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Response of fine particulate matter to reductions in anthropogenic emissions in Beijing during the 2014 Asia–Pacific Economic Cooperation summit

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ABSTRACT

The nested-grid capability of the global chemical transport model GEOS-Chem, with a horizontal resolution of 1/4° × 5/16° (latitude × longitude), was used to identify the chemical species whose reductions made the largest contributions to decreases in $PM_{2.5}$ concentrations (fine particulate matter; diameter ≤ 2.5 μm; defined in this study as the sum of sulfate, nitrate, ammonium, black carbon, and organic carbon aerosols) in Beijing during the 2014 Asia–Pacific Economic Cooperation (APEC) summit. A number of numerical experiments were carried out for the period 15 October–29 November 2014. The model reproduced the observed daily variations of concentrations of $PM_{2.5}$ and gas-phase species (carbon monoxide, nitrogen dioxide, and sulfur dioxide). Simulated $PM_{2.5}$ concentrations decreased by 55.9%–58.5% during the APEC period, compared to other periods in October and November 2014, which agreed closely with measurements. Sensitivity results showed that emissions control measures regarding nitrogen oxides and organic carbon over North China led to the largest reductions in $PM_{2.5}$ concentrations in Beijing during the APEC summit, which led to overall reductions in the $PM_{2.5}$ concentration of Beijing by 5.7% and 4.6%, respectively. The control of ammonia emissions was found to be able to greatly reduce $PM_{2.5}$ concentrations in the whole of North China during the APEC meeting.

摘要

研究使用全球大气化学传输模式GEOS-Chem高分辨率（1/4° × 5/16°）区域嵌套版本评估2014年亚洲-太平洋经济合作峰会（APEC）期间不同地区不同污染物减排对北京地区$PM_{2.5}$（粒径小于2.5 μm的气溶胶颗粒，本文中定义为硫酸盐、硝酸银、铵盐、一次有机碳和黑碳气溶胶浓度之和）浓度降低的不同影响。在2014年10月15日至11月29日期间，模拟结果表明：模式可以重现观测结果中$PM_{2.5}$及主要气态污染物（一氧化碳、二氧化氮和二氧化硫）浓度的日变化趋势。在APEC期间，模拟$PM_{2.5}$浓度相比会议前期和会议后期下降55.9%–58.5%，与观测结果具有较好的一致性。敏感性实验结果表明：APEC期间华北地区氮氧化物和一次有机碳的减排对于北京地区$PM_{2.5}$浓度的降低影响最为显著，相应减排措施致使北京地区$PM_{2.5}$浓度分别下降5.7%和4.6%。同时，对氨气排放的控制可以有效地降低整个华北地区在APEC期间的$PM_{2.5}$浓度。

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关键词
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1. Introduction

High $PM_{2.5}$ concentrations (fine particulate matter; diameter ≤ 2.5 μm) in China have garnered considerable attention because of their role in the deterioration of air quality and harm to human health (Pui, Chen, and Zuo 2014). Observed wintertime $PM_{2.5}$ concentrations can exceed 500 μg m^{-3} on heavily polluted days in Beijing (Wang et al. 2014), which makes it essential to reduce emissions to improve air quality in North China. Emissions reduction measures have proved to be effective in improving air quality in Beijing and its surrounding regions (Wang et al. 2009; Gao et al. 2011). During the 22nd Asia–Pacific Economic Cooperation (APEC) summit, which was hosted in Beijing (5–11 November 2014), tough emissions reduction measures were implemented for the city and its surrounding provinces. The measures resulted in reductions in emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), PM_{10}, $PM_{2.5}$, and non-methane volatile organic compounds (NMVOCs) by 39.2%, 49.6%, 66.6%, 61.6%, and 33.6%, respectively, according to the air quality evaluation report

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of the APEC period released by the Chinese Environmental Protection Administration (CNEPA) (http://www.mep.gov.cn/zhxx/hjyw/201412/t20141218_293140.htm). The summit provided an experimental opportunity to study the impact of emissions reduction measures on the air quality in Beijing and surrounding provinces.

Modeling studies of $PM_{2.5}$ sensitivities to the emissions control measures during the APEC period have been reported in the literature (Liu et al. 2015; Zhai et al. 2016). For example, by using the Nested Air Quality Prediction Model System, Liu et al. (2015) showed that the $PM_{2.5}$ concentrations in Beijing would have increased by 15–30 μg m^{-3} (40%–60%) if no emissions control measures were conducted during the APEC period. Although previous studies provide valuable knowledge regarding the effectiveness of the emissions reduction measures over North China, there is still room for further studies. $PM_{2.5}$ has been proved to change nonlinearly in response to its precursors (Ansari and Pandis 1998; West, Ansari, and Pandis 1999; Holt, Selin, and Solomon 2015), and the control of different precursor emissions in different regions may result in different efficiencies in reducing $PM_{2.5}$ concentrations. For example, NO_x emissions are generally considered to be important for nitrate formation, but nitrate concentrations could be more sensitive to ammonia (NH_3) emissions under NH_3-poor conditions when NH_3 is insufficient to neutralize nitric acid (Wang et al. 2011). Therefore, it is important to quantify the sensitivities of $PM_{2.5}$ to the changes in emissions of different species in different regions over North China.

The goal of this work was to identify the chemical species whose reductions made the largest contributions to the decreases in $PM_{2.5}$ concentrations during the APEC period in Beijing. The observational data, GEOS-Chem model, and numerical experiments are described in Section 2. Section 3 presents the model evaluation, as well as the results from sensitivity simulations. Section 4 summarizes the major conclusions of this study.

2. Data and methods

2.1. GEOS-Chem model

We simulated aerosol concentrations using a nested-grid capability of the global chemical transport model GEOS-Chem (version 9-02; http://geos-chem.org) driven by the GEOS-FP assimilated meteorological fields from the Goddard Earth Observing System of the NASA Global Modeling and Assimilation Office. The model has a horizontal resolution of 1/4° × 5/16° (latitude × longitude) for the East Asia domain (15–55°N, 70–140°E) and 47 vertical layers extending from the surface to 0.01 hPa. The chemical boundary conditions were provided by a global GEOS-Chem simulation at 4° × 5° (latitude × longitude) horizontal resolution and updated in the nested-grid region every 3 h (Chen et al. 2009; Kim et al. 2015).

GEOS-Chem has a fully coupled treatment of tropospheric NO_x–carbon monoxide (CO)–hydrocarbon-ozone chemistry and aerosols including sulfate (SO_4^{2-}), nitrite (NO_3^-), ammonium (NH_4^+), organic carbon (OC), black carbon (BC) (Park et al. 2003, 2004; Pye et al. 2009), mineral dust (Fairlie, Jacob, and Park 2007), and sea salt (Jaeglé et al. 2011). Convective transport in GEOS-Chem mimics that in the parent GEOS general circulation model (Hack 1994; Zhang and McFarlane 1995), accounting for updraft, downdraft, and entrainment mass fluxes archived separately for deep and shallow convection (Wu et al. 2007). The aerosol wet deposition scheme follows that of Liu et al. (2001). For the scavenging of aerosols, SO_4^{2-}, NH_4^+, nitrate, and hydrophilic OC and BC, aerosols are assumed to be fully soluble. Dry deposition follows the standard resistance-in-series model of Wesely (1989).

2.2. Emissions

Global emissions of aerosols and their precursors in GEOS-Chem follow Park et al. (2003, 2004), with anthropogenic emissions in East Asia overwritten by the MIX Asian anthropogenic emissions inventory for the year 2010 (http://www.meicmodel.org/data-set-mix.html) developed by Li et al. (2015). The diurnal variation of NH_3 emission is applied in the model following Zhu et al. (2013). Anthropogenic emissions of SO_2, NO_x, CO, NH_3, BC, and OC are, respectively, 28.6, 29.1, 170.9, 9.8, 1.8, and 3.4 Tg yr^{-1} in China; and 0.15, 0.33, 1.92, 0.07, 0.02, and 0.03 Tg yr^{-1} in Beijing. We defined three regions for the emissions control tests: the North China domain (NC, (31.5–43.0°N, 110.0–123.1°E)), Beijing (BJ, (39.5–41.2°N, 115.6–117.5°E)), and the North China domain excluding Beijing (NC-B).

2.3. Numerical experiments

To identify the chemical species whose reductions in emissions made the largest contribution to the decrease in $PM_{2.5}$ concentrations during the APEC period in Beijing, we performed the following numerical experiments:

(1) NoCTRL: Simulation for the period 15 October–29 November 2014, with default emissions in the model.
(2) CTRL: As in NoCTRL except that, during the APEC summit (3–12 November 2014), emissions of SO_2, NO_x (NO_x = NO + NO_2), CO, BC, OC, and NMVOCs were reduced, respectively, by 39.2%, 49.6%, 30.0%, 30%, 30%, and 33.6% in Beijing, and by 30% in NC-B, according to the air quality evaluation report of the APEC period released by CNEPA.

(3) CTRL_NC, CTRL_NC-B, and CTRL_BJ, for each of species of SO_2, NO_x, OC, and BC: As in NoCTRL except that, during the APEC summit (3–12 November 2014), the emissions control was applied in NC, NC-B, and BJ, respectively. The rates of reduction of a single species in BJ and NC-B were the same as those in (2). For example, for the case of SO_2 reduction, CTRL_NC, CTRL_NC-B, and CTRL_BJ indicate that SO_2 emissions control was conducted in NC, NC-B, and BJ, respectively, during 3–12 November 2014, with a 39.2% reduction in SO_2 in Beijing and a 30% reduction in SO_2 in NC-B.

(4) CTRL_NC, CTRL_NC-B, and CTRL_BJ for NH_3: As in NoCTRL except that, during the APEC summit (3–12 November 2014), the emissions control of NH_3 was carried out in NC, NC-B, and BJ, respectively. The same rate of reduction of 30% was assumed for NC, NC-B, and BJ.

We performed a two-month spin-up run to generate the initial conditions. All the simulations used the same initial and lateral boundary conditions for meteorological variables and concentrations of gas-phase species and aerosols.

2.4. Observational data

The observations used included meteorological parameters and concentrations of $PM_{2.5}$, SO_2, NO_2, and CO. The hourly meteorological measurements were obtained from the NCDC of NOAA (http://gis.ncdc.noaa.gov/map/viewer/#app=cdo). The measurements of meteorological fields in Beijing were carried out at the site of Beijing Capital International Airport (40.080°N, 116.585°E), with hourly data from 31 October 1945 to the present day. The ground-based observations of gases and aerosols were obtained from the China National Environmental Monitoring Center during 15 October–29 November 2014 (http://106.37.208.233:20035/). There are eight monitoring sites in Beijing and, here, we averaged the hourly measurements of all sites to obtain the daily concentrations of $PM_{2.5}$, SO_2, NO_2, and CO in Beijing, which were used to evaluate the daily model results.

3. Results

3.1. Comparisons between the GEOS-FP meteorological fields and measurements

Since $PM_{2.5}$ concentrations can be greatly influenced by metrological factors (Gao et al. 2011), we compared the GEOS-FP meteorological parameters used in the model with measurements for RH, SLP, 10-m temperature, and 10-m wind speed and direction, in Beijing, during 15 October–29 November 2014 (Figure 1), as an essential part of model evaluation. Because the GEOS-FP data were available with a temporal resolution of 3 h, the hourly measurements from the NCDC were averaged over the 3 h for comparison. During the APEC period (3–12 November 2014), the wind direction changed frequently and RH was relatively low, with a mean value of 47.3%. As discussed in Liu et al. (2015), such a meteorological condition in Beijing during the APEC period was relatively conducive for the diffusion of air pollutants. For all five of the meteorological parameters shown in Figure 1, the correlation coefficients (R) between the GEOS-FP meteorological data and measurements were in the range of 0.44–0.97 ($p = 0.01$). At the Beijing Capital International Airport site, the normalized mean bias,

$$\mathrm{NMB} = \frac{\sum_{i=1}^{n}(A_i - O_i)}{\sum_{i=1}^{n} O_i} \times 100\%,$$

where A_i and O_i are the assimilated GEOS-FP meteorological fields and NCDC observations at time i for each parameter, respectively, was −12.7%, −0.1%, −42.0%, +48.1% and +32.0% for RH, SLP, temperature, wind speed, and wind direction, respectively, indicating that the GEOS-FP meteorological fields agreed reasonably well with observations.

3.2. Concentrations of aerosols and gas-phase species during the APEC summit

Figure 2 compares the daily concentrations from the CTRL and NoCTRL simulations with ground-based measurements in Beijing for $PM_{2.5}$, CO, NO_2, and SO_2 concentrations at Beijing during 15 October–29 November 2014. The daily concentrations of $PM_{2.5}$, CO, and NO_2 were underestimated, and the daily concentrations of SO_2 were overestimated (Figure 2). There are several reasons for the model biases in Beijing. First, the characteristics of local emissions might not have been captured well by the emissions inventories. Chen et al. (2016) indicated that the emissions inventory underestimated the emissions of NO_x and CO, but overestimated SO_2 emissions, during October 2014, based on a WRF model coupled with online chemistry (WRF-Chem) simulation. With the boundary layer heights and winds reasonably simulated, they reported that the peak concentrations of CO and NO_2 on polluted days were underestimated by 50%–70%. Though WRF-Chem has different chemical schemes to GEOS-Chem, similar biases in simulated concentrations of CO and NO_2 in Beijing can be obtained with a similar emissions inventory. It is likely that the emissions inventory might not have captured the high CO and NO_2 emissions in October in Beijing. With the concentrations of all the other pollutants underestimated, model results (both

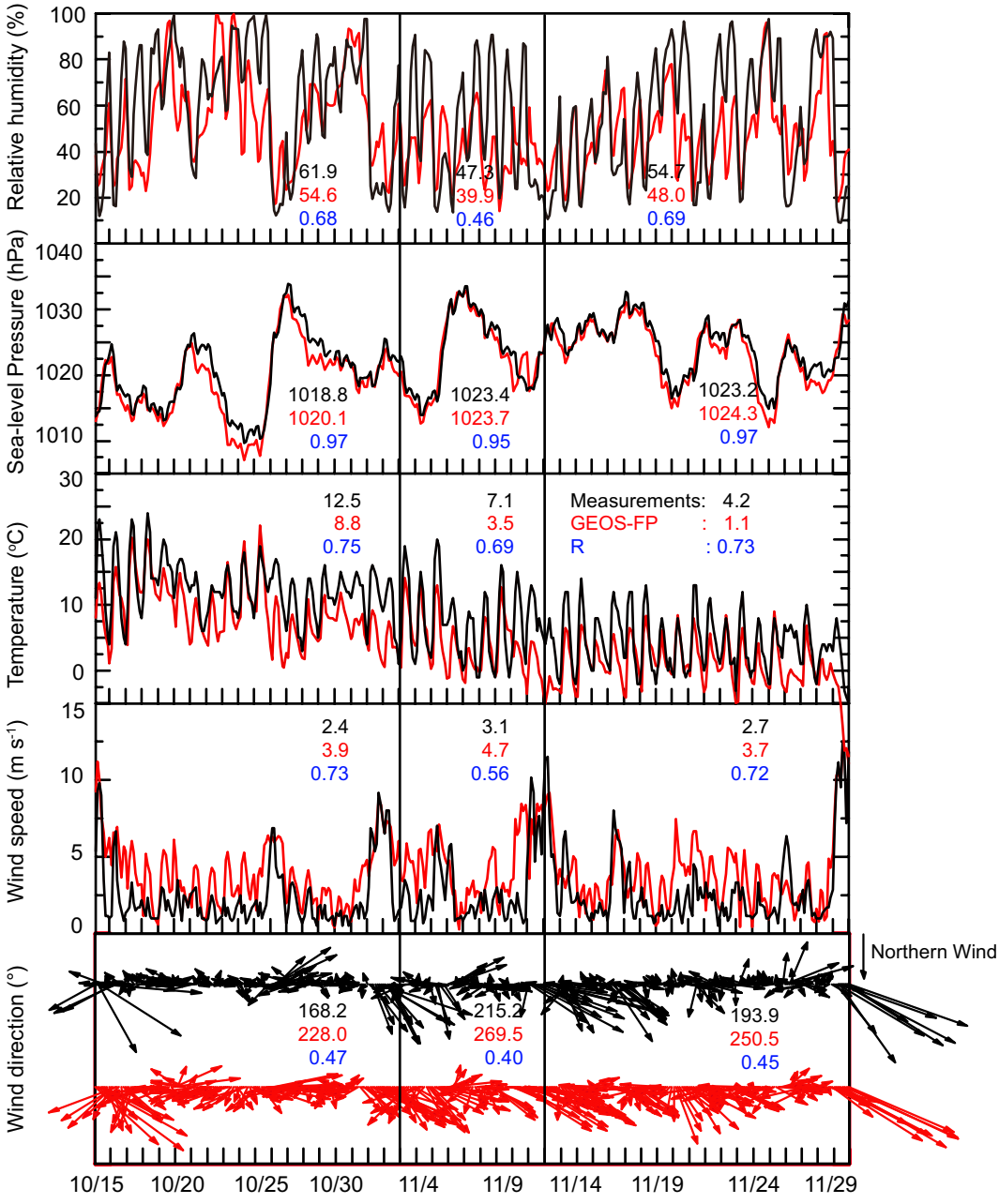

Figure 1. Comparison of measured (black) and GEOS-FP (red) 3-h RH, SLP, 10-m temperature, 10-m wind speed, and wind direction, in Beijing, during 15 October–29 November 2014. The area between the two central black lines represents the APEC time period (3–12 November). Mean values before, during, and after the APEC summit, and the corresponding correlation coefficients (*R*) between the GEOS-FP meteorological data and measurements, are also shown.

in Chen et al. (2016) and this study) show a severe overestimation of SO_2 concentrations in Beijing. The simulated SO_2 concentrations in other cities over NC were in the range of 30–70 μg m^{-3}, showing much smaller model positive biases than those in Beijing, and indicating that SO_2 emissions might have been overestimated in Beijing, as new regulations have been applied in recent years. Secondly, we used the anthropogenic emissions for the year 2010, whereas the observed concentrations were taken in 2014, which likely had a considerable impact on the simulated SO_2 concentrations. As a result of China's 'Twelfth Five-Year' Plan for National Economic and Social Development (FYP, 2011–2015), national emissions of SO_2 were estimated to have decreased by 12.9% within 2010–2014, due to the wide implementation of flue gas desulfurization systems at thermal power units in China (http://www.mep.gov.cn/gkml/hbb/qt/201507/t20150722_307020.htm). Additionally, the model may have missed some chemical mechanisms or oxidants that oxidize SO_2 to SO_4^{2-} (Wang et al. 2014), which requires further study.

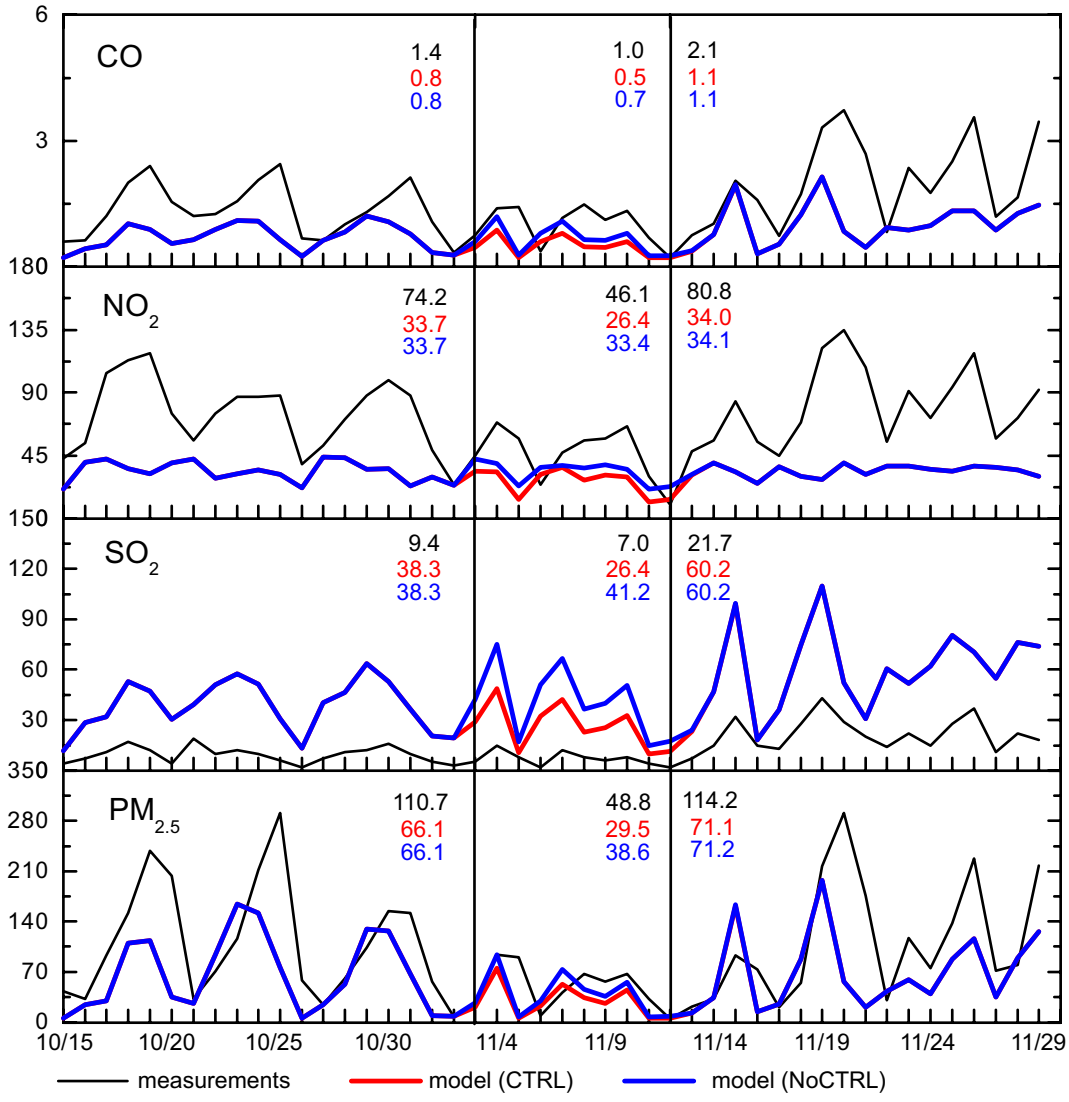

Figure 2. Comparison of the measured (black) and GEOS-Chem simulated (CTRL: red; NoCTRL: blue) daily surface $PM_{2.5}$, CO, NO_2, and SO_2 concentrations, in Beijing, during 15 October–29 November 2014. The area between the two central black lines represents the APEC time period (3–12 November). The inset numbers are the mean concentrations averaged before, during, and after the APEC summit. Units are mg m^{-3} for CO and μg m^{-3} for the other panels.

During 15 October–29 November 2014, the correlation coefficients between the simulated concentrations from CTRL and observations of $PM_{2.5}$, CO, NO_2, and SO_2 were 0.58, 0.63, 0.44, and 0.83 ($p = 0.01$), respectively, indicating the model successfully captured the daily variations of each species in Beijing, despite the biases in concentrations. The simulation time period in Figure 2 can be classified as: before the APEC period (BAP, 15 October to 2 November); during the APEC period (AP, 3–12 November); and after the APEC period (AAP, 13–29 November). Averaged over the different time periods, the observed $PM_{2.5}$ concentration in Beijing was 48.8 μg m^{-3} in AP, which was 55.9% lower than the value of 110.68 μg m^{-3} in BAP and 57.3% lower than the value of 114.18 μg m^{-3} in AAP. The reduction of $PM_{2.5}$ in Beijing in AP was reproduced by GEOS-Chem; relative to the simulated concentrations in BAP and AAP, $PM_{2.5}$ concentrations in Beijing in AP in CTRL decreased by 57.4% and 58.5%, respectively. The concentrations of CO, NO_2, and SO_2 also showed reductions during AP, in both observations and the CTRL results (Figure 2).

The effects of the emissions control measures on $PM_{2.5}$ concentrations can be obtained by examining the differences in concentrations in AP between the CTRL and NoCTRL simulations. The simulated $PM_{2.5}$ concentration was 29.5 μg m^{-3} in AP in CTRL, which was 23.4% lower than the value of 38.6 μg m^{-3} in NoCTRL.

3.3. Sensitivity of the $PM_{2.5}$ concentration to emission controls of different species

Sensitivity simulations were performed to identify the chemical species whose reductions in emissions made

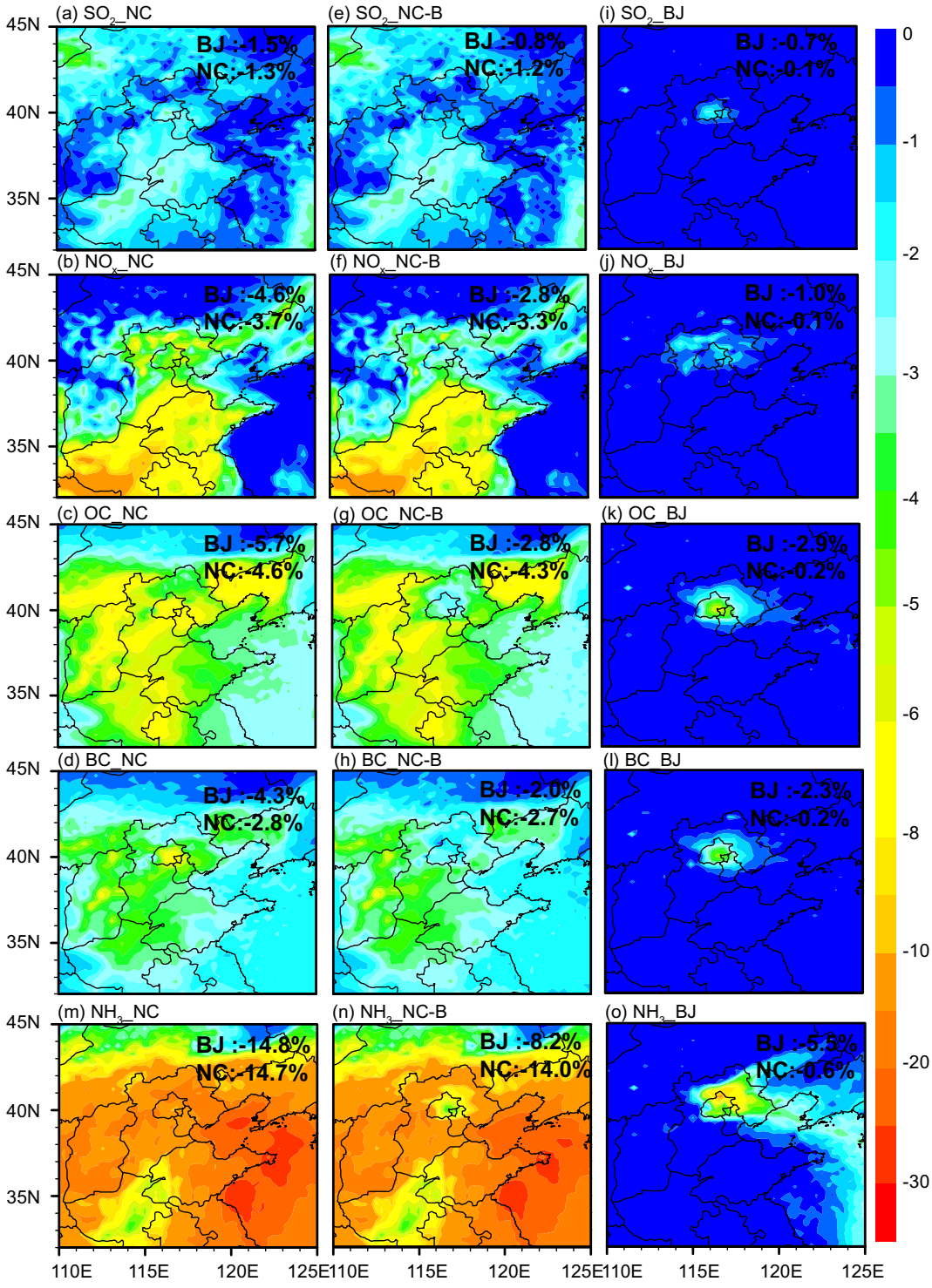

Figure 3. Distribution of the reduction rate of the $PM_{2.5}$ concentration averaged over the APEC summit period (3–12 November 2014) due to emissions reductions of (a, e, i) SO_2, (b, f, j) NO_x, (c, g, k) OC, (d, h, i) BC, and (m, n, o) NH_3, in NC, NC-B, and BJ, as described in Section 2.3. Units: %. The inset numbers are reductions in the $PM_{2.5}$ concentration averaged over BJ and NC for each scenario.

the largest contribution to the decrease in $PM_{2.5}$ concentrations during the APEC period in Beijing, as described in Section 2.3. Figure 3 shows the horizontal distributions of reductions in the $PM_{2.5}$ concentration averaged over AP, defined as

$$\left(\left[PM_{2.5}\right]_s - \left[PM_{2.5}\right]_{NoCTRL}\right) \times 100\% / \left[PM_{2.5}\right]_{NoCTRL},$$

where $[PM_{2.5}]_s$ and $[PM_{2.5}]_{NoCTRL}$ are the simulated $PM_{2.5}$ concentrations in the sensitivity case and the NoCTRL simulation, respectively.

Emissions of NO_x, SO_2, OC, and BC were decreased by tough emissions control measures in Beijing and surrounding areas during AP (Liu et al. 2015). When control measures were carried out for the whole of NC (Figure 3(a)–(d)), the controls of OC and NO_x led to the largest reductions in $PM_{2.5}$ concentrations in NC during AP. With emissions reductions of OC and NO_x in NC, the average $PM_{2.5}$ concentration decreased by, respectively, by 5.7% and 4.6% in Beijing, and by 4.6% and 3.7% in NC. The reductions in SO_2 emissions in NC resulted in only 1%–4% reductions in the $PM_{2.5}$ concentration in NC, indicative of the success of the control of SO_2 emissions in recent years (Zhao, Zhang, and Nielsen 2013). Based on observations during periods when humans use domestic heating (i.e. in winter) of 2013 and 2014, Yang et al. (2016) reported that the concentrations of nitrate and SO_4^{2-} were 9.89 and 4.90 μg m^{-3}, respectively, during 1–15 November 2014, and 23.08 and 16.68 μg m^{-3}, respectively, during 16–30 November 2014. The model results together with the observations suggest that the control of NO_x emissions was important for reducing $PM_{2.5}$ concentrations in NC.

For emissions control measures conducted in NC-B (Figure 3(e)–(h)), the reductions in NO_x and OC emissions resulted in the largest reductions (2.8%) in the $PM_{2.5}$ concentration in Beijing. With emissions control measures applied locally in Beijing (Figure 3(i)–(l)), the $PM_{2.5}$ concentration in Beijing was most sensitive to the control of OC. With OC and BC emissions reduced by 30% in Beijing, the average $PM_{2.5}$ concentration in Beijing during AP decreased by 2.9% and 2.3%, respectively, relative to the NoCTRL case. The reductions in the $PM_{2.5}$ concentration were within 2% in the cases of NO_x or SO_2 control. Since emissions of OC and BC derive mainly from the residential sector (Li et al. 2015), these results from the sensitivity experiments indicate that the control of local residential emissions is important for reducing the $PM_{2.5}$ concentration in Beijing. Overall, the decreases in the $PM_{2.5}$ concentration in Beijing during AP were most sensitive to reductions in NO_x and OC emissions in NC-B and the local reduction in emissions of carbonaceous aerosols.

We also conducted sensitivity experiments to examine the sensitivity of $PM_{2.5}$ concentrations to reductions in NH_3 emissions in the same regions (Figure 3(m)–(o)). With NH_3 emissions reduced by 30% in NC, the average $PM_{2.5}$ concentration in Beijing and NC decreased, respectively, by 14.8% and 14.7%, compared to the NoCTRL case, suggesting that $PM_{2.5}$ concentrations in Beijing and the surrounding provinces are all very sensitive to NH_3 emissions. As a result of the competing system of NH_4^+–nitrate–SO_4^{2-}, emissions reductions of SO_2 (NO_x) can reduce ammonium sulfate (nitrate) concentrations but increase ammonium nitrate (sulfate) concentrations in $PM_{2.5}$. With emission reductions of SO_2, NO_x, and NH_3 in NC, the NH_4^+ concentrations decreased by 2.8%, 6.0%, and 19.8%, respectively, in Beijing, indicating that the emissions control of NH_3 in NC is the most efficient in reducing NH_4^+ in $PM_{2.5}$. Since 90% of NH_3 emissions in China come from the agriculture (Li et al. 2015), NH_3 emissions can hardly be reduced with short-term emissions control measures. Therefore, it is essential to reduce NH_3 emissions from farmland and livestock wastes in the long term. Technologies, such as using polymer-coated urea products instead of the common use of nitrogen fertilizer, and optimizing feeding to avoid surplus protein in the animal diet, have been considered to be effective in reducing NH_3 emissions in western countries (Webb et al. 2008).

The results from the sensitivity simulations provide useful information on emissions reduction strategies in Beijing. In general, cooperating with surrounding provinces and cities could significantly improve the effectiveness of emissions control measures, compared to conducting control measures in Beijing alone. For short-term emissions control during wintertime, like in the APEC case, reducing local emissions of carbonaceous aerosols (OC and BC) and regional emissions of NO_x and OC is the most efficient approach in reducing $PM_{2.5}$ concentrations in Beijing. For long-term emissions control strategies, reducing NH_3 emissions from agricultural sources is an effective way to improve the air quality in Beijing. However, decreases in NH_3 emissions may result in enhancement of aerosol acidity, since SO_4^{2-} and nitrate may become insufficiently neutralized. Thus, NH_3 emissions should be carefully controlled in parallel with appropriate SO_2 and NO_x controls in NC.

4. Conclusion

This work used a nested-grid capability of the global chemical transport model GEOS-Chem to simulate gases and aerosols to identify the chemical species whose reductions made the largest contribution to the decrease in $PM_{2.5}$ concentrations during the APEC period in Beijing. A series of numerical experiments were conducted to investigate the sensitivity of surface $PM_{2.5}$ concentrations to the reductions in emissions of SO_2, NO_x, OC, BC, and NH_3, from specific regions.

Results showed that the model successfully captured the daily variations of $PM_{2.5}$, CO, NO_2, and SO_2 in Beijing, despite the biases in concentrations, with correlation coefficients ranging from 0.44 to 0.83. The discrepancies in peaks between the model results and observations may have arisen from uncertainties in the emissions inventory for local emissions, the mismatch of the emissions base year and model year, and the differences between actual meteorological conditions (such as wind speed) and those in the model. The concentrations of $PM_{2.5}$ showed similar reductions during AP in both observations and the model simulation. The observed and simulated $PM_{2.5}$ concentrations

during AP were, respectively, 55.9% and 57.4% lower than the values during BAP, and 57.3% and 58.5% lower than the values during AAP. By comparing simulations with and without emissions control measures, it was found that the emissions control measures led to a 23.4% reduction in the $PM_{2.5}$ concentration during the APEC period.

Considering the emissions control measures conducted during AP, the results from the sensitivity simulations showed that the control measures for NO_x and OC over NC led to the largest reductions in $PM_{2.5}$ concentrations in Beijing. Compared to the control of SO_2 and NO_x, the control of NH_3 emissions was found to be able to greatly reduce the NH_4^+ concentration in $PM_{2.5}$ in the whole of NC. To examine the effectiveness of emissions control measures of various species for the APEC case, we set the emission reduction rates for NO_x, SO_2, OC, and BC according to the air quality evaluation report of the APEC period released by CNEPA. We also conducted sensitivity tests with same reduction percentages (−30%) for all the species in BJ, NC-B, and NC, respectively. The model results of the two designs of sensitivity tests produced the same major conclusions as described above.

Finally, it is important to highlight that this study focused mainly on the emissions control of primary organic carbon. In fact, secondary organic aerosols were also significantly reduced in AP, due to the emissions control of NMVOCs (Sun et al. 2016). This aspect should be investigated in future studies.

Disclosure statement

No potential conflict of interest was reported by the authors.

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