



# Sensitivity analysis of the surface ozone and fine particulate matter to meteorological parameters in China

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Received: 23 February 2020 – Discussion started: 2 March 2020

Revised: 18 August 2020 – Accepted: 4 September 2020 – Published: 12 November 2020

**Abstract.** Meteorological conditions play important roles in the formation of ozone (O<sub>3</sub>) and fine particulate matter (PM<sub>2.5</sub>). China has been suffering from serious regional air pollution problems, characterized by high concentrations of surface O<sub>3</sub> and PM<sub>2.5</sub>. In this study, the Community Multi-scale Air Quality (CMAQ) model was used to quantify the sensitivity of surface O<sub>3</sub> and PM<sub>2.5</sub> to key meteorological parameters in different regions of China. Six meteorological parameters were perturbed to create different meteorological conditions, including temperature (*T*), wind speed (WS), absolute humidity (AH), planetary boundary layer height (PBLH), cloud liquid water content (CLW) and precipitation (PCP). Air quality simulations under the perturbed meteorological conditions were conducted in China in January and July of 2013. The changes in O<sub>3</sub> and PM<sub>2.5</sub> concentrations due to individual meteorological parameters were then quantified. *T* has a great influence on the daily maximum 8 h average O<sub>3</sub> (O<sub>3</sub>-8 h) concentrations, which leads to O<sub>3</sub>-8 h increases by 1.7 in January in Chongqing and 1.1 ppb K<sup>-1</sup> in July in Beijing. WS, AH, and PBLH have a smaller but notable influence on O<sub>3</sub>-8 h with maximum change rates of 0.3 ppb %<sup>-1</sup>, -0.15 ppb %<sup>-1</sup>, and 0.14 ppb %<sup>-1</sup>, respectively. *T*, WS, AH, and PBLH have important effects on PM<sub>2.5</sub> formation of both in January and July. In general, PM<sub>2.5</sub> sensitivities are negative to *T*, WS, and PBLH and positive to AH in most regions of China. The sensitivities in January are much larger than in July. PM<sub>2.5</sub> sensitivity to *T*, WS, PBLH, and AH in January can be up

to -5 μg m<sup>-3</sup> K<sup>-1</sup>, -3 μg m<sup>-3</sup> %<sup>-1</sup>, -1 μg m<sup>-3</sup> %<sup>-1</sup>, and +0.6 μg m<sup>-3</sup> %<sup>-1</sup>, respectively, and in July it can be up to -2 μg m<sup>-3</sup> K<sup>-1</sup>, -0.4 μg m<sup>-3</sup> %<sup>-1</sup>, -0.14 μg m<sup>-3</sup> %<sup>-1</sup>, and +0.3 μg m<sup>-3</sup> %<sup>-1</sup>, respectively. Other meteorological factors (CLW and PCP) have negligible effects on O<sub>3</sub>-8 h (less than 0.01 ppb %<sup>-1</sup>) and PM<sub>2.5</sub> (less than 0.01 μg m<sup>-3</sup> %<sup>-1</sup>). The results suggest that surface O<sub>3</sub> and PM<sub>2.5</sub> concentrations can change significantly due to changes in meteorological parameters, and it is necessary to consider these effects when developing emission control strategies in different regions of China.

## 1 Introduction

China has serious air pollution problems, and fine particulate matter (PM<sub>2.5</sub>) and ozone (O<sub>3</sub>) are the two major air pollutants (Lin et al., 2010; Hu et al., 2016; Lu et al., 2019; Wu et al., 2019). The annual average PM<sub>2.5</sub> concentrations were higher than 50 μg m<sup>-3</sup> in 26 out of the total 31 provincial capital cities in mainland China during 2013–2014 (Wang et al., 2014a), and the national fourth highest daily maximum 8 h average O<sub>3</sub> (O<sub>3</sub>-8 h) was 86.0 ppb during the warm seasons (April–September) in 2013–2017, which is 6.3%–30% higher than that in other industrialized regions of the world (Lu et al., 2018). PM<sub>2.5</sub> alone caused 0.87–1.36 million deaths every year in China, and long-term exposure to O<sub>3</sub> was responsible for an extra 254 000 deaths (Cohen et al.,

2017; Silver et al., 2018; Apte et al., 2015; Hu et al., 2017b). China has made remarkable improvement in air quality during recent years (Zhang et al., 2017; Zheng et al., 2018; Zhao et al., 2017); however, air pollution is still severe, making it the fourth-ranked health risk factor (Stanaway et al., 2018).

Surface PM<sub>2.5</sub> and O<sub>3</sub> concentrations are determined by atmospheric processes of emissions, transport and dispersion, chemical transformation (due to gas-phase, aqueous-phase, and aerosol chemistry), and dry and wet deposition. These processes are affected by meteorological conditions. Studies have shown that the surface O<sub>3</sub> and PM<sub>2.5</sub> concentrations are sensitive to different meteorological parameters. For example, Dawson et al. (2007b) investigated the sensitivity of surface O<sub>3</sub> to different meteorological parameters in the eastern United States (US) using the comprehensive air quality model with extensions (CAM<sub>X</sub>). The results showed that temperature ( $T$ ) had the greatest influence on daily O<sub>3</sub>-8 h of 0.34 ppb K<sup>-1</sup>, followed by absolute humidity (AH) of 0.025 ppb %<sup>-1</sup>. Bernard et al. (2001) also confirmed that  $T$  presented a notable positive correlation with the surface O<sub>3</sub> concentration. The effects of meteorological parameters on PM<sub>2.5</sub> are even more complicated. Tran and Mölders (2011) showed that elevated PM<sub>2.5</sub> concentrations tended to occur under the conditions of calm wind, low  $T$ , and relative humidity in Fairbanks, Alaska. Olvera Alvarez et al. (2018) used a land use regression model to analyze the effects of different meteorological parameters on PM<sub>2.5</sub> in El Paso, Texas, and obtained the same conclusion in winter, but in spring, the high PM<sub>2.5</sub> level was associated with high wind speed (WS) and low humidity. Dawson et al. (2007a) studied the effects of individual meteorological parameters in the eastern US and found that PM<sub>2.5</sub> concentration decreased markedly as the precipitation increased (PCP) in winter, but in summer, the main meteorological factors affecting the PM<sub>2.5</sub> concentration were  $T$ , WS, and planetary boundary layer height (PBLH). Dawson et al. (2009) simulated the effects of climate change on regional and urban air quality in the eastern US and found that PM<sub>2.5</sub> concentration decreased by 0.3 μg m<sup>-3</sup> in January, mostly due to increasing PCP, and increased by 2.5 μg m<sup>-3</sup> in July, largely due to decreasing PBLH and WS. Horne and Dabdub (2017) altered various meteorological parameters to investigate their effects on O<sub>3</sub>, PM<sub>2.5</sub>, and secondary organic aerosols (SOA) and found that the  $T$  predominated the effects of meteorology in California.

Many studies have proved that meteorological conditions play very important roles in air pollution events in China. Studies found that the pollutant concentrations could vary by up to several times, due to meteorological changes with the same emission sources (Zhang et al., 2010; Zheng et al., 2015; Cai et al., 2017; Ning et al., 2018; Yang et al., 2018; Li et al., 2019b; Xing et al., 2011; Liu et al., 2017). For example, Xing et al. (2011) studied the difference between the effects of 2007 and 2008 meteorological conditions on air quality during the 2008 Beijing Olympics. They found that higher humidity in August 2008 was beneficial to the formation of

SO<sub>4</sub><sup>2-</sup> by up to ~ 60 %, and lower  $T$  prevented the evaporation of NO<sub>3</sub><sup>-</sup> by up to ~ 60 %. Liu et al. (2017) reported that the monthly mean PM<sub>2.5</sub> concentrations in the Jing-Jin-Ji (JJJ) area in December 2015 increased by 5 %–137 % due to the unfavorable weather conditions such as low WS and high humidity.

A few studies investigated the relationships between air quality and meteorological conditions in China. Zhang et al. (2015) conducted a correlation analysis between air quality and meteorology in three megacities: Beijing, Shanghai, and Guangzhou in China. The result showed that air pollutants were significantly negatively correlated with WS, and O<sub>3</sub> had a positive correlation with  $T$ . Yin et al. (2016) found that the relationship between WS and PM<sub>2.5</sub> has a complicated influence, with higher PM at low and high WS than in light to moderate winds in Beijing from 2008 to 2014. Xu et al. (2018) examined the variations of PM<sub>2.5</sub> concentration in January 2017 in China compared to that in January 2016 and found that meteorological conditions of low WS, high humidity, low PBLH, and low PCP contributed to PM<sub>2.5</sub> concentration worsening by 29.7 %, 42.6 %, and 7.9 % in the JJJ region, the Pearl River delta (PRD) region, and the Cheng-Yu Basin (CYB) region, respectively. Ma et al. (2019) analyzed the effects of meteorology on air pollution in the Yangtze River delta (YRD) region during 2014–2016 and found that PM<sub>2.5</sub> was highly negatively correlated with WS, while O<sub>3</sub> concentration was positively correlated with  $T$  but negatively related to relative humidity. Zhu et al. (2017) reported that the surface concentrations of O<sub>3</sub> increased by 2–6 in January and 8–12 ppb in July 2014 in the PRD, mainly due to the increase in  $T$  and the decrease in NO<sub>x</sub> emissions.

These studies have investigated the impacts of meteorological conditions on PM<sub>2.5</sub> and O<sub>3</sub> in certain regions of China; however, quantitative sensitivity of PM<sub>2.5</sub> and O<sub>3</sub> to meteorological parameters has not been examined. The objective of this study is to quantify the sensitivity of O<sub>3</sub> and PM<sub>2.5</sub> to different meteorological parameters in winter and summer in different regions of China. The paper is constructed as follows: Sect. 2 describes the method used to estimate the sensitivity, and Sect. 3 presents the effects of each meteorological variable on O<sub>3</sub> and PM<sub>2.5</sub> in China and in five representative cities. Conclusions are then summarized in Sect. 4.

## 2 Methods

The sensitivity of O<sub>3</sub> and PM<sub>2.5</sub> associated with changes in meteorological parameters was quantified using the Community Multiscale Air Quality (CMAQ) model version 5.0.2. The meteorological parameters include  $T$ , WS, AH, PBLH, PCP, and cloud liquid water content (CLW). A base case was firstly simulated with meteorological fields predicted by the Weather Research and Forecasting (WRF) model v3.7.1 (<https://www2.mmm.ucar.edu/wrf/users/>) using the

**Table 1.** Meteorological perturbations imposed in this study.

Meteorological parameter	Changes in values examined
Temperature ( <i>T</i> )	±0.5, ±1.0, ±1.5 K
Wind speed (WS)	±5 %, ±10 %, ±20 %
Absolute humidity (AH)	±5 %, ±10 %, ±20 %
Boundary layer height (PBLH)	±10 %, ±20 %, ±30 %
Cloud liquid content (CLW)	±5 %, ±10 %, ±20 %
Precipitation (PCP)	±5 %, ±10 %, ±20 %

NCEP FNL Operational Model Global Tropospheric Analyses dataset as the initial and boundary conditions. The base case has been described in a previous study and the model configurations of the base case were reported there (Hu et al., 2015). The WRF-predicted meteorological parameters and the CMAQ-predicted surface O<sub>3</sub> and PM<sub>2.5</sub> have been evaluated against observations at 422 sites in 60 major cities in China, and the accuracy of the model performance has been validated (Hu et al., 2016).

A suite of perturbation scenarios was created, and in each scenario, a certain meteorological parameter was perturbed to a certain extent. The details of the perturbation scenarios are listed in Table 1. Among those changes, *T* was absolute changes and other parameters were relative variations. The magnitude ranges of perturbations are based on the IPCC AR5 report and the study of Dawson et al. (2007a, 2007b), and the references therein. For each parameter, three positive and three negative perturbations were then designed within its range to have a more comprehensive examination of the sensitivity of PM<sub>2.5</sub> and O<sub>3</sub> to this parameter. All perturbations were implemented uniformly in space on the modeling domain and in time through the modeling periods. The perturbations on temperature, wind speed, and absolute humidity were made in all layers. To separate the effects of individual meteorological parameters, only one parameter was changed in each case, while all the other parameters were kept unchanged. Therefore, cloud dissipating or forming in response to changing temperature was not considered in the simulations. Please note that these types of perturbations are not what happens in the real world, where meteorological parameters are inter-linked. When perturbing horizontal wind speed, to avoid unphysical situations that mass would not be conserved, the vertical wind speed was adjusted in the vertical transport calculation based on the air density changes to conserve mass.

Then the CMAQ model was re-run to predict the air quality under the perturbed meteorological condition. The emissions and other inputs were kept unchanged in each perturbed meteorological scenario; therefore, the difference of O<sub>3</sub> and PM<sub>2.5</sub> concentrations between each of the perturbation case and the base case was due to the change in the specific meteorological parameter, and the sensitivity of O<sub>3</sub> and PM<sub>2.5</sub> to individual meteorological parameters could be quantitatively determined. It is worthwhile noting that some meteorological

parameters could have significant impacts on emissions, such as the effect of *T* on biogenic VOC and soil NO<sub>x</sub> emissions, the cloud cover/convection on lightning NO<sub>x</sub> emissions, and the effect of *T* on power plant NO<sub>x</sub> emissions (high *T* leads to higher electricity demand in summer), which would affect air quality. Therefore, the sensitivities in this study only include the “direct” effects of individual meteorological parameters on air quality. A full evaluation of the impacts of climate/weather changes on air quality should consider effects of the emissions changes.

The modeling domain covers East Asia, including all of China, with a horizontal resolution of 36 × 36 km<sup>2</sup>. The base and perturbation cases were conducted in January and July in 2013, representing the winter and summer conditions, respectively. In addition to the regional analysis, five representative megacities were selected, i.e., Beijing, Shanghai, Guangzhou, Chongqing, and Xi’an (Fig. 1). These cities are located in the North China Plain (NCP), YRD, PRD, CYB, and Guanzhong Plain, respectively, where serious air pollution problems often occur. In this study, O<sub>3</sub>-8 h was used in the O<sub>3</sub> analyses, and 24 h average PM<sub>2.5</sub> was used in the PM<sub>2.5</sub> analyses, if not specifically stated. The O<sub>3</sub>-*T* relationship is examined using the method in Rasmussen et al. (2012) in the five cities. Observed and predicted O<sub>3</sub>-*T* relationships were estimated using the daily observed and predicted O<sub>3</sub>-8 h concentrations and daily maximum *T* in July (O<sub>3</sub> observations became available from March 2013 in China, so no O<sub>3</sub> observations in January). The results are shown in Fig. S1 (in the Supplement). CMAQ predicts a positive O<sub>3</sub>-*T* relationship in most cities except in Beijing, and the model tends to underestimate the daily O<sub>3</sub>-*T* relationship except in Shanghai. The underestimation of O<sub>3</sub>-*T* by the CMAQ model in this study is consistent with the findings in Rasmussen et al. (2012). Please note that we only have 1-month data and that we use daily O<sub>3</sub>-8 h and daily maximum temperature in the evaluation, while a much more meaningful evaluation should be performed to use monthly average O<sub>3</sub> and monthly average temperature over a long-term period (Rasmussen et al., 2012).

### 3 Results and discussion

#### 3.1 Impacts of meteorological parameters on surface O<sub>3</sub>

Figure 2a and b show the spatial distribution of the predicted monthly average O<sub>3</sub>-8 h concentrations in January and July, respectively. In January, the highest average concentrations are about 70 ppb in the Sichuan basin, and the concentrations in South and East China are generally higher than those in North China. In July, the highest average concentrations are over 80 ppb in the large areas of NCP and YRD, CYB, and Guangzhou in the PRD.



Figure 1. Location map of China and the five cities.

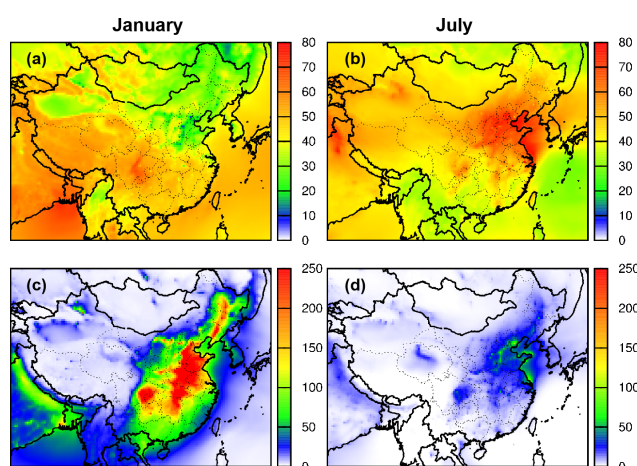


Figure 2. Spatial distributions of monthly average O<sub>3</sub>-8 h (ppb) in (a) January and (b) July and monthly average PM<sub>2.5</sub> ( $\mu\text{g m}^{-3}$ ) in (c) January and (d) July 2013.

Figure 3 shows the spatial distribution of the concentration changes in O<sub>3</sub>-8 h in January and July due to changes of  $T + 1.0\text{ K}$ ,  $WS - 10\%$ ,  $AH + 10\%$ ,  $PBLH - 20\%$ ,  $CLW + 10\%$ , and  $PCP + 10\%$ , respectively. Figures S2–S4 show the results due to other extent changes in these parameters. When  $T$  increases by 1.0 K (Fig. 3a), O<sub>3</sub>-8 h increases by 1–2 ppb in most areas of East and Central China in January and in NCP and YRD in July, which is consistent with the high O<sub>3</sub> spatial distribution in the base case (shown in Fig. 2). O<sub>3</sub>-8 h decreases by up to 4 ppb in January in Northeast China and by up to 2 ppb in the southwestern border of China and the East China Sea, which are the areas of low O<sub>3</sub> concentrations (generally less than the background O<sub>3</sub> concentration of 35 ppb). Therefore, the effect of  $T$  on O<sub>3</sub> is dependent on the O<sub>3</sub> formation regime. An increase in  $T$  promotes O<sub>3</sub> formation chemistry in net O<sub>3</sub> formation areas (O<sub>3</sub> concentrations greater than 35 ppb) but accelerates O<sub>3</sub> consumption chem-

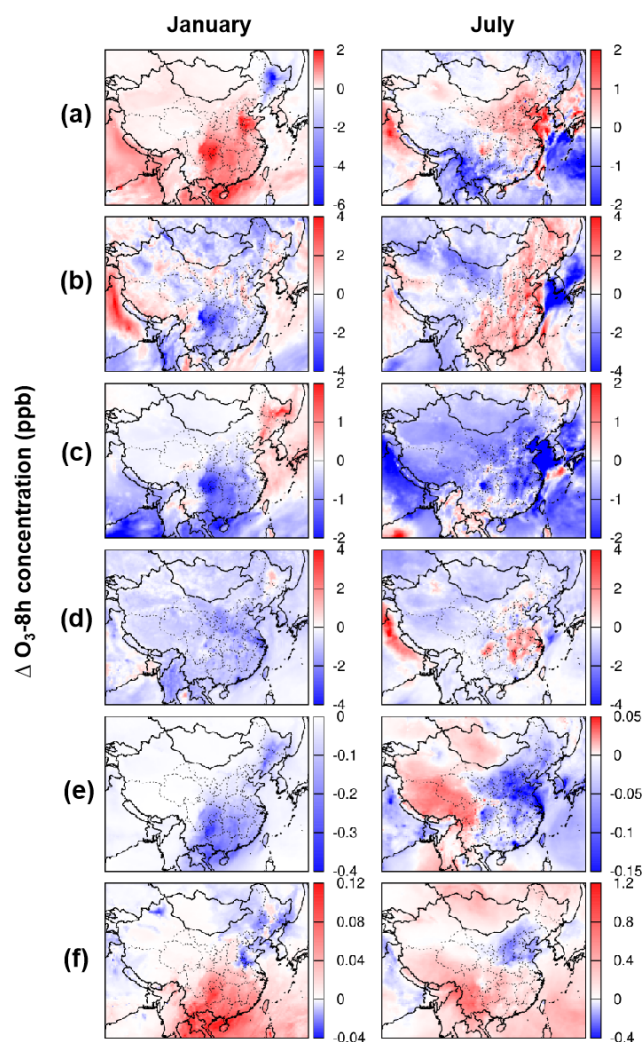


Figure 3. Changes in monthly average O<sub>3</sub>-8 h (ppb) in January and July 2013 due to (a)  $T + 1.0\text{ K}$ , (b)  $WS - 10\%$ , (c)  $AH + 10\%$ , (d)  $PBLH - 20\%$ , (e)  $CLW + 10\%$ , and (f)  $PCP + 10\%$ .

istry in the net O<sub>3</sub> loss areas (O<sub>3</sub> concentrations less than 35 ppb).

Figure 3b shows the differences of O<sub>3</sub>-8 h in January and July when  $WS$  is 10 % less than the base case in 2013. The influence of wind on O<sub>3</sub> concentration is complex, but generally, slower  $WS$  decreases O<sub>3</sub> in January in most parts of China, particularly in Sichuan by up to 3 ppb, but increases O<sub>3</sub> in July by a few ppb over most areas in East and Central China. Therefore, the impact of  $WS$  on O<sub>3</sub> appears opposite in winter and summer. Weaker winds slow down the dispersion of NO<sub>x</sub> and VOCs, which is conducive to O<sub>3</sub> formation in summer when the vertical mixing is strong but increases O<sub>3</sub> titration in the surface in winter due to weaker vertical mixing.

Figure 3c shows that the surface O<sub>3</sub> is expected to decrease generally less than 1 ppb when  $AH$  increases by 10 % (relative change) in both January and July in most land areas of



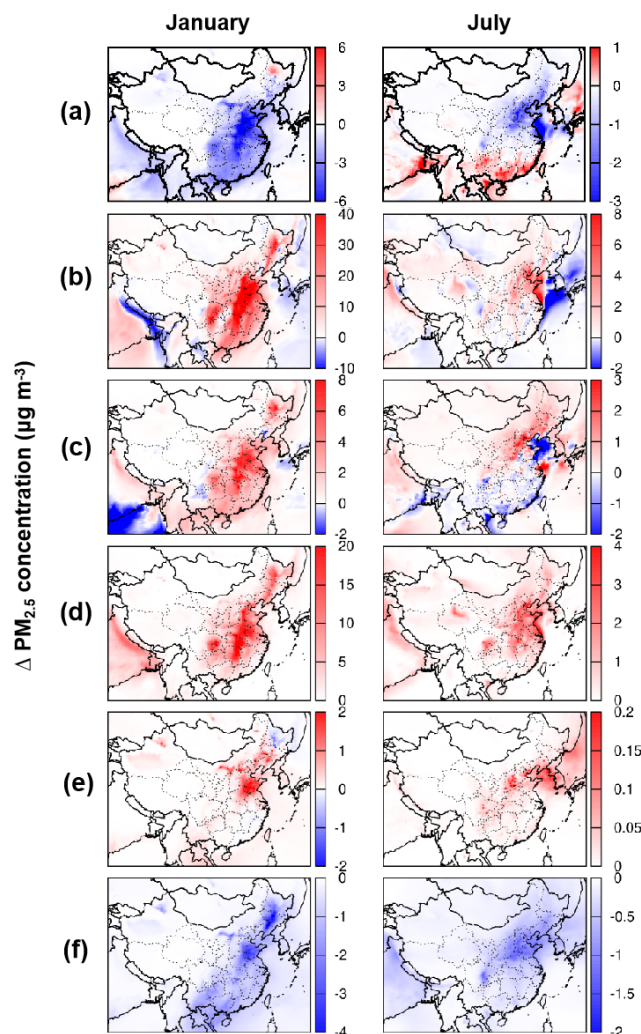
China except in the northeastern area. Figure 3d shows that a 20 % decrease in PBLH leads to O<sub>3</sub>-8 h decreases by a few ppb in most areas in January, while in July O<sub>3</sub>-8 h increases in the eastern and central regions, especially in YRD, CYB, and areas in Hubei–Hunan–Jiangxi in Central China. Sensitivity of O<sub>3</sub> to CLW and PCP is relatively small. Figure 3e demonstrates that O<sub>3</sub>-8 h changes by −0.03 to 0.03 ppb in January and July for a 10 % increase in CLW. Figure 3f demonstrates that a 10 % increase in PCP results in −0.1 to 0.2 ppb changes in O<sub>3</sub>-8 h. O<sub>3</sub> changes due to the six meteorological factors with different extents of perturbation. Figs. S2–S4 show the similar trends and spatial patterns.

### 3.2 Impacts of meteorological parameters on surface PM<sub>2.5</sub>

Figure 2c and d show the spatial distribution of the monthly average surface PM<sub>2.5</sub> concentrations in January and July. PM<sub>2.5</sub> in January reaches over 200 μg m<sup>−3</sup> in JJJ, SYB, Central China, and urban areas in Northeast China. PM<sub>2.5</sub> is much lower in July, generally lower than 50 μg m<sup>−3</sup>, but is high (up to 70 μg m<sup>−3</sup>) in areas in the JJJ, YRD, and Central China regions.

Figure 4 shows the spatial distribution of PM<sub>2.5</sub> changes due to the same changes in meteorological factors, as in Fig. 3. The PM<sub>2.5</sub> results of other cases of the sensitivity study are shown in Figs. S5–S7 of the Supplement. The results indicate that in January, a 1.0 K increase in *T* leads to an up to 5–6 μg m<sup>−3</sup> decrease in PM<sub>2.5</sub> in JJJ and Central China; in July, a 1.0 K increase in *T* causes a PM<sub>2.5</sub> increase by about 1 μg m<sup>−3</sup> in South China but a decrease by 1–3 μg m<sup>−3</sup> in JJJ and the eastern coastal region. A 10 % decrease in WS causes a PM<sub>2.5</sub> increase to over 40 μg m<sup>−3</sup> in January and up to 5 μg m<sup>−3</sup> in July. A 10 % relative increase in AH leads to a PM<sub>2.5</sub> increase of up to 6 μg m<sup>−3</sup> in January and up to 2 μg m<sup>−3</sup> in JJJ and northeastern regions but a slight decrease of less than 1 μg m<sup>−3</sup> in South China in July. A 20 % decrease in PBLH causes PM<sub>2.5</sub> increases by up to 20 μg m<sup>−3</sup> in January and up to 4 μg m<sup>−3</sup> in July. The impact of CLW on PM<sub>2.5</sub> is small, and generally an increase in CLW increases surface PM<sub>2.5</sub> and an increase in PCP decreases PM<sub>2.5</sub>.

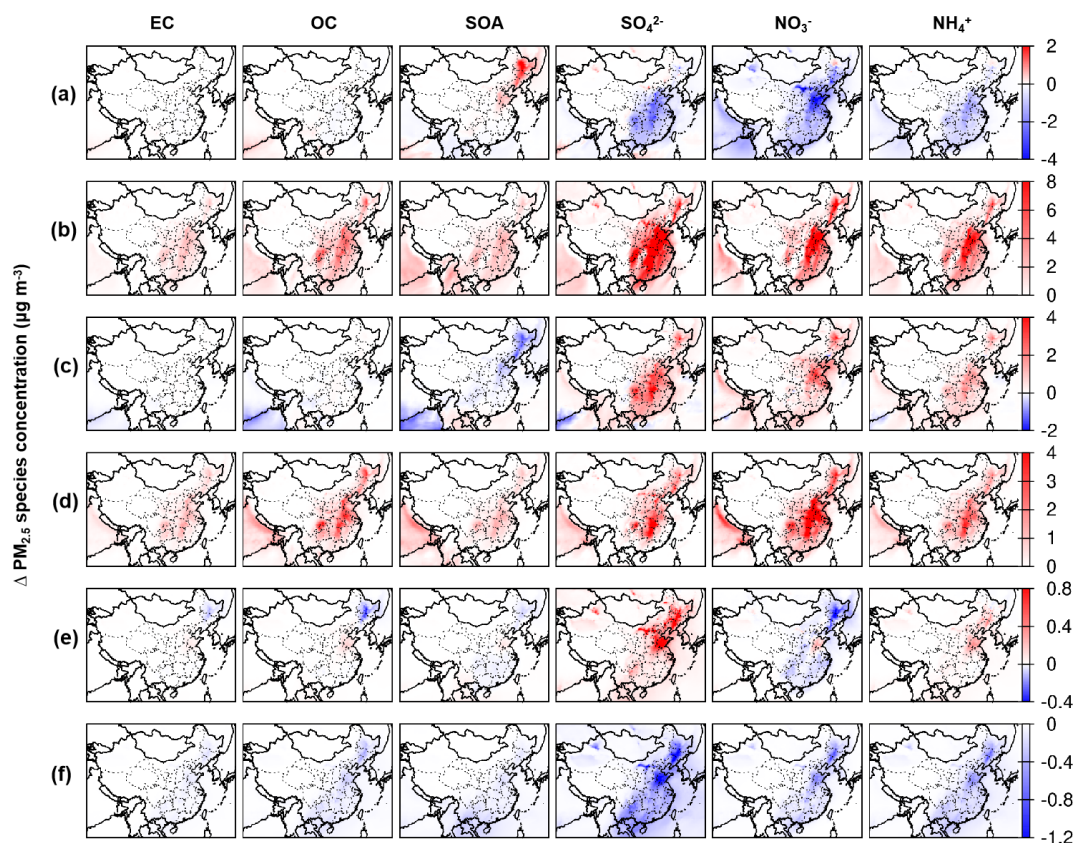
The changes in the total PM<sub>2.5</sub> mass concentrations are determined by the changes in the chemical components of PM<sub>2.5</sub>. Figure S9 displays the fraction of PM<sub>2.5</sub> species, elemental carbon (EC), primary organic carbon (POC), secondary organic aerosol (SOA), sulfate (SO<sub>4</sub><sup>2−</sup>), nitrate (NO<sub>3</sub><sup>−</sup>), and ammonium (NH<sub>4</sub><sup>+</sup>), in five representative cities. Secondary inorganic aerosols (SO<sub>4</sub><sup>2−</sup>, NO<sub>3</sub><sup>−</sup>, NH<sub>4</sub><sup>+</sup>) are the major PM components, accounting for over 50 % of PM<sub>2.5</sub> in January and about 40 % in July. Figures 5 and 6 show the changes in the major PM<sub>2.5</sub> components due to the same changes in meteorological factors as in Fig. 4 in January and in July, respectively. The results show that the effects of the meteorological parameters on the total PM<sub>2.5</sub> (shown



**Figure 4.** Changes in monthly average PM<sub>2.5</sub> concentration (μg m<sup>−3</sup>) in January and July 2013 due to (a) *T* + 1.0 K, (b) WS − 10 %, (c) AH + 10 %, (d) PBLH − 20 %, (e) CLW + 10 %, and (f) PCP + 10 %.

in Fig. 4) are mainly due to their effects on SO<sub>4</sub><sup>2−</sup>, NO<sub>3</sub><sup>−</sup>, and NH<sub>4</sub><sup>+</sup> in January and due to the changes in SO<sub>4</sub><sup>2−</sup>, NO<sub>3</sub><sup>−</sup>, NH<sub>4</sub><sup>+</sup>, and SOA in July. In general, PBLH, WS, and PCP are negatively correlated with SO<sub>4</sub><sup>2−</sup>, NO<sub>3</sub><sup>−</sup>, and NH<sub>4</sub><sup>+</sup> formation, but AH and CLW are positively correlated with these components. SOA concentrations are much higher in July than in January due to the contribution from biogenic emissions (Hu et al., 2017a). SOA formation is affected by reaction rates (positively affected by *T*), availability of oxidants (such as changes in O<sub>3</sub>), and hydrogen ion strength (affected by changes in SO<sub>4</sub><sup>2−</sup>, NO<sub>3</sub><sup>−</sup>, and NH<sub>4</sub><sup>+</sup>). SOA concentrations mainly increase in South China.

It is worthwhile noting the effects of *T* on SO<sub>4</sub><sup>2−</sup> and NO<sub>3</sub><sup>−</sup> (changes in NH<sub>4</sub><sup>+</sup> are determined by changes in SO<sub>4</sub><sup>2−</sup> and NO<sub>3</sub><sup>−</sup>). In both January and July, an increase in *T* decreases



**Figure 5.** Changes in monthly average PM<sub>2.5</sub> component concentration ( $\mu\text{g m}^{-3}$ ) in January due to (a)  $T + 1.0\text{ K}$ , (b)  $WS - 10\%$ , (c)  $AH + 10\%$ , (d)  $PBLH - 20\%$ , (e)  $CLW + 10\%$ , and (f)  $PCP + 10\%$ .

$\text{SO}_4^{2-}$  and  $\text{NO}_3^-$  in the major areas of East China. The  $\text{NO}_3^-$  decrease is expected because volatile  $\text{NH}_4\text{NO}_3$  favors more the gas phase at higher temperature, and this result is consistent with studies in other regions (Dawson et al., 2007a; Horne and Dabdub, 2017).  $\text{SO}_4^{2-}$  is found to increase with  $T$  increase in those studies because of faster gas- and aqueous-phase reactions of  $\text{SO}_4^{2-}$ . However, our finding of  $\text{SO}_4^{2-}$  in China is the opposite. The CMAQ-Sulfur Tracking Model (CMAQ-STM) was further used to track the  $\text{SO}_4^{2-}$  formation from different processes. The results confirm that the  $\text{SO}_4^{2-}$  production from the gas and aqueous phases increases with  $T$  increase, but meanwhile  $\text{SO}_4^{2-}$  production from heterogeneous reactions is reduced more when  $T$  is increased. Heterogeneous  $\text{SO}_4^{2-}$  formation has been proposed as a major  $\text{SO}_4^{2-}$  formation pathway during China haze events (Gen et al., 2019; Huang et al., 2019; Li et al., 2019a; Wang et al., 2014b), and in this study it accounts for up to  $\sim 75\%$  of total  $\text{SO}_4^{2-}$  production. The treatment of heterogeneous  $\text{SO}_4^{2-}$  formation currently is modeled as a surface-controlled uptake process in which the formation rate is determined by the aerosol surface area and the uptake coefficient of  $\text{SO}_2$  on the particle surface (Ying et al., 2014). When  $T$  is increased, the particle surface area decreases (as particle mass concentration decreases due to a combined effect of other compo-

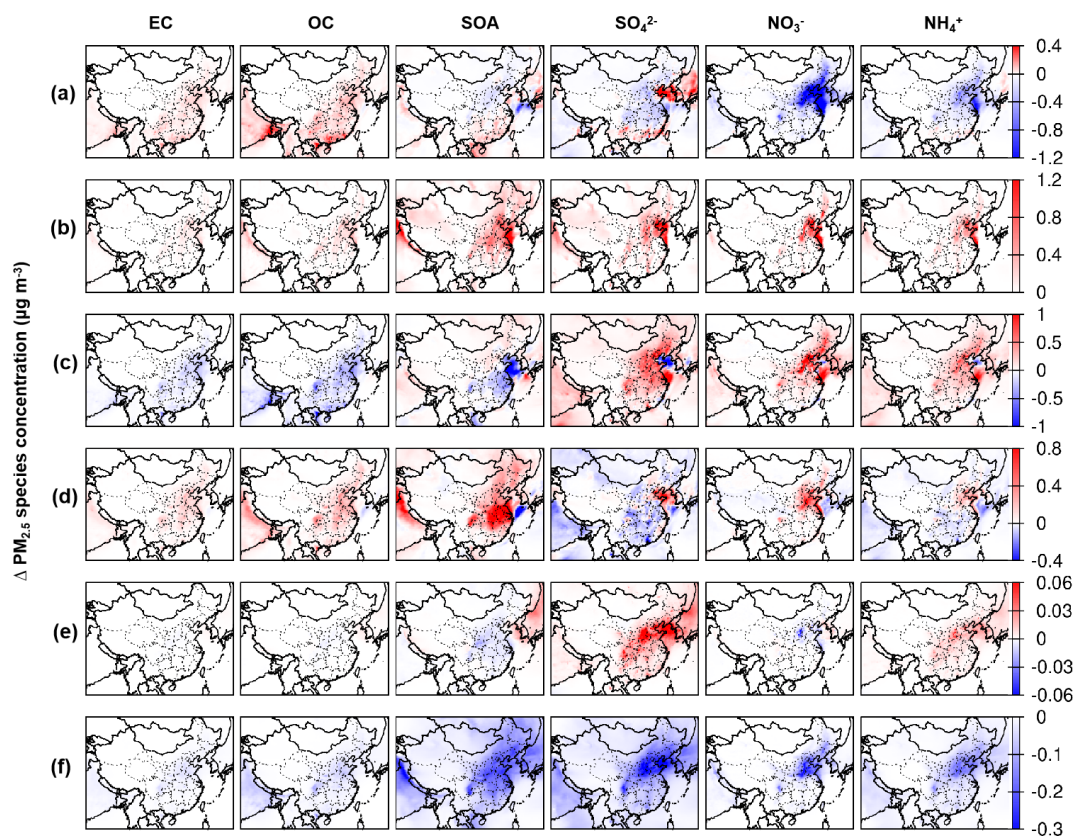
nents), resulting in a decrease in the heterogeneous  $\text{SO}_4^{2-}$  formation.

An additional simulation was run to illustrate the combined effects of perturbations in all meteorological parameters ( $T + 1.0\text{ K}$ ,  $WS - 10\%$ ,  $AH + 10\%$ ,  $PBLH - 20\%$ ,  $CLW + 10\%$ , and  $PCP + 10\%$ ) on O<sub>3</sub> and PM<sub>2.5</sub> in January and July. The results are shown in Fig. S8. The average O<sub>3</sub>-8 h concentration in this combined-change simulation dropped by  $\sim 2$  ppb in January, except in the northeast. In July, O<sub>3</sub> in East China and the Sichuan basin rose by 2 ppb. The changes in PM<sub>2.5</sub> resulting from this combined-change simulation were significantly higher compared to the base-case concentrations and even increased by up to  $50\ \mu\text{g m}^{-3}$  in January.

### 3.3 Quantitative sensitivity of O<sub>3</sub> and PM<sub>2.5</sub> to individual meteorology parameters

The quantitative sensitivity of O<sub>3</sub> and PM<sub>2.5</sub> concentrations to individual meteorological parameters is calculated by linear fitting of the changes in monthly average concentrations under all of the six perturbed cases of the meteorological parameter. Figures S10–S12 in the Supplement show the calculation examples of  $T$ ,  $WS$ , and  $AH$  on O<sub>3</sub> at the five ma-





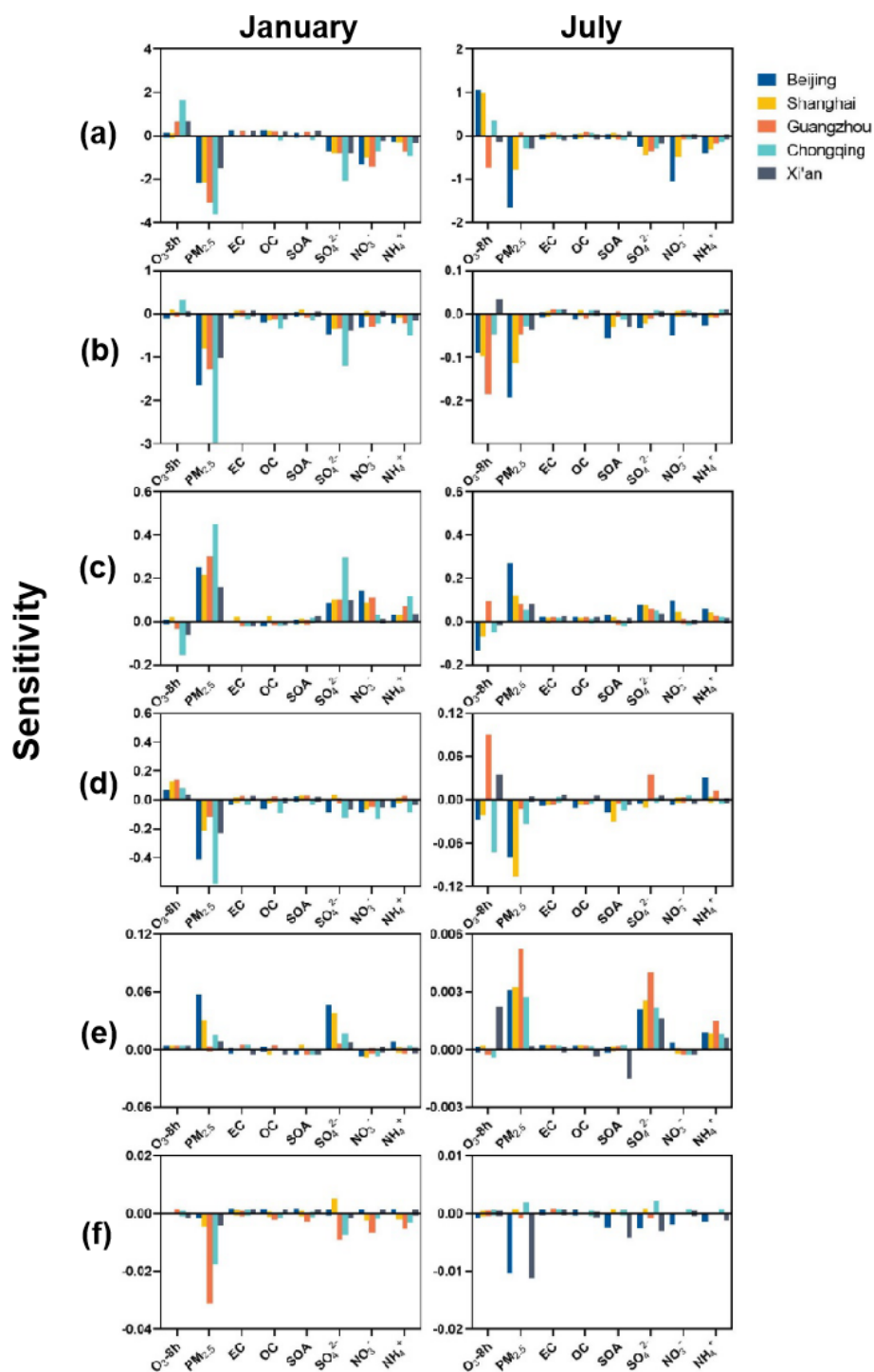
**Figure 6.** Changes in monthly average PM<sub>2.5</sub> component concentration ( $\mu\text{g m}^{-3}$ ) in July due to (a)  $T + 1.0\text{ K}$ , (b)  $WS - 10\%$ , (c)  $AH + 10\%$ , (d)  $PBLH - 20\%$ , (e)  $CLW + 10\%$ , and (f)  $PCP + 10\%$ .

for cities of Beijing, Chongqing, Guangzhou, Shanghai and Xi'an, and Figs. S13–S15 show the examples for the PM<sub>2.5</sub> cases. Figure 7 demonstrates the sensitivities of O<sub>3</sub>-8 h and PM<sub>2.5</sub> and its components to each meteorological parameter in the five cities. In January,  $T$  has a positive impact on O<sub>3</sub> in all cities, and the largest impact is in Chongqing with a rate of  $+1.69\text{ ppb K}^{-1}$ . In July, O<sub>3</sub> also shows a strong positive sensitivity to  $T$  in Beijing with  $+1.06$  and in Shanghai with  $+0.98\text{ ppb K}^{-1}$  but has a small negative sensitivity ( $-0.15\text{ ppb K}^{-1}$ ) in Xi'an and a moderate negative sensitivity ( $-0.74\text{ ppb K}^{-1}$ ) in Guangzhou. The O<sub>3</sub> sensitivity to  $T$  in Guangzhou in July shows a highly nonlinear trend and is very different from other cities (Fig. S10c). More studies are needed to investigate the effects of  $T$  on O<sub>3</sub> pollution in the YRD region during summertime. WS and PBLH both have positive effects on O<sub>3</sub>-8 h in January: the effects vary significantly among cities, with  $0.004\text{ ppb \%}^{-1}$ – $0.3\text{ ppb \%}^{-1}$  for WS and  $0.04\text{ ppb \%}^{-1}$ – $0.14\text{ ppb \%}^{-1}$  for PBLH. AH has a negative effect on O<sub>3</sub>-8 h in January, ranging from  $-0.01\text{ ppb \%}^{-1}$  to  $-0.15\text{ ppb \%}^{-1}$ , but in July, the impacts of WS, AH, and PBLH are negative in most cities, with ranges of  $-0.05\text{ ppb \%}^{-1}$  to  $-0.18\text{ ppb \%}^{-1}$ ,  $-0.05\text{ ppb \%}^{-1}$  to  $-0.13\text{ ppb \%}^{-1}$ , and  $-0.02\text{ ppb \%}^{-1}$  to  $-0.07\text{ ppb \%}^{-1}$ , respectively. Generally speaking,  $T$ , WS, AH, and PBLH led

to rather larger O<sub>3</sub> changes. The sensitivity of O<sub>3</sub> to CLW and PCP is even minimal (less than  $0.1\text{ ppb \%}^{-1}$ ) and mostly negative.

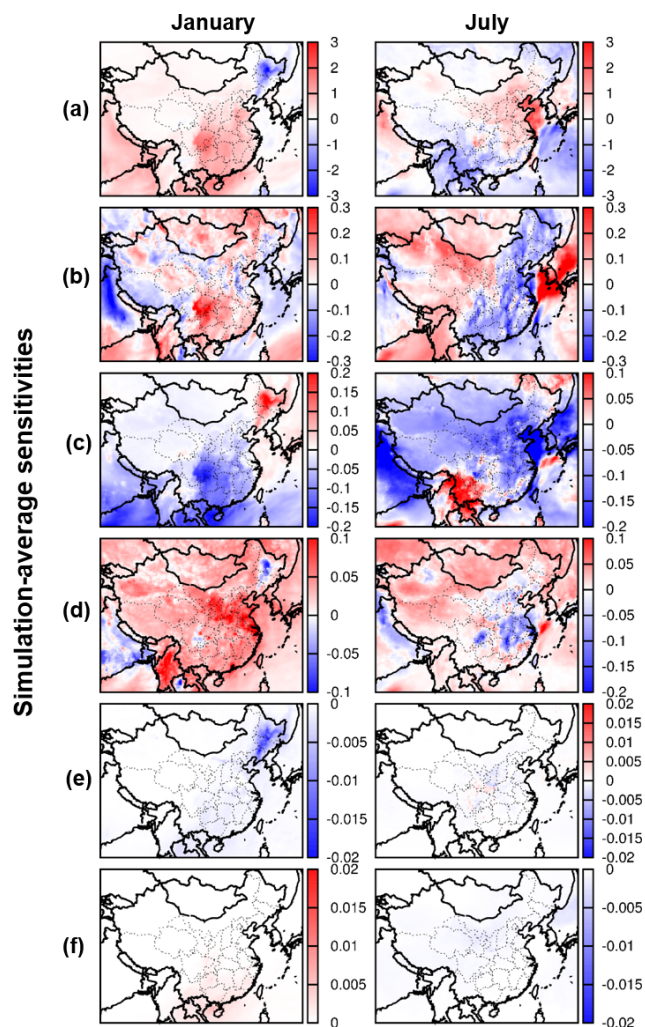
Negative sensitivities are found for surface PM<sub>2.5</sub> concentrations to  $T$ , WS, PBLH, and PCP and positive sensitivities for PM<sub>2.5</sub> to AH and CLW. The sensitivity of  $T$  in the five cities ranges from  $-1.5$  to  $-3.6\text{ }\mu\text{g m}^{-3}\text{ K}^{-1}$  in January and  $-0.3$  to  $-1.65\text{ }\mu\text{g m}^{-3}\text{ K}^{-1}$  in July. PM<sub>2.5</sub> is also very sensitive to WS in January, with a range of  $-0.8\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$  to  $-2.97\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$ , while the sensitivity ( $-0.03\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$  to  $-0.19\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$ ) becomes much smaller in July. The sensitivity to PBLH is  $-0.12\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$  to  $-0.58\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$  in January and  $-0.003\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$  to  $-0.23\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$  in July. The sensitivity to AH is  $0.16\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$  to  $0.30\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$  in January and  $0.05\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$  to  $0.27\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$  in July. Sensitivity to CLW and PCP is small in January and July, mostly less than  $0.01\text{ }\mu\text{g m}^{-3}\text{ \%}^{-1}$ . The PM<sub>2.5</sub> sensitivities can be explained by the major components of SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, and NH<sub>4</sub><sup>+</sup> in January and by SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>, and SOA in July.

Figure 8 shows the spatial variations of the sensitivity of O<sub>3</sub>-8 h and PM<sub>2.5</sub> to the meteorological parameters. The sensitivity of O<sub>3</sub>-8 h to temperature is more significant in



**Figure 7.** Sensitivity of O<sub>3</sub>-8 h, PM<sub>2.5</sub>, and its components to the meteorological parameter of (a) *T*, (b) WS, (c) AH, (d) PBLH, (e) CLW, and (f) PCP in five cities in China. The unit of sensitivity is ppb K<sup>-1</sup> for O<sub>3</sub>-8 h to *T* and is ppb %<sup>-1</sup> for O<sub>3</sub>-8 h to other meteorological parameters; the unit is μg m<sup>-3</sup> K<sup>-1</sup> for PM<sub>2.5</sub> and its components to *T* and is μg m<sup>-3</sup> %<sup>-1</sup> for PM<sub>2.5</sub> and its components to other meteorological parameters.

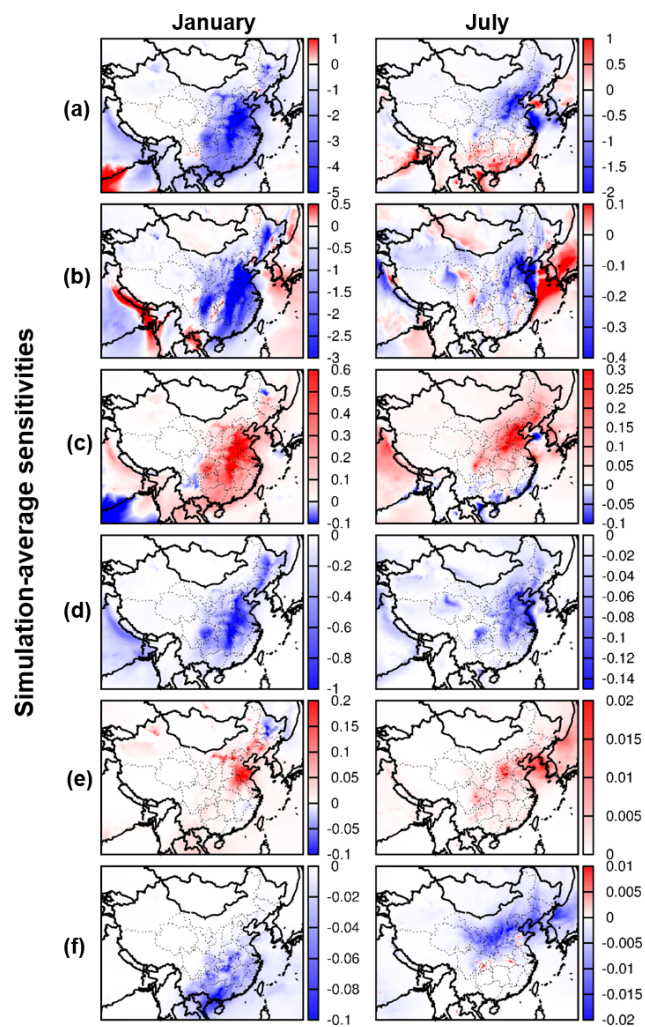




**Figure 8.** Sensitivity of the O<sub>3</sub>-8 h mean to meteorological perturbations (a) *T*, (b) WS, (c) AH, (d) PBLH, (e) CLW, and (f) PCP in China. The value in *T* is measured in ppb K<sup>-1</sup> and others in ppb %<sup>-1</sup>.

Sichuan and southern provinces of China in January, and, in the NCP and YRD in July, up to +2 ppb K<sup>-1</sup> in both January and July. O<sub>3</sub>-8 h sensitivity to WS is diverse in space and is generally positive in Sichuan and southern provinces in January, and it is negative in East China but positive in West China. O<sub>3</sub>-8 h sensitivity to AH is generally negative in both months in most regions of China, except the northeast in January and southwest in July. O<sub>3</sub>-8 h sensitivity to PBLH is mostly positive in January but becomes negative in the YRD, CYB, and NCP and Central China in July. O<sub>3</sub>-8 h sensitivity to CLW and PCP is negligible.

Figure 9 displays the spatial variations of the sensitivity of surface PM<sub>2.5</sub> to the meteorological parameters. PM<sub>2.5</sub> sensitivities to the meteorological parameters are more consistent in January and July than the cases of O<sub>3</sub>, i.e., negative sensitivity to *T*, WS, PBLH, and PCP and positive to AH



**Figure 9.** Sensitivity of the PM<sub>2.5</sub> mean to meteorological perturbations (a) *T*, (b) WS, (c) AH, (d) PBLH, (e) CLW, and (f) PCP in China. The value in *T* is measured in μg m<sup>-3</sup> K<sup>-1</sup> and others in μg m<sup>-3</sup> %<sup>-1</sup>.

and CLW in most regions of China in both months. On the other hand, PM<sub>2.5</sub> sensitivities are more profound in January than in July. PM<sub>2.5</sub> sensitivity to *T* is up to -5 μg m<sup>-3</sup> K<sup>-1</sup> in January and up to -2 μg m<sup>-3</sup> K<sup>-1</sup> in July. PM<sub>2.5</sub> sensitivity to WS is up to -3 μg m<sup>-3</sup> %<sup>-1</sup> in January and up to -0.4 μg m<sup>-3</sup> %<sup>-1</sup> in July. PM<sub>2.5</sub> sensitivity to PBLH is up to -1 μg m<sup>-3</sup> %<sup>-1</sup> in January and up to -0.14 μg m<sup>-3</sup> %<sup>-1</sup> in July. PM<sub>2.5</sub> sensitivity to AH is up to +0.6 μg m<sup>-3</sup> %<sup>-1</sup> in January and up to 0.3 μg m<sup>-3</sup> %<sup>-1</sup> in July. The sensitivities to CLW and PCP are small compared to the other four meteorological parameters. PM<sub>2.5</sub> sensitivity to *T* is negative in most land areas of China in January and in the NCP and YRD in July because of the negative effects of *T* on SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, and NH<sub>4</sub><sup>+</sup>, as discussed in previous sections. PM<sub>2.5</sub> sensitivity to *T* is positive in South China in July due to more SOA with higher *T*.

#### 4 Conclusions

Meteorological conditions can have a great influence on surface O<sub>3</sub> and PM<sub>2.5</sub> concentrations. In this study, the sensitivities of O<sub>3</sub>-8 h and PM<sub>2.5</sub> to *T*, WS, AH, PBLH, PCP, and CLW are quantitatively estimated in January and July, respectively, in China. The response of O<sub>3</sub>-8 h to *T* is important and the sensitivity can be up to +2 ppb K<sup>-1</sup> in both January and July, and the sensitivity is dependent on the O<sub>3</sub> chemistry formation or loss regime, i.e., positive in the net O<sub>3</sub> formation areas and negative in the O<sub>3</sub> consumption areas. In general, PM<sub>2.5</sub> sensitivities are negative to *T*, WS, PBLH, and PCP and positive to AH and CLW in most regions of China in both January and July. The sensitivities in January are much larger than in July. PM<sub>2.5</sub> sensitivities to *T*, WS, AH, and PBLH are important. The PM<sub>2.5</sub> sensitivities to these meteorological parameters are through major effects on SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>, and SOA. The sensitivities of O<sub>3</sub> and PM<sub>2.5</sub> to CLW and PCP are negligible. The results show that O<sub>3</sub> and PM<sub>2.5</sub> concentrations in China are greatly affected by meteorological conditions; therefore, changes in these meteorological parameters due to climate change or inter-annual meteorological variations could potentially alter O<sub>3</sub> and PM<sub>2.5</sub> concentrations significantly, and it should consider these effects when developing emission control strategies. The results also show that the O<sub>3</sub> and PM<sub>2.5</sub> sensitivities to meteorological parameters have substantial spatial variations. Future studies can further investigate how the changes in meteorological conditions affect the effectiveness of emission control plans in reaching the designed air quality objectives in the different regions of China.

*Data availability.* All of the modeling results will be available online after we publish the paper. The data used in this paper can be provided upon request from the corresponding author: Jianlin Hu (jianlinhu@nuist.edu.cn).

*Supplement.* The supplement related to this article is available online at: <https://doi.org/10.5194/acp-20-13455-2020-supplement>.

*Author contributions.* ZS and JH designed the research. ZS, LH, JL, QY, HZ, and JH contributed to model development and configuration. ZS, LH, JL, and JH analyzed the data. ZS prepared the manuscript and all the coauthors helped improve the manuscript.

*Competing interests.* The authors declare that they have no conflict of interest.

*Acknowledgements.* This work has been supported by the National Key R&D Program of China (2016YFC0203500 and 2018YFC0213800), the National Natural Science Foundation of China (41975162, 41675125 and 41705102), and the Jiangsu Environmental Protection Research Project (2016015).

*Financial support.* This research has been supported by the National Key R&D Program of China (grant no. 2016YFC0203500, and 2018YFC0213800), the National Natural Science Foundation of China (grant nos. 41975162, 41675125, and 41705102), and the Jiangsu Environmental Protection Research Project (grant no. 2016015).

*Review statement.* This paper was edited by Jianping Huang and reviewed by two anonymous referees.

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