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Simulation of the impact of the emergency control measures on the reduction of air pollutants: a case study of APEC blue

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Abstract Serious air pollution motivates governments to take control measures. However, specific emission reduction effects of various temporary emission reduction policies are difficult to evaluate. During the Asia-Pacific Economic Cooperation meeting in Beijing in 2014, the Chinese government implemented a number of emergency emission control measures in the Beijing-Tianjin-Hebei area to maintain the air quality in this region. This gave us an opportunity to quantify the effectiveness of the emission reduction measures separately and identify the efficient policy combinations for the reduction of major pollutants. In this study, we evaluated the impacts of specific emission reduction measures on the concentrations of two major air pollutants ($PM_{2.5}$ and O_3) under eight policy scenarios using the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem). Comparing these scenarios, we found that the control policies against the primary $PM_{2.5}$ emission achieved the most significant results. Meanwhile, all the emission control measures raised the ozone concentrations in different degrees, which might be partly attributed to the changes of $PM_{2.5}$ concentration and the ratio of NO_x and VOCs caused by the emission control measures. Our results suggest that, in VOC-sensitive areas like Beijing, emergency control measures focusing on primary $PM_{2.5}$ emission could lead to significant $PM_{2.5}$ reduction and relatively small ozone increase, and should be considered as a priority policy. Joint emission control at the regional scale is also important especially under unfavorable meteorological conditions.

Highlights
- We attempt to quantify the effectiveness of individual emission reduction measures.
- Measures on primary sources provide significant emergency $PM_{2.5}$ reduction results.
- O_3 level rose due to the changes of $PM_{2.5}$ and NO_x/VOCs caused by the measures.
- Less $PM_{2.5}$ reduction was achieved under more unfavorable weather conditions.
- Regional joint application of control measures could achieve better results.

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Introduction

Fine particulate matter ($PM_{2.5}$) is associated with an increased risk to human health. In the urban areas of many countries in Asia, especially in some densely populated developing countries such as China and India, the high concentration of $PM_{2.5}$ has become one of the primary factors that hinders the social and economic development and threatens human health in these areas (Xu et al. 2013; Chowdhury et al. 2017). With the rapid development of the economy since the reform and opening up, the Beijing-Tianjin-Hebei (BTH) area has been one of the most polluted areas in Asia (Chen et al. 2009). In 2014, the Asia-Pacific Economic Cooperation (APEC) meeting was held in Beijing. To maintain good air quality during the APEC meeting, the Chinese government implemented a series of emergency pollution control measures, which resulted in a blue sky in Beijing, which is called “APEC blue.” “APEC blue” caused extensive discussion among media and the public. More importantly, it gave us an opportunity to evaluate the effects of numerous emergency emission control measures.

Unlike regular (long-term) pollution control policies (Carvalho et al. 2015), the emergency control measures, including odd-even traffic restrictions, suspending or reducing the operations of power plants and factories, the shutting down of construction sites, the delay of central heating, the exchange of holidays, and increased road cleaning, are designed to rapidly cut emissions and mitigate air pollution (Liu et al. 2015b; Li et al. 2015). Most previous studies have focused on the impacts of different regional emission control measures on local (Beijing) air quality (Guo et al. 2016) or have evaluated the impacts of meteorology and the co-benefits of reduced aerosol feedbacks (Gao et al. 2016). However, the roles of specific emergency emission reduction measures for the improvement of air quality are rarely studied.

$PM_{2.5}$ includes sulfate, nitrate, organic carbon, black carbon, and mineral aerosols, and is the primary particulate from human emissions and natural sources and a secondary particulate formed in the atmosphere from other gaseous pollutants. Atmospheric pollution can also influence weather, such as air temperature and rainfall (Wang et al. 2014; Ding et al. 2013).

Ozone is an important trace component in the atmosphere. Ground-level ozone in urban areas is generated through photochemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) (Trainer et al. 2000; Sillman 1999). In China, with the progress in the prevention and control of air pollution, the concentrations of other major airborne pollutants like $PM_{2.5}$ and SO_2 have declined significantly. However, ozone concentrations in many urban areas have been increasing in recent years (Cheng et al. 2018). Ground-level ozone can harm human health and ecosystems and has been considered one of the major air pollutants in addition to $PM_{2.5}$ (Ghude et al. 2016; Neidell and Kinney 2010). Ozone pollution has drawn increased attention.

Besides emission and meteorological conditions, some researchers have suggested that regional transport played an important role in the increase of Beijing’s $PM_{2.5}$ concentrations (Gao et al. 2017). But other studies have shown that the contribution from outside of Beijing was insignificant (Guo et al. 2014). Since identifying that regional transport contributions to air pollutants across administrative regions have always been a problem, a good emission inventory and model are essential to help solve this problem.

In this study, numerical simulations based on the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem Version 3.9) were performed to investigate the effectiveness of specific emergency emission control measures during the APEC meeting in Beijing in 2014 on the air quality at local and regional scales. The aim of the simulation was also to investigate the most effective control measures and to assess the need for regional collaborative air pollution control, providing reasonable suggestions for further atmospheric pollution control. $PM_{2.5}$ and ozone were selected to be used in the study. The results of the study could help policy makers adopt reasonable emergency control measures for the reduction of air pollutants in some specific periods such as heavy air pollution times or important days such as the APEC meeting.

Data and methodology

Model description and configuration

WRF is a non-hydrostatic model. It uses the Arakawa staggered C-Grid in its atmospheric calculations and has been widely used as numerical weather forecasting model. In our study, we used the WRF3.9 with an ARW (Advanced Research WRF) core, which included OBSGRID (WRF objective analysis program), WPS (WRF Preprocessing System), and other post-processing modules. WRF contains a chemistry package, which consists of dry deposition, biogenic emission, the chemical mechanism from RADM2 (second-generation Regional Acid Deposition Model), a complex photolysis scheme, and a state-of-the-art aerosol module (Grell et al. 2005).

The WRF-Chem model was simulated on two domains, with a horizontal grid spacing of 12 and 4 km, respectively. Domain d01 is centered on the BTH area (38.25°N, 116.55°E); it covers the primary polluted area of North China (108°–125°E, 32°–44°N) and includes Shandong, Henan, Shanxi, Liaoning, and parts of some other provinces (Fig. 1(b)). Domain d02 covers most of the BTH area. All the simulation results presented here are based on domain d02. In the vertical dimension, we set 31 layers from the ground level to the 50 hPa pressure level. From the top to the bottom, the heights of layers were shortened gradually, and a total of 12 layers had heights below 2 km. The simulations were run continuously from 00:00 October 20, 2014, to 00:00 November 18, 2014 (UTC). The first 12 days were used as spin-up.

WRF-Chem allows flexible combinations of physical and chemical parameters. The major parameterization schemes used in our study are listed in Table S1 including the RADM2 chemical mechanism, which contains 63 reactive species treated in 136 chemical reactions (Balzarini et al. 2015), the MADE/SORGAM (Modal Aerosol Dynamics model for Europe/Secondary Organic Aerosol model) aerosol module for secondary inorganic (SIA) and organic aerosols (SOA), and the Madronich F-TUV photolysis scheme. Our model used the US Geological Survey (USGS) land cover data to represent the surface features with the default grid interval. The initial and lateral boundary conditions were forced from the 6-h Global Forecast System (GFS) dataset with a horizontal grid spacing of 0.5° × 0.5° to drive the meteorological fields of the model. The MEIC (Multi-resolution Emission Inventory for China) developed by Tsinghua University was selected for the anthropogenic emissions for 2014 on a monthly grid with the horizontal grid spacing of 0.25° × 0.25°. This inventory includes five sectors: power (POW), industry (IND), residential (RES), transportation (TRA), and agriculture (AGR) (Zhang et al. 2009; M. Li et al. 2014; Zheng et al. 2014; Liu et al. 2015a). The MEGAN model was used to calculate the online emissions of gases and particles from terrestrial ecosystems, including isoprene, terpenes, and other organic substances (Guenther et al. 2006; Guenther et al. 2012). To reflect the influences of emission control policies, 24 different species in the anthropogenic emissions inventory were revised.

To improve the simulation results and minimize numerical error accumulation, we adopted three methods to correct the differences between the simulated results and the observed values. The global chemical transport model MOZART-4 was used to provide the initial and boundary concentrations of air pollutants (Emmons et al. 2010). In the simulation process, we applied four-dimensional data assimilation (FDDA), an analysis nudging method, with the dataset GFS to improve the performance of the key meteorological variables such as wind speed, temperature, and humidity (Stauffer and Seaman 1990). In addition, we utilized a new surface nudging system FASDAS (the flux-adjusting surface data assimilation system), which was added in WRF-Chem 3.8, to make the predicted meteorological parameters closer to the observations (Alapaty et al. 2008).

Emission control scheme

During the APEC meeting, an emission reduction campaign was initiated by the government that included odd-even traffic restriction, reducing the operations of factories, shutting down construction sites, and a 6-day mandatory holiday. These measures resulted in a significant emission reduction in Beijing and its surrounding regions. To reflect the reduction caused by these measures in our simulation, a modification on the inventory is necessary. Since Beijing, Tianjin, Hebei, and the surrounding areas might adopt different pollution reduction measures, the whole study area was divided into 3 domains: BJ (Beijing), HB-TJ (Hebei-Tianjin), and SA (surrounding areas), as shown in Fig. 1. To calculate the boundary areas more accurately, we used the population data in the BJ and HB-TJ domains to calculate the coefficient of the boundary raster, which could provide a better boundary area simulation. The SA domain includes western Liaoning, northeastern Shandong, northern Henan, eastern Shanxi, and a few regions of Inner Mongolia. The edge of SA was also blurred.

The emission control measures implemented during the APEC meeting in Beijing are classified into four sectors (TRA, IND, POW, and RES) according to MEIC. For the five primary pollutants (SO_2, NO_x, PM_{10}, $PM_{2.5}$, and VOCs), the reduction effects of the odd-even traffic restrictions were estimated based on a bottom-up method (Fan et al. 2016). The measures of reducing operations of power plants and factories, shutting down construction sites, and strengthening road cleaning were taken according to a report of Beijing Municipal Environmental Protection Bureau (BMEPB 2014). For the delay of central heating, we calculated its contribution from the heating area, heating energy consumption, proportion of energy types, and emission factors. The VOC emission factor of gas was cited from the EPA, and other relevant data came from some previous researches (Pang et al. 2015; Liu et al. 2017). The effect of the 6-day mandatory holiday was estimated using the inbound and outbound traffic of Beijing and the

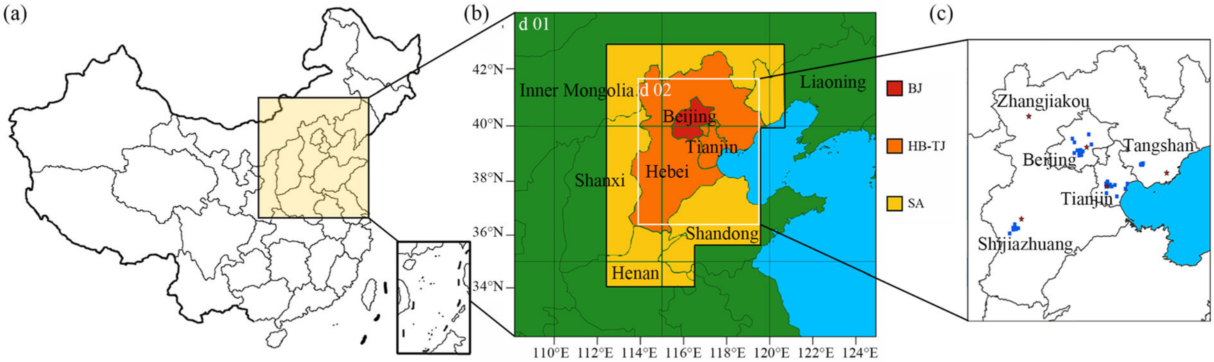

Fig. 1 (a) Location of the study area. (b) WRF model simulation domain. BJ, HB-TJ, and SA represent three different emission control regions (shown in different colors). (c) Space distribution of ground-based observational stations used for model evaluation (red pentagrams represent the five meteorological monitoring stations; blue squares are the air quality monitoring stations, with 12 in Beijing, 14 in Tianjin, 7 in Tangshan, and 6 in Shijiazhuang)

telecommunication operator's statistics on the number of mobile phones in the network. For the HB-TJ and SA regions, the effectiveness of the emission control measures was estimated based on the government's pollution reduction targets and was extrapolated from the proportion of vehicles forced to stop and the factories that were forced to close or reduce their production during the period. Considering the significant impacts of black carbon (BC) and organic carbon (OC) on the air quality and meteorological conditions, we use the reduction proportion of $PM_{2.5}$ to estimate the measures' influences on the reduction of BC and OC. Detailed results can be seen in Tables 1 and S2, as well as in the Supporting Materials.

To evaluate the effects of specific emission control measures as well as the local and regional contributions to air quality in Beijing, we set eight different emission control schemes for the simulation (Table 2). All the schemes were identical except for the emissions. Schemes Ctrl and NoCtrl were set to reflect the effects of emission control measures with real meteorological conditions. Schemes Factory, Heating, Const_road, and Traffic referred to the scenario of "specific measure." Schemes Only_HB-TJ and Only_SA referred to the scenario of "regional contribution."

Results and discussion

Model performance

To ensure that the model can provide a reliable simulation and the results could be used to evaluate the reduction effects of the measures adopted during the APEC meeting, we need to test the model performances. We used the Pearson correlation coefficient r and the normalized mean bias (NMB) as the descriptive statistics. The calculation formula of NMB is as follows:

$$\mathrm{NMB} = 100\% \times \frac{\Sigma_{i=1}^{n}(M_i - o_i\}}{\Sigma_{i=1}^{n} o_i} \qquad (1)$$

In Eq. (1), M_i and O_i represent the individual simulated values and observed values, respectively. n is the number of observations.

Table 1 Reduction percentages of primary emission sources during the APEC meeting

	Beijing					Hebei/Tianjin (%)	Surrounding area (%)
	SO_2 (%)	NO_x (%)	PM_{10} (%)	$PM_{2.5}$ (%)	VOCs (%)		
Industry	60.9	52.7	22.1	26.0	9.9	33.4	20
Power	–	14.7	–	–	8.9	33.4	20
Transportation	39.3	43.4	42.9	42.9	39.9	28.2	20
Residential	10	46.3	61.8	34.9	25.1	30	20
Total	41.6	46.3	46.3	39.2	14.7	–	–

Table 2 Eight emission control schemes for the simulation

Type of scheme	Description
Ctrl	Actual emission reduction in Beijing and surrounding areas
NoCtrl	No emission reduction at all
Factory	Reducing operations of power plants and factories
Heating	Central heating delayed
Const_road	Shut down of construction sites and increasing road cleaning
Traffic	Odd-even traffic restriction
Only_HB-TJ	Emission reduction only in HB-TJ
Only_SA	Emission reduction only in SA

To assess the fit of the meteorological variation, we compared the simulated 2 m temperature, RH, and 10 m wind vectors with the observed data in Beijing and surrounding areas because they are the most representative meteorological variables. We used GFS reanalysis data and land-based station data as the observation data. The hourly datasets from five meteorological observatories located in the BTH area were downloaded from the National Centers for Environmental Information website (Fig. 1(c)). The comparison started at 0:00 on Nov. 1, 2014, and terminated at 0:00 on Nov. 18, 2014 (UTC). Comparison results from the observed results are shown in Table S3. Figure 2 is the comparison between simulated and reanalysis data extracted from the same grid of the Beijing observation site with a 6-h time interval. The correlation coefficients (*r*) and NMB between the reanalysis data and simulated temperature, RH, and wind speed were 0.92/0.00, 0.86/− 0.13, and 0.78/0.15, respectively ($n = 69$). Figure S1 is the wind rose and wind barb derived from the simulated, observed, and reanalysis data in Beijing. Overall, these results demonstrate good model performances and consistency with both reanalysis data and land-based station data, especially in the wind vector simulation, even though the time interval is relatively small.

The observed concentrations of pollutants were measured at 39 state-level monitoring stations in Beijing and surrounding areas, with a time interval of 1 h (Fig. 1(c)). The simulated concentrations of $PM_{2.5}$ and O_3 during the APEC meeting under the real emission reduction scheme Ctrl are used for comparison. A 12-day spin-up period is used in our simulation to avoid an unstable result; data from the first 12 days are not included in the calculation. Figure 3 shows the simulated and observed hourly mean concentrations in four cities: Beijing, Tianjin, Tangshan, and Shijiazhuang. The concentration is the average for all monitoring sites in each city. The simulated concentrations reflect the actual observed data in both concentration variation and peak heights. The correlation coefficient (*r*) and the NMB of $PM_{2.5}$ range from 0.59 to 0.83 and − 0.22 to 0.08, respectively, and for O_3, they range from 0.72 to 0.84 and 0.42 to 0.62 ($n = 409$, $p < 0.01$), respectively, which demonstrates a strong correlation. The figure indicates that the model tends to overestimate the concentration of O_3 but underestimate $PM_{2.5}$. The overestimation of O_3 might be because the model simulation consistently expands the width of the ozone daytime peak. In general, the simulated results could reflect the major meteorological and chemical evolutions during the APEC meeting.

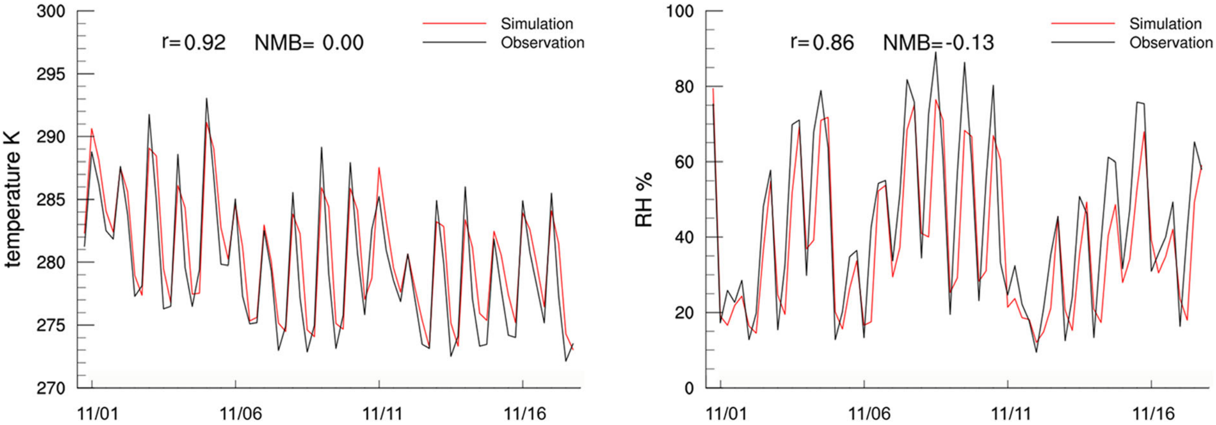

Fig. 2 Comparison of hourly mean near-surface temperature and RH between simulated results and reanalysis datasets in Beijing (every 6 h)

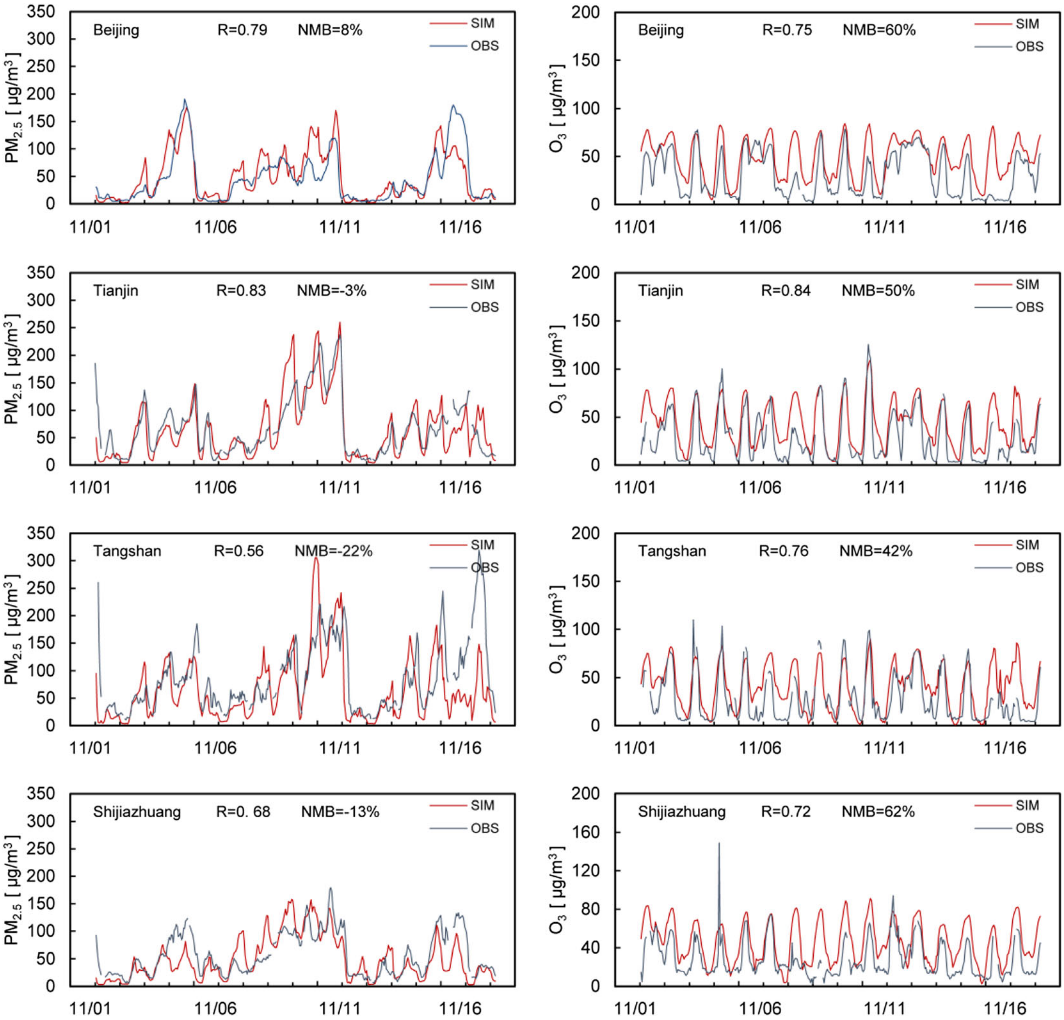

Fig. 3 Simulated and observed hourly mean $PM_{2.5}$ and ozone concentration in Beijing, Tianjin, Tangshan, and Shijiazhuang during the APEC meeting

Impacts of specific emission control schemes on the air quality of Beijing

During the APEC meeting period, $PM_{2.5}$ concentrations in Beijing and the surrounding areas were significantly lower (40–50%) than in late October. Based on the eight different emission control schemes listed in Table 2, we simulated the concentrations of $PM_{2.5}$ and O_3 in Beijing from Nov. 6 to 12, 2014, to evaluate the contributions of the emergency reduction measures. The simulation results showed that if no emission reduction measures were taken, the concentration of $PM_{2.5}$ would rise to 63.9 μg/m^3, which is 38.1% higher than the observed concentration of 46.3 μg/m^3. The implementation of various emission control measures achieved a significant effect on the improvement of air quality. Additionally, favorable meteorological conditions also played important roles. As shown in Fig. 4, some heavy pollution areas, such as Shijiazhuang, Baoding, and Tangshan in Hebei province, achieved more than a 20% reduction in pollution. The air quality in the entire BTH area was significantly improved through adopting the measures. Under the four local specific measure schemes, Factory, Heating, Const_road, and Traffic, the simulated $PM_{2.5}$ concentration reductions (compared with scheme NoCtrl) of $PM_{2.5}$ were 3.21%, 3.37%, 6.86%, and 3.94%, respectively (Fig. 5). The most effective measure was Const_road (shutting down construction sites and increasing road cleaning), which could reduce the $PM_{2.5}$ pollution from the primary sources significantly.

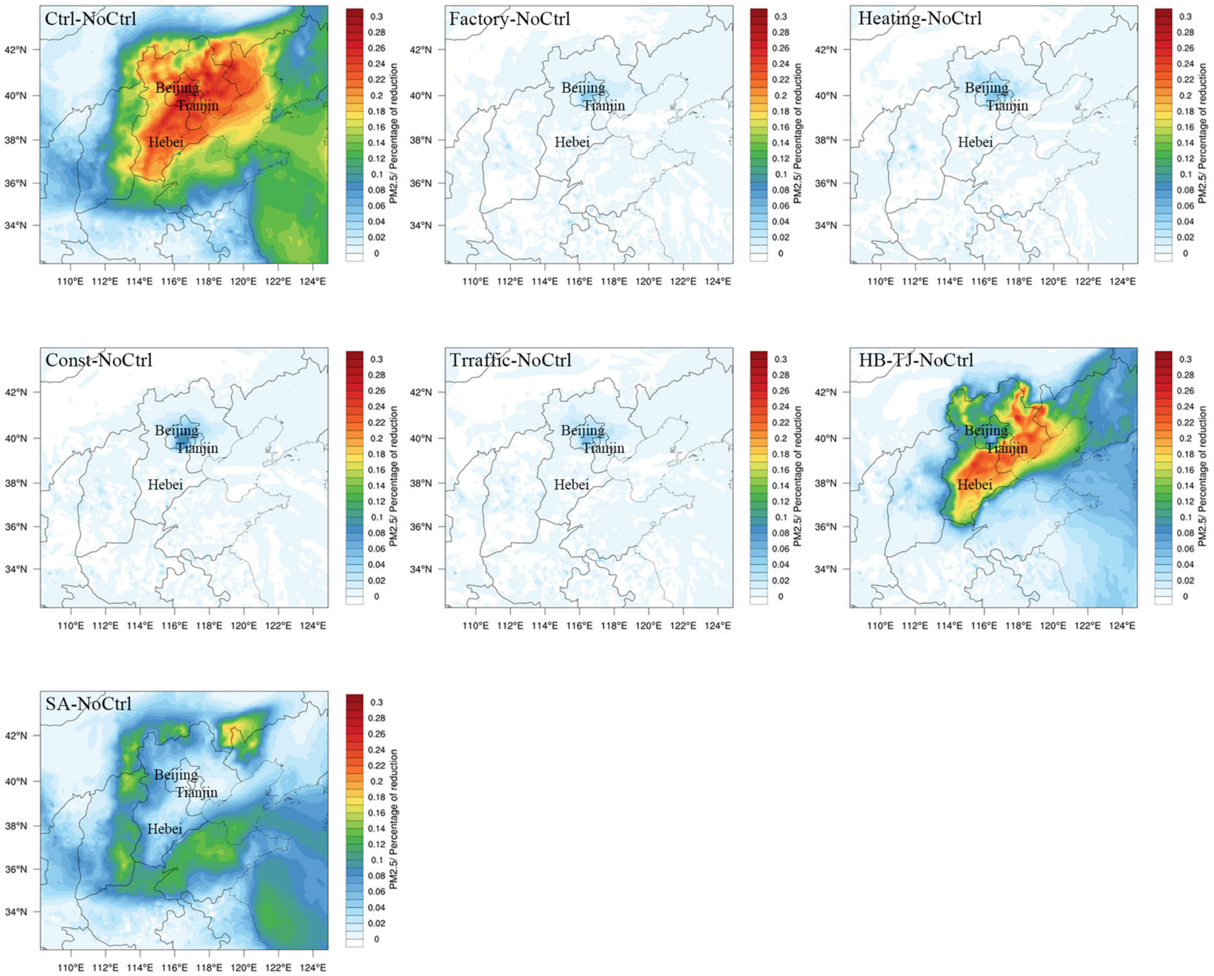

Fig. 4 Spatial percentage changes of average $PM_{2.5}$ concentrations between the NoCtrl scenario and seven control scenarios in the BTH region during the APEC meeting

For ground-level ozone, the simulated concentration in scheme NoCtrl was 23.3 ppb, which was 10.2% lower than the result of scheme Ctrl. The result suggested that the emission control measures implemented in the BTH area during the APEC meeting might increase the O_3 pollution in Beijing. The other four specific local measure schemes, Factory, Heating, Const_road, and Traffic, resulted in 0.21%, 6.19%, 0.72%, and 3.39% increases (compared with scheme NoCtrl) in ozone levels in Beijing, respectively (Fig. 5). Although the ozone pollution in Beijing is not significant, especially in winter, the lowering of $PM_{2.5}$ concentrations caused by the emission control measures

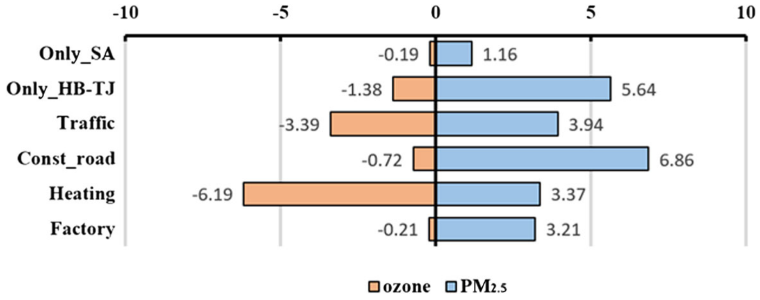

Fig. 5 Air quality improvement contributions of six specific emergency emission reduction measures. Note that all these measures have negative effects on ozone concentrations

might have enhanced ultraviolet light radiation, disturbed the balance of nitrogen oxides and hydrocarbons, and increased the O_3 pollution (Lin et al. 1988). The local government should pay more attention to this issue in the future and implement coordinated control measures on $PM_{2.5}$ and ozone.

Scheme Const_road is the most effective at reducing $PM_{2.5}$, but its influence on increasing ozone is relatively small. Schemes Factory and Heating had different effects on the ozone concentration increase (0.21% and 6.19%) but had similar effects on $PM_{2.5}$ reduction (3.21% and 3.37%). The differences of the effects of these schemes could be explained by how much the reduction measures could change the ratio of NO_x and VOCs. Some previous studies found that in the urban area of Beijing, the level of VOCs is insufficient and is under the VOCs-limited regime (Xing et al. 2011; Zou et al. 2015; Ji et al. 2016). Since scheme Heating could reduce a large amount of NO_x emissions but had little effect on VOCs, the ratio of NO_x and VOCs obviously decreased. In a VOCs-limited area, the unbalanced reduction in NO_x emission may have negative effects on the ozone concentration, and the ozone level may thus be higher than that in the Factory scheme. Scheme Const_road reduced the $PM_{2.5}$ emissions from primary sources significantly but only had a small impact on the precursor of ozone and thus, its influence on ozone is negligible.

Although the emission control measures could lower the level of $PM_{2.5}$ in this area, they had negative effects on ozone concentrations. It is expected that ozone will become an important environmental problem in the future. Thus, we conclude two key points: (1) more attention should be paid to the reduction of primary sources of $PM_{2.5}$. Curbing construction sites and road dust can achieve positive impacts; (2) when implementing emission control measures, the ratio of NO_x and VOCs needs to be carefully considered.

Effects of emission control measures implemented in surrounding areas

During the APEC meeting, the government implemented emission control measures not only in Beijing but also in surrounding areas in order to reduce emissions as much as possible. Schemes Only_HB-TJ and Only_SA reduced the amount of $PM_{2.5}$ in Beijing, and the reductions in percentages in concentrations (compared with scheme NoCtrl) of $PM_{2.5}$ were 5.64% and 1.16%, respectively, but also caused 1.38% and 0.19% increases (compared with scheme NoCtrl) in ozone levels, respectively (Fig. 5). The regional control measures contributed to a decrease of $PM_{2.5}$ in Beijing of approximately 25%. Additionally, schemes Only_HB-TJ and Only_SA reduced the air pollution in the HB-TJ area effectively, with decreases in $PM_{2.5}$ concentrations between 20 and 30 $\mu g/m^3$, especially in large industrial cities such as Tangshan and Shijiazhuang.

In the simulation period, the meteorological conditions in the study area are relatively beneficial to the diffusion of air pollutants. To make the results more applicable for unfavorable meteorological conditions, we applied the same schemes and emission inventory for another period from 00:00 October 25, 2014, to 00:00 November 01, 2014 (UTC) during a moderate pollution event. In this period, the simulated average concentration of $PM_{2.5}$ in Beijing was 85.1 $\mu g/m^3$ when the emission reduction scheme Ctrl was implemented, which was 200% higher than that during the APEC meeting. The differences between average $PM_{2.5}$ concentrations in Ctrl and NoCtrl schemes represented a reduction of 28.2 $\mu g/m^3$ (33.2%) in this period. The decline percentage in $PM_{2.5}$ concentration was less compared with that in the APEC period. The simulation results showed that regional control schemes Only_HB-TJ and Only_SA reduced $PM_{2.5}$ concentrations by 27.9% and 4.0%, respectively, which in contrast had more emission reduction contributions.

The major industrial pollution regions in the BTH area mainly located on the south and east sides of Beijing. In the before APEC period, 70 h of east wind and 49 h of south wind have been detected compared with 23 and 27 h, respectively, in the APEC period. The relatively warm and moist air came from the industrial areas and made regional transportation more important. As shown in Table 3, the effects of the emission control measures in the surrounding areas are greater under unfavorable meteorological conditions and thus, joint emission control at the regional scale has more potential and effects for heavy air pollution periods.

Conclusions

In this study, we investigated the impact of the emergency control measures on the reduction of air pollutants during the APEC meeting. In this period, the observed $PM_{2.5}$ concentration in Beijing was reduced by 40–50% compared with the concentration in late October. The

Table 3 Simulated $PM_{2.5}$ concentrations and changes during two simulation periods (10–25 to 11–01, before APEC and 11–06 to 11–12, APEC period)

Type of scheme	Mean pollutant concentrations ($\mu g/m^3$)		Changes in pollutant concentrations (%, compared with scheme NoCtrl)	
	Before APEC (pollution event)	APEC period	Before APEC (pollution event)	APEC period
Ctrl	85.11	46.35	24.91%	27.57%
Only_HB-TJ	105.48	60.38	6.94%	5.64%
Only_SA	112.22	63.25	0.99%	1.16%
NoCtrl	113.35	63.99	0.00%	0.00%
Contribution of regional joint emission control measures			31.83%	24.67%

numerical simulation results from WRF-Chem were used to evaluate the roles of specific emission reduction measures on the improvement of air quality. Both the simulated meteorological conditions and the concentrations of $PM_{2.5}$ and ozone were in good agreement with the observed data.

The emission control measures implemented during the APEC meeting reduced the concentration of $PM_{2.5}$ in Beijing by 38.1%. The most effective measure for the reduction of the primary emission sources of $PM_{2.5}$ was shutting down construction sites and increasing road cleaning. For ozone, the results showed that these measures had a negative effect on ozone concentration. The emission control measures implemented from areas outside of Beijing contributed to the improvement of air quality in Beijing by approximately 24.7%; the effects are more significant under heavy pollution periods.

For $PM_{2.5}$ control, additional effort towards emissions reduction from primary sources should be made, since these measures are cost-effective and have more potential than other measures. Meanwhile, the ratio of NO_x and VOCs should be taken into consideration in the adoption of control measures, since it could affect ozone generation. Strengthening the regional joint emission control could also benefit the air quality in the area, especially in Beijing. The findings of this study could help the government take more effective measures during heavy pollution events or important activities such as the winter Olympics that will be held in Beijing in 2022.

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