the GFDL AM3 model, Persad et al. (2017) suggested that the surface dimming impact of absorbing aerosols at present-day condition could outweigh its atmospheric heating in the response of EASM, resulting in a net decrease of EASM circulation and precipitation due to the reduced land–sea thermal contrast. However, Herbert et al. (2021) removed aerosols over East Asia and South Asia in the IGCM4 model and indicated that Asian summer monsoon response to aerosol emissions reductions was highly nonlinear. To pursue the carbon neutrality goals, the AA over China would be significantly reduced, which could have different impacts on the EASM (Yang et al., 2023).

Extreme weather events related to aerosols have drawn much attention from the research community in recent years (Samset et al., 2018; Wang et al., 2023; Zhao et al., 2018). Using the fully coupled Community Earth System Model version 1 (CESM1), Samset et al. (2018) found that extreme weather indices were more responsive to declining AA than to increasing greenhouse gases in key aerosol-emitting regions. Zhao et al. (2018) used CESM1 with prescribed sea surface temperature (SST) to study the response of precipitation extremes over the Asian monsoon region to AA in future projections and suggested that the extreme rainfall over East Asia monsoon region can be significantly exacerbated in the future under the strong warming scenario due to the decrease of AA. Wang et al. (2023) also suggested that the future mitigation of aerosol pollution across the globe would increase the frequency and intensity of weather extremes.

AA shares similar sources with greenhouse gases. The measures of reducing greenhouse gases can also decrease AA emissions. Specifically, in order to mitigate climate warming, China has committed to achieve carbon peak (i.e., reaching the peak of carbon dioxide emissions) by 2030 and then carbon neutrality (i.e., carbon dioxide emissions offset by emission reduction measures) by 2060 (Ren et al., 2024). Following the carbon neutral pathway, both the climate and environmental policies require substantial reductions in emissions of air pollutants (Cheng et al., 2021). As a result, AA in China would decline significantly, which potentially affects EASM and weather extremes, including heat waves and heavy precipitation, in the carbon neutral future (Jiang et al., 2025; Liu et al., 2023; Partanen et al., 2018; Samset et al., 2018; Zhao et al., 2019). Previous studies mostly focused on the effects of aerosols on historical changes in EASM and changes in weather extremes under global climate scenarios, or directly removed all aerosols from one entire region, with insufficient emphasis on local clean air actions (Wang et al., 2021). It should be noted that the aerosol emissions and loading are highly heterogeneous in spatial distribution and the climate responses to aerosols are nonlinear depending on the location where the specific aerosols are perturbed, as well as the perturbed aerosol species. The aerosol reductions projected in a certain scenario may not cause the same climate influences with those derived from entire aerosol removal or following historical emission scenario (Gao et al., 2025). The climate responses for a certain scenario should also be quantitatively assessed, in addition to the mechanisms of the aerosol influences. Furthermore, the responses of multiple weather extremes are taken into account.

In this study, using the fully coupled CESM1 together with local clean air scenarios, we investigate the impacts of aerosol reduction in China on EASM and weather extremes in June–July–August (JJA) toward carbon neutrality in China in years 2030 and 2060 relative to 2015, which are the two key time nodes for projected carbon peak and carbon neutral in China. The focus of China's emission reduction alone is because China is one of the most polluted regions across the globe and the EASM is sensitive to emission changes in China (Liu et al., 2023). However, it should be noted that using the regional scenario of carbon neutrality in China is an idealized approach, which can not represent the future climate in a global carbon neutral scenario. For the rest of this paper, data and methods are described in Section 2; results of changes in EASM and weather extremes in response to the reductions in AA in China are analyzed in Section 3, and Section 4 summarizes the conclusions and discussions.

2. Methods

The responses of EASM and weather extremes in JJA to aerosol reductions under carbon neutrality in China are investigated using the fully coupled CESM version 1.2.2 (Hurrell et al., 2013). Simulations are conducted at the 1.9° × 2.5° latitude-longitude grids and 30 vertical layers (spanning from the surface to 3.6 hPa). CAM5, the atmospheric component of CESM1.2.2, predicts aerosol components that include sulfate, mineral dust, sea salt, primary organic matter (POM), black carbon (BC), and secondary organic aerosol (SOA) using an online modal aerosol model (Liu et al., 2016). The model comprehensively considers both aerosol–radiation interaction and aerosol–cloud interaction. We adopt the modifications in CAM5 by Wang et al. (2013) to improve the representation of aerosol vertical transport and wet scavenging in convective clouds. The aerosol representation in CESM1 over China has been widely evaluated in numerous studies (Fan et al., 2018; Gao et al., 2022; Ren et al., 2021). All these studies found that the model can well simulate the aerosol spatial pattern, while the near-surface concentrations of aerosols in China are substantially underestimated. This has been a known and common issue, existing in many climate models.

Three experiments are performed with AA emissions over China in years 2015, 2030 and 2060, respectively, to investigate the responses of EASM and extreme high temperature and precipitation to aerosol reductions in China during the path to carbon peak (2030) and carbon neutrality (2060) periods, named DPEC_2015, Neutral_2030, and Neutral_2060. The DPEC (Dynamic Projection for Emissions in China) v1.1 "Ambitious-pollution-Neutral-goals" scenario is used in this study to represent carbon neutral emission conditions, which comprehensively considers local socio-economic development, climate policies, and pollution mitigation measures in China (Tong et al., 2020) and is better than the widely used Shared Socioeconomic Pathways (SSPs) scenarios for global climate simulations in capturing the substantial aerosol emissions reduction in China (Cheng et al., 2021; Wang et al., 2021). If the bias and inadequate considerations of pollution control policies in SSPs are still considered in the model simulations, the $PM_{2.5}$ concentrations with SSPs mitigation scenarios would be 59%–73% higher than those projected with DPEC in China. AA emissions from other regions and biomass burning emissions follow the input data for the Coupled Model Intercomparison Project Phase 6 (CMIP6) and kept at the present-day (2015) levels. Greenhouse gas concentrations, ozone distributions and biomass burning emissions are also fixed at the 2015 levels. The differences between DPEC_2015 and two future-scenario experiments (Neutral_2030 and Neutral_2060) arise from the effects of AA decline during the carbon peak and carbon neutrality periods, respectively, in China. Three ensemble members by slightly perturbing initial atmospheric temperatures are conducted for all experiments to lessen the natural variability. The initial SST for coupled simulations is given by the Levitus/PHC2 data set at present-day conditions. Experiments are conducted over 70 years, with the ensemble mean of the final 50 years being used in analysis. In addition to the coupled atmosphere–ocean configuration, atmospheric experiments forced by the observed climatological monthly SST along with sea ice concentrations (SIC) at present-day conditions are also performed to estimate the effective radiative forcing (ERF) attributed to AA reduction (Ghan, 2013), with the same other configurations as the coupled experiments. The atmosphere-only experiments are conducted over 10 years with the mean of the final 9 years being used for analysis. In this study, we focus on the responses of EASM and weather extremes in JJA.

3. Results

3.1. Changes in Aerosols and Effective Radiative Forcing

Figures S1 and S2 in Supporting Information S1 show changes in JJA mean emissions of anthropogenic aerosols and precursors in China and the simulated column burden of major anthropogenic aerosol species, respectively, in 2030 and 2060s relative to the present-day condition (2015) under the carbon neutral scenario. Relative to present-day, anthropogenic SO_2, BC, POM and SOA gas emissions in China are projected to decrease by 68%, 67%, 56%

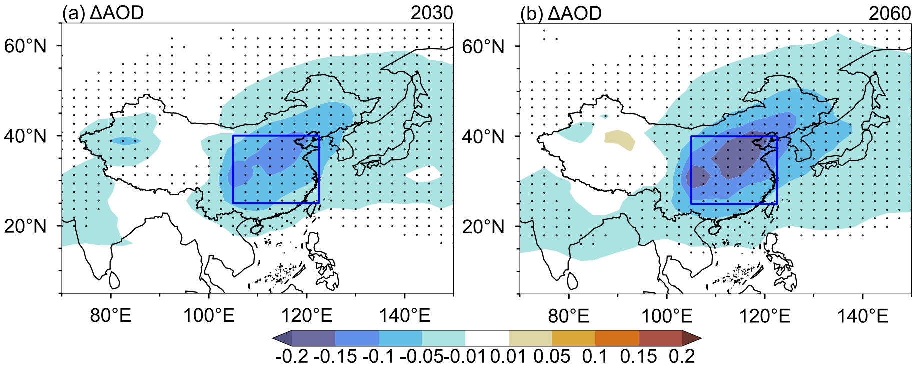

Figure 1. Changes in June–July–August (JJA) mean aerosol optical depth (AOD) at 550 nm (a) between DPEC_2015 and Neutral_2030 and (b) between DPEC_2015 and Neutral_2060. The stippled areas represent statistically significant results at the 90% confidence level, determined by a two-tailed Student's *t*-test.

and 35% in 2030s and 94%, 92%, 88% and 65% in 2060s from the DPEC carbon neutral scenario. The significant reductions in AA emissions over China result in a remarkable decrease in column burden of aerosols. Sulfate burden decreases by 4.6 mg m^{-2} in 2030s and 6.8 mg m^{-2} in 2060s relative to present-day over eastern China (25°–40°N, 105°–122.5°E) in JJA, followed by POM, BC and SOA. Due to the substantial AA reductions, the aerosol optical depth (AOD) significantly decreases in China, especially over eastern China where the heavy air pollution is currently located (Figure 1). By the carbon peak year around 2030s and carbon neutrality year around 2060s, the AOD in JJA decreases by 0.08 and 0.12, respectively, in eastern China, which changes the regional radiation balance and could further affect EASM and weather extremes.

The changes in effective radiative forcing (ERF) at the top of the atmosphere (TOA) due to the AA reduction in JJA are shown in Figure 2. Curbing AA emissions in China toward carbon neutrality mainly induces positive changes in ERF over many regions of China and the downwind western North Pacific, although insignificant negative changes in ERF are also found in southern China likely due to changing clouds associated with the rapid atmospheric adjustments. Averaged in eastern China, reductions in anthropogenic emissions produce positive ERF changes of 1.63 W m^{-2} in 2030s and 3.37 W m^{-2} in 2060s relative to present-day in JJA, which are primarily via aerosol-cloud interactions (Figure 3).

3.2. Changes in EASM Due To Aerosol Reduction Toward Carbon Neutrality in China

As shown in Figure 4b, the positive aerosol forcing changes associated with the AA reductions in China lead to the rising surface air temperature primarily over eastern China and western North Pacific toward carbon neutrality. The reductions in AA emissions lead to a warming of 0.16°C over eastern China in 2030s relative to present-day, and this warming is enhanced to 0.40°C in 2060s in JJA simulated by the fully coupled CESM1.

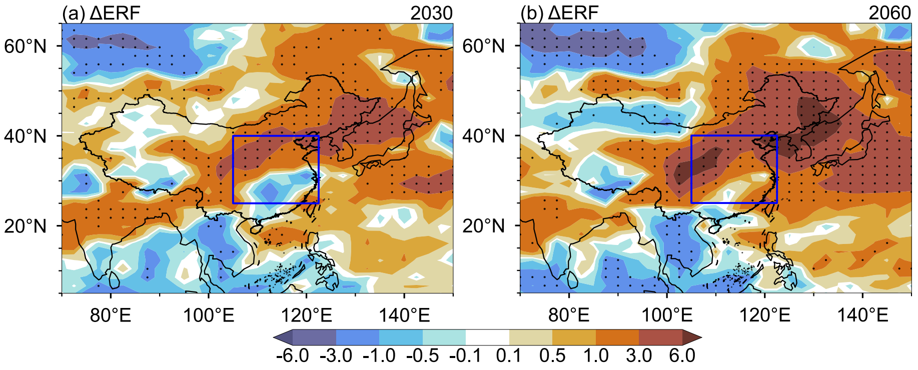

Figure 2. Same as Figure 1 but for changes in mean ERF of aerosol at TOA (W m^{-2}) from experiments using the atmosphere-only configuration. The blue box (25°–40°N, 105°–122.5°) in (a) marks the region of eastern China. The stippled areas represent statistically significant results at the 90% confidence level, determined by a two-tailed Student's *t*-test.

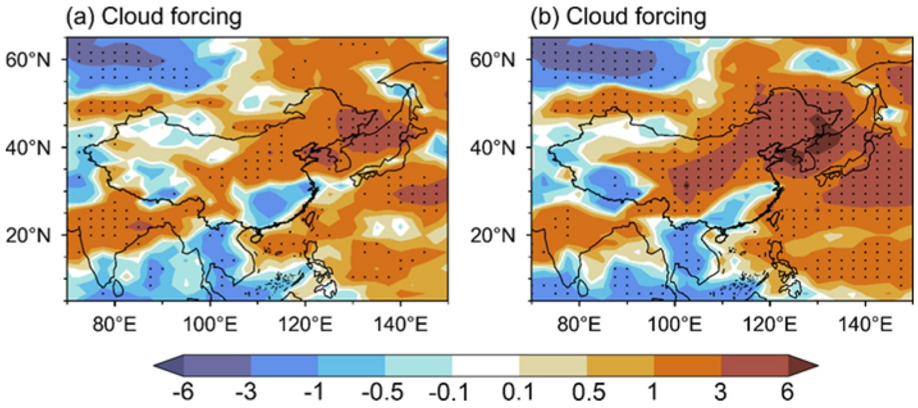

Figure 3. Changes in JJA mean effect radiative forcing (W m^{-2}) due to aerosol-cloud interactions (a) between DPEC_2015 and Neutral_2030 and (b) between DPEC_2015 and Neutral_2060. The stippled areas represent statistically significant results at the 90% confidence level, determined by a two-tailed Student's *t*-test.

The warming over eastern China induced by AA reductions intensifies the land-sea thermal contrast between lands of eastern China and the South China Sea/Philippine Sea, resulting in an enhancement of sea level pressure over 10°–30°N of the northwestern Pacific in the carbon neutral future (Figure 5) than the present-day condition (Figure S3 in Supporting Information S1). The anomalous southerlies in eastern China related to the anomalous high can bring more moisture from oceans to the land. This mechanism is similar to that caused by the emissions reductions in AA during the COVID-19 period, which contributed to an enhanced moist inflow and extreme precipitation in eastern China (Yang et al., 2022). The meridional wind at 850 hPa, averaged over eastern China, increases by 0.04 m s^{-1} in 2030s and 0.06 m s^{-1} in 2060s relative to present-day in JJA. The anomalous high leads to a stable atmosphere, which decreases the precipitation over western Pacific, and increases the water vapor import to southern China, which enhances precipitation there (Figure 6). The AA reduction in China leads to an increase in precipitation by 0.05 mm day^{-1} (0.8%) over eastern China in 2030s relative to the present-day condition in JJA, while causes a 0.12 mm day^{-1} increase (2.0%) in 2060s.

Figure 7 shows the latitude–altitude distribution of JJA mean temperature changes induced by the projected AA decline in China. Averaged over 110°–130°E, the AA reduction leads to the increases in air temperature by 0.1–0.2°C from the surface to 850 hPa in 2030s and 0.2–0.4°C in 2060s. It enhances the meridional thermal gradient around 40°N, which increases the low-level atmospheric baroclinicity (Figure S4 in Supporting Information S1) (Jiang et al., 2017). The enhanced development of atmospheric baroclinicity is the main cause of anomalous cyclonic circulation over western North Pacific between 30° and 50°N (Figure 5). Changes in the atmospheric heating rate and circulation caused by AA reduction toward carbon neutrality in China are shown in Figure 8. The heating rate of atmosphere increases around 30°N resulting from the decreased AA, accompanied by an anomalous updraft, which enhances the atmospheric instability. Although the enhanced anomalous high pressure pushes the moist air northward, the anomalous northerly airflow along the west edge of the cyclone prevents the

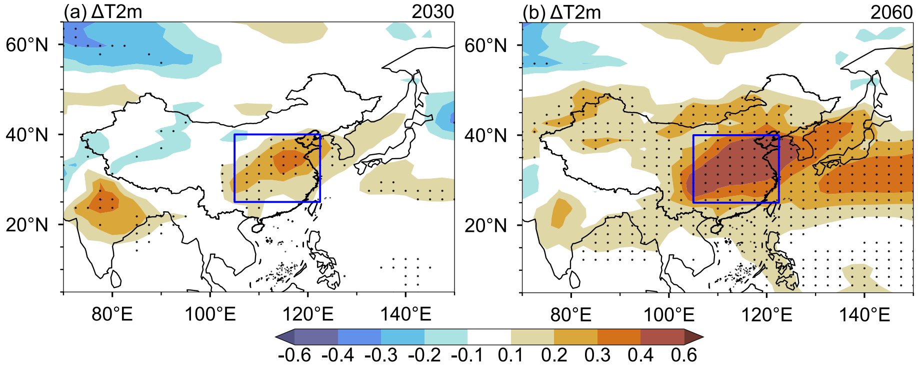

Figure 4. Same as Figure 1 but for JJA mean surface air temperature (°C).

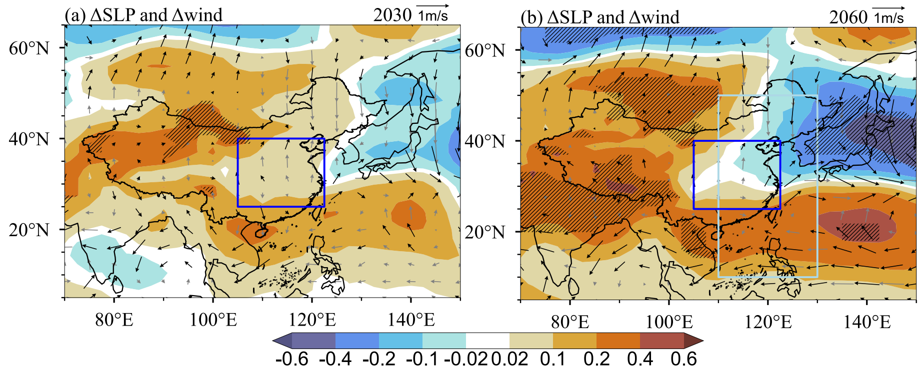

Figure 5. Same as Figure 1 but for JJA mean sea level pressure (SLP) (contours, hPa) and overlaid 850 hPa winds (vectors, m s^{-1}). The dark blue boxes (25°–40°N, 105°–122.5°) mark the region of eastern China. The light blue box marks the region over 110°–130°E and 10°–50°N. The shaded areas and black vectors represent statistically significant results at the 90% confidence level, determined by a two-tailed Student's *t*-test.

development of southerly airflow over 30°–40°N, which weakens the precipitation around 35°N in eastern China (Figure 6). Note that since the total heating rate calculation here does not include the temperature tendency related to moist processes, it does not exactly match the vertical temperature anomaly, especially over mid-to high troposphere.

The responses of EASM to AA reductions associated with clean air policies in China under the localized carbon neutral emission scenario are examined above. The extent to which reduction in AA emissions over China affects the EASM requires further detailed analysis. As shown in Table 1, three indices that consider various features of thermal contrast in the east–west and north–south directions (Sun et al., 2002), shear vorticity in north–south (Lau et al., 2008), and the southwest Asian summer monsoon (Wu & Ni, 1997) are used to characterize the EASM intensity in this study. A more credible result can be given using three different indices than applying any individual index. Although the changes in EASM intensity vary with the definition of the indices, all three indices show that the EASM intensity in JJA increase by 1%–18% in 2030s and 4%–34% in 2060s relative to present-day. It indicates that AA reductions associated with clean air actions in China toward carbon neutrality could enhance the EASM strength.

3.3. Changes in Weather Extremes Due To Aerosols Reduction Toward Carbon Neutrality in China

The changing EASM induced by reductions in AA emissions over China toward carbon neutrality can further influence weather extremes in summer. Here, we adopt the threshold for extreme high temperatures as the 95th percentile of daily maximum temperature in JJA from the DPEC_2015 simulation. The changes in frequency (occurrence in JJA), maximum duration (defined as the maximum number of consecutive days), and maximum magnitude (maximum exceedance of the threshold) of extreme high temperatures are shown in Figure 9. The frequency, maximum duration, and maximum magnitude of extreme high temperatures increase significantly

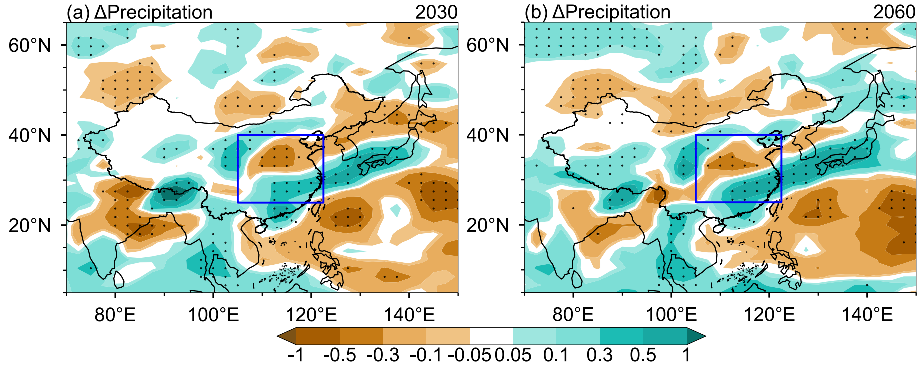

Figure 6. Same as Figure 1 but for JJA mean precipitation rate (mm day^{-1}).

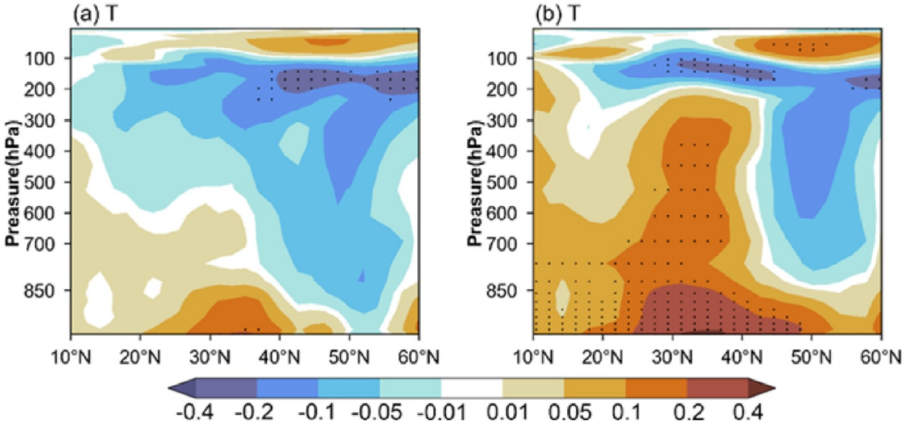

Figure 7. Pressure-latitude cross sections averaged over 110°–130°E for changes in JJA mean temperature (°C) (a) between DPEC_2015 and Neutral_2030 and (b) between DPEC_2015 and Neutral_2060. The stippled areas represent statistically significant results at the 90% confidence level, determined by a two-tailed Student's *t*-test.

over China under the carbon neutral scenario. Owing to the clean air measures under localized future emission scenario, the frequency, maximum duration, and maximum magnitude of extreme high temperatures averaged over eastern China in JJA have an increase of 14 (24) days, 13 (24) days, and 1.0 (1.2) °C in 2030s (2060s) relative to the present-day conditions. In addition, the frequency and maximum duration of extreme high temperatures over western Pacific also increase by 10–50 days owing to the AA reductions in China.

Four indices are employed to quantify the future changes in extreme precipitation, including PRCPTOT (defined as total wet-day daily precipitation in mm when daily rate exceeds 1 mm), R95p (defined as total precipitation in mm when daily rate exceeds the 95th percentile), R99p (total precipitation in mm when daily rate exceeds the 99th percentile), and R10 mm (number of days with precipitation greater than 10 mm). Similar to the changes in EASM precipitation pattern, associated with the emission reductions in AA over China, PRCPTOT, R95p and R99p present a pattern of increases in southern China and decreases in eastern China around 35°N (Figure 10). Averaged over eastern China, PRCPTOT, R95p, R99p and R10 mm in JJA increase from 1,328, 178, 43 mm and 9 days in year 2015 to 1,361, 213, 69 mm and 11 days in 2030s and 1,381, 239, 82 mm and 13 days in 2060s,

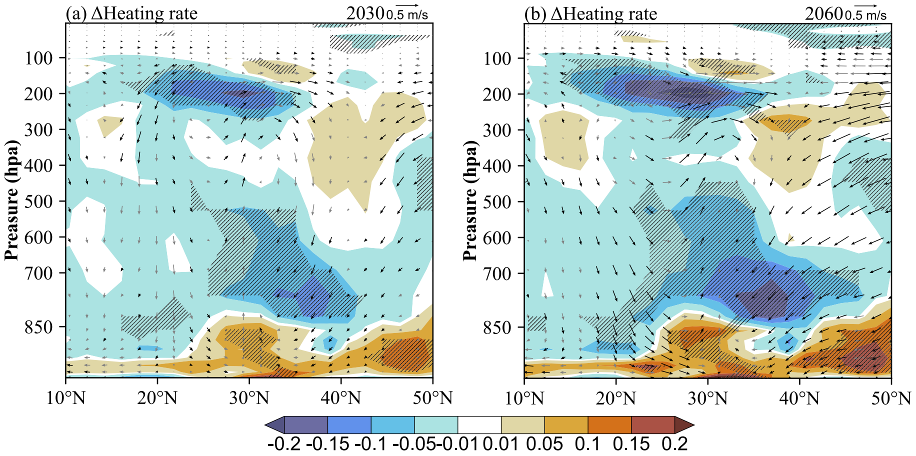

Figure 8. Pressure-latitude cross sections (averaged over 110°–130°E, region shown in Figure 5b) for changes in JJA mean atmospheric heating rate (contours, K day^{-1}) and overlaid meridional winds (vectors, m s^{-1}) (a) between DPEC_2015 and Neutral_2030 and (b) between DPEC_2015 and Neutral_2060. Heating rate is calculated as the sum of shortwave heating rate, longwave heating rate and temperature vertical diffusion without considering temperature tendency related to moist processes. The shaded areas and black vectors represent statistically significant results at the 90% confidence level, determined by a two-tailed Student's *t*-test.

Table 1
The Relative Changes in Three EASM Indices in Neutral_2030 and Neutral_2060 Relative to DPEC_2015

Indices	Definition	Parameters	Percentage changes in 2030 and 2060s relative to present-day (%)	
I_{Sun}	$4/5(T_{\mathrm{EC}}–T_{\mathrm{NWP}}) + 1/5(T_{\mathrm{SC}}–T_{\mathrm{SCS}})$	T2m	+18.0	+33.4
I_{Lau}	U200 (40°–50°N,110°–150°E)–U200 (25°–35°N,110°–150°E)	U200	+2.6	+11.0
I_{Wu}	V850 (20°–30°N,110°–130°E)	V850	+0.8	+3.7

Note. T_{EC}, T_{NWP}, T_{SC} and T_{SCS} denote the regional mean surface air temperature (T2m) over the EASM area (27°–35°N, 105°–122.5°E), Northwest Pacific region (15°–30°N, 120°–150°E), South China (18°–27°N, 105°–122.5°E), and the South China Sea (5°–18°N, 105°–120°E), Respectively. U200 denotes 200 hPa zonal wind. V850 is meridional wind at 850 hPa.

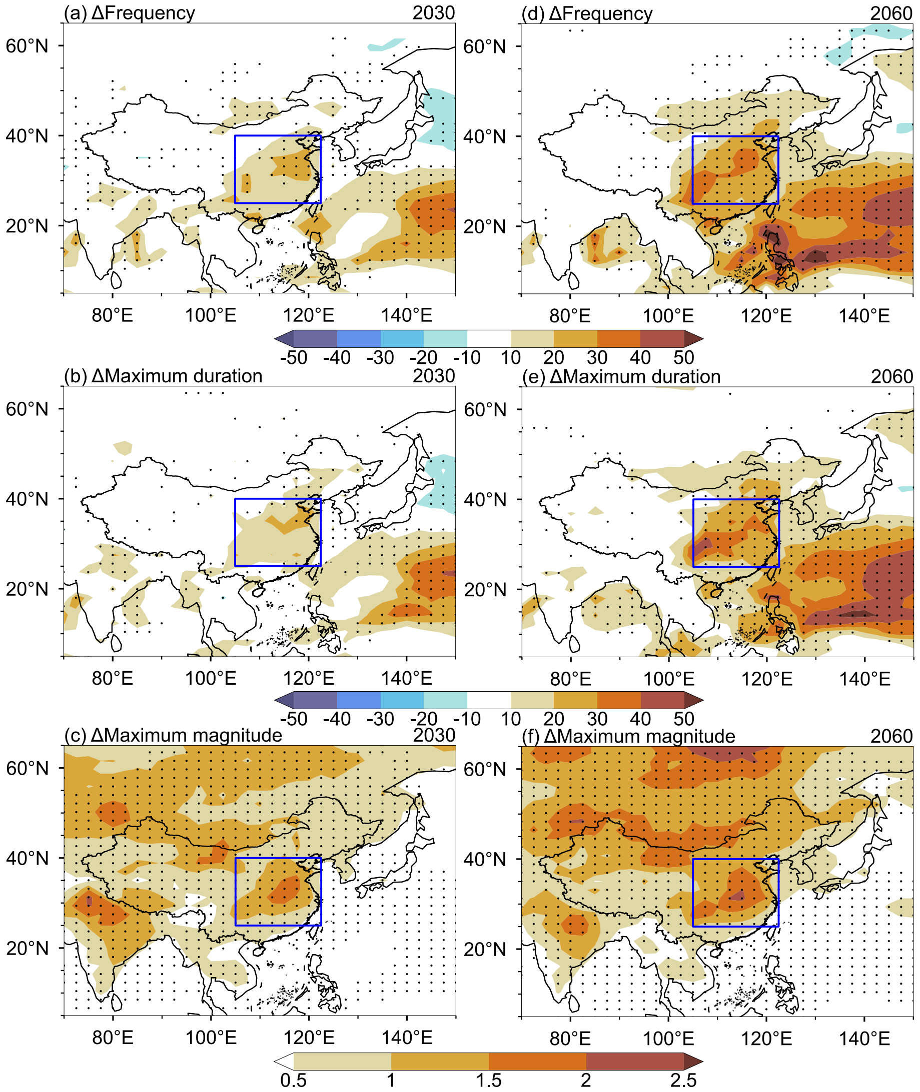

Figure 9. Changes in frequency (a, d, unit: days), maximum duration (b, e, unit: days), and maximum magnitude (c, f, unit: °C) of extreme high temperatures in JJA between DPEC_2015 and Neutral_2030 (left) and between DPEC_2015 and Neutral_2060 (right). The blue boxes (25°–40°N, 105°–122.5°) mark the region of eastern China. The stippled areas represent statistically significant results at the 90% confidence level, determined by a two-tailed Student's *t*-test.

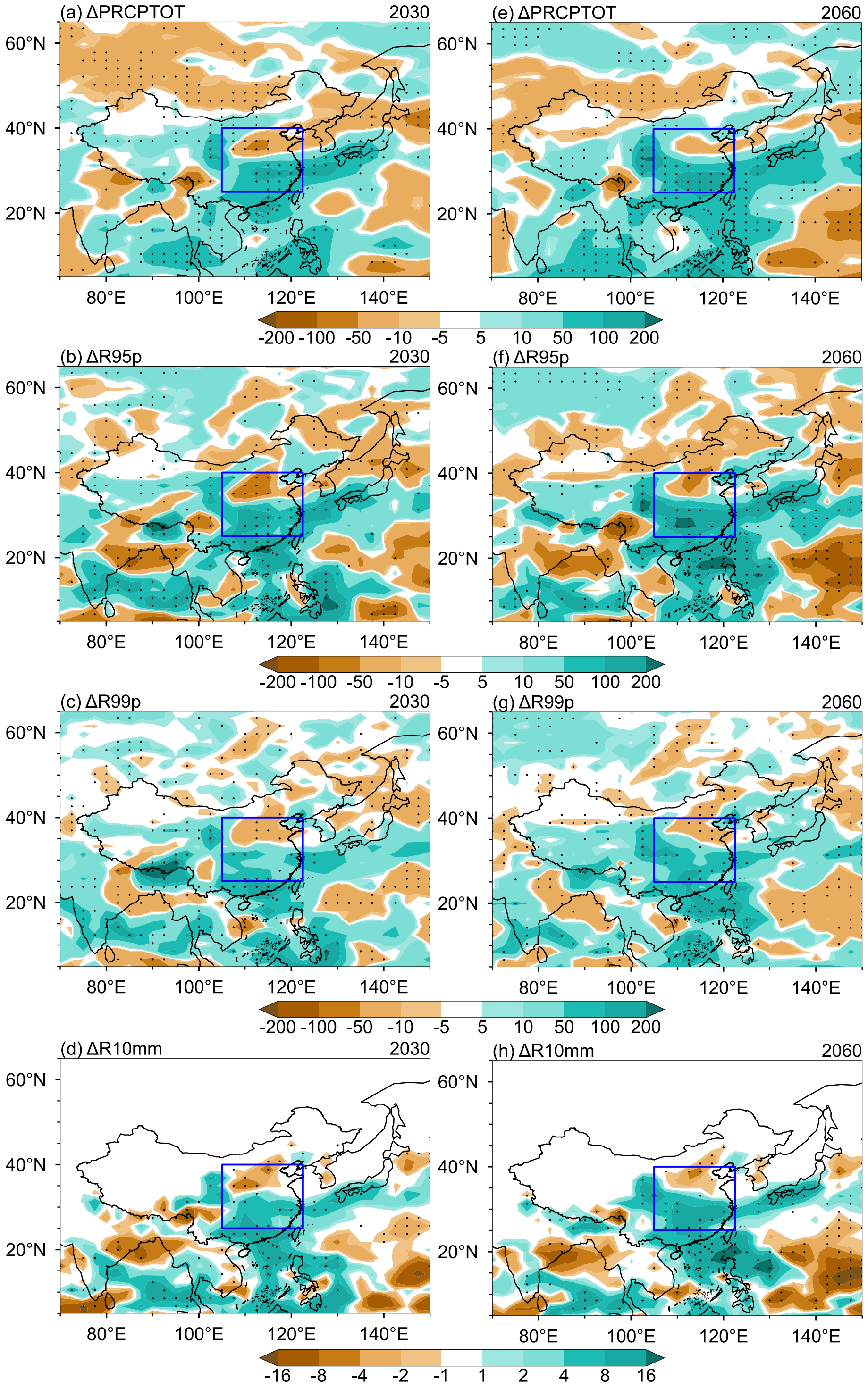

Figure 10. Changes in PRCPTOT (a, e, unit: mm, total wet-day daily precipitation in mm when daily rate exceeds 1 mm), R95p (b, f, unit: mm, total precipitation in mm when daily rate exceeds the 95th percentile), R99p (c, g, unit: mm, total precipitation in mm when daily rate exceeds the 99th percentile) and R10 mm (d, h, unit: days, number of days with precipitation greater than 10 mm) between DPEC_2015 and Neutral_2030 (left) and between DPEC_2015 and Neutral_2060 (right). The blue boxes (25°–40°N, 105°–122.5°) mark the region of eastern China. The stippled areas represent statistically significant results at the 90% confidence level, determined by a two-tailed Student's *t*-test.

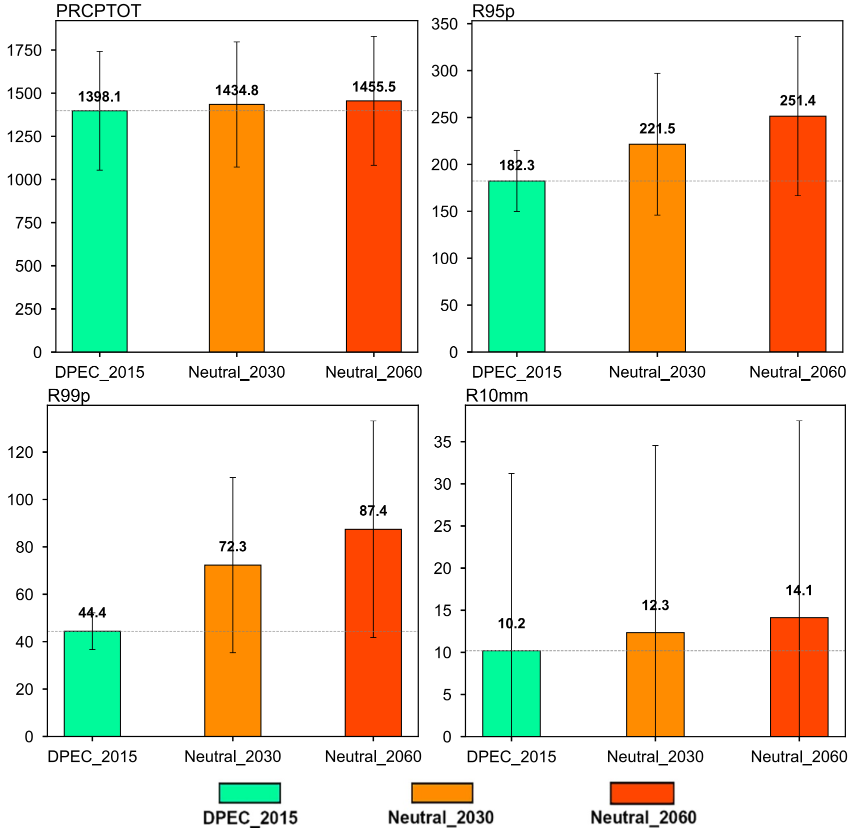

Figure 11. PRCPTOT (unit: mm), R95p (unit: mm), R99p (unit: mm) and R10 mm (unit: days) in DPEC_2015, Neutral_2030 and Neutral_2060 averaged over eastern China (25°–40°N, 105°–122.5°). Error bars indicate the 1σ of extreme precipitation indices.

respectively (Figure 11). It suggests that AA emission reductions in China toward carbon neutrality potentially intensify the extreme precipitation, especially in southern China.

4. Conclusions and Discussions

Following the carbon neutral pathway, China plans to implement a series of climate policies to reduce greenhouse gases. Meanwhile, the anthropogenic emissions of aerosols and precursors are also projected to decrease substantially related to the emissions reduction measures. Here, the responses of EASM and weather extremes in JJA to AA reductions from 2015 to 2030 and 2060 in China toward carbon neutrality are investigated using the CESM1 model, while greenhouse gases and other anthropogenic climate forcers are kept at the present-day levels. The years 2030 and 2060 are two key time nodes for the zero-carbon polity in China. Note that, since the external forcings do not change outside China, the quantitative projections do not represent the future climate in the real world of global carbon neutrality.

As a result of the decreases in AA emissions in China, eastern China experiences a positive change in JJA aerosol ERF by 1.63 W m^{-2} in 2030s and 3.37 W m^{-2} in 2060s relative to present-day, resulting in a 0.16°C and 0.40°C warming, respectively. The land-sea temperature difference between the land area of eastern China and the South China Sea/Philippine Sea is intensified by the warming, which strengthen the sea level pressure over 10°–30°N of the northwestern Pacific and then increase JJA precipitation by 0.05 mm day^{-1} (0.8%) in 2030s and 0.12 mm day^{-1} (2.0%) in 2060s relative to present-day in eastern China. The enhanced meridional temperature gradient near 40°N increases the low-level atmospheric baroclinicity, which leads to the anomalous low-pressure over western North Pacific between 30° and 50°N, favoring cyclonic circulations. The anomalous northerlies along the west edge of cyclones weaken southerly winds, which reduces the precipitation around 35°N in eastern

China. Based on the multiple EASM indices, EASM intensity in JJA is estimated to be strengthened by 1%–18% in 2030s and by 4%–34% in 2060s relative to present-day associated with China's emission reductions in AA toward carbon neutrality.

Averaged over eastern China, the AA emissions reduction in China under carbon neutral scenario leads to an increase in the frequency, the maximum duration, and the maximum magnitude of extreme high temperatures by 14 (24) days, 13 (24) days, and 1.0 (1.2) °C in 2030s (2060s) relative to the present-day conditions. All four extreme precipitation indices in summer over eastern China, including PRCPTOT, R95p, R99p and R10 mm, also increase from 1,328, 178, 43 mm and 9 days in year 2015 to 1,361, 213, 69 mm and 11 days in year 2030s and to 1,381, 239, 82 mm and 13 days in year 2060s, respectively. These suggest an unintended effect of clean air actions that AA emission reductions in China toward carbon neutrality can potentially intensify the summertime extreme temperatures and precipitation in China, which warrants careful assessment prior to the implementation of emissions reduction strategies.

This study highlights the significant role of AA emission reduction toward carbon neutrality in China in influencing EASM and weather extremes. Previous studies have reported that the removal of AA or reduction in AA due to COVID-19 would intensify EASM rainfall (He et al., 2022; Herbert et al., 2021; Yang et al., 2022). This study quantitatively investigated the influences of aerosol reductions in China toward carbon neutrality on EASM and weather extremes and also found that the AA reductions following the carbon neutral pathway would strengthen the EASM intensity and increase the weather extremes, complementing previous studies with localized clean air scenarios. Many studies have also revealed intensified EASM rainfall and precipitation extremes in the future (Katzenberger & Levermann, 2024; Xue et al., 2023). The changing EASM can in turn influence aerosols in China through changing transport and deposition processes (Liao et al., 2015). There are also some uncertainties in this study. Firstly, many previous studies reported that the CESM1 significantly underestimates aerosol concentrations in China, due to factors such as uncertainties in new aerosol particle formation/aging, excessive aerosol wet removal, the coarse model resolution, and biases in the model input of anthropogenic emissions. The underestimation in AA burden may introduce a low bias in the model's responses of EASM and weather extremes to in AA emissions reductions from China toward carbon neutrality. Secondly, changes in nitrate and ammonium aerosols that are not accounted in the model likely have an impact on the climate responses. Thirdly, using only China's aerosol reductions without global or hemispheric context may not be appropriate in estimating future changes in EASM, given the known teleconnections of aerosol changes in other regions on the EASM. However, this study aims to examine the impacts of aerosol reduction in China on East Asian summer monsoon and weather extremes, rather than the future climate projections. Furthermore, we conducted only three ensemble members of 70-year fully coupled equilibrium simulations, while achieving an equilibration in the deep ocean may need to run the model for thousands of years. Future studies by applying more ensemble members with longer simulations are recommended to improve the reliability of the findings. Finally, our results are only based on CESM1 equilibrium simulations, and future research should incorporate multi-model ensemble simulations to address potential model dependency concerns, and also perform transient simulations to offer a more accurate depiction of the time-varying effects of aerosol changes (King et al., 2020; Smith et al., 2020).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The results are available for download at Yang (2024).

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