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Analysis of the causes of heavy aerosol pollution in Beijing, China: A case study with the WRF-Chem model

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ABSTRACT

The causes and variability of a heavy haze episode in the Beijing region was analyzed. During the episode, the $PM_{2.5}$ concentration reached a peak value of 450 μg/kg on January 18, 2013 and rapidly decreased to 100 μg/kg on January 19, 2013, characterizing a large variability in a very short period. This strong variability provides a good opportunity to study the causes of the haze formation. The in situ measurements (including surface meteorological data and vertical structures of the winds, temperature, humidity, and planetary boundary layer (PBL)) together with a chemical/dynamical regional model (WRF-Chem) were used for the analysis. In order to understand the rapid variability of the $PM_{2.5}$ concentration in the episode, the correlation between the measured meteorological data (including wind speed, PBL height, relative humidity, etc.) and the measured particle concentration ($PM_{2.5}$ concentration) was studied. In addition, two sensitive model experiments were performed to study the effect of individual contribution from local emissions and regional surrounding emissions to the heavy haze formation. The results suggest that there were two major meteorological factors in controlling the variability of the $PM_{2.5}$ concentration, namely, surface wind speed and PBL height. During high wind periods, the horizontal transport of aerosol particles played an important role, and the heavy haze was formed when the wind speeds were very weak (less than 1 m/s). Under weak wind conditions, the horizontal transport of aerosol particles was also weak, and the vertical mixing of aerosol particles played an important role. As a result, the PBL height was a major factor in controlling the variability of the $PM_{2.5}$ concentration. Under the shallow PBL height, aerosol particles were strongly confined near the surface, producing a high surface $PM_{2.5}$ concentration. The sensitivity model study suggests that the local emissions (emissions from the Beijing region only) were the major cause for the heavy haze events. With only local emissions, the calculated peak value of the $PM_{2.5}$ concentration was 350 μg/kg, which accounted for 78% of the measured peak value (450 μg/kg). In contrast, without the local emissions, the calculated peak value of the $PM_{2.5}$ concentration was only 100 μg/kg, which accounted for 22% of the measured peak value.

Introduction

Currently, China is rapidly undergoing economic development, which has resulted in a higher demand for energy and greater use of fossil fuels. Inevitably, this has led to more emissions of pollutants into the atmosphere. Along the eastern coast of China, there are four "mega" cities (cities with more than 10 million residents), including Beijing, Tianjin, Shanghai, and Guangzhou. Such dense urbanization has had important effects on the atmospheric environment. Satellite observations have revealed that the aerosol pollution in eastern China is much higher than in eastern U.S. (Tie et al., 2006).

In this study, the air pollutants in Beijing were analyzed. As the capital of China, Beijing is a highly urbanized metropolitan region with a population of 20 million. Such high urbanization has caused aerosol pollution, with Beijing being frequented by pollution events. High aerosol pollution has a wide-range of consequences that affect human health, cultivated and natural ecosystems, visibility, weather, radiative forcing, and tropospheric oxidation (self-cleaning) capacity (Cao et al., 2003a, 2003b; Charlson,

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Lovelock, Andreae, & Warren, 1987; Charlson et al., 1992; Deng et al., 2008; Tegen, Koch, Lacis, & Sato, 2000; Tie et al., 2005).

In order to analyze the causes and variability of aerosol pollution in Beijing, a high aerosol pollution episode, which occurred in the middle of January 2013, was studied by using several remote sensing instruments, aerosol concentration measuring instruments, and a chemical/dynamical regional model (WRF-Chem). Several model sensitivity studies were also conducted to analyze the major processes, which control aerosol pollution during the episode.

Methods

Measurement information

The instruments used in this study include three remote sensing instruments, namely, a boundary layer wind profiler radar (Airda-3000, Airda Co., China), a microwave radiometer (MP-3000A, Radiometrics Co., USA), and a micro-pulse lidar (MPL-4B, Sigmaspace Co., USA). These instruments were employed to study the evolution and vertical distribution of wind direction, wind speed, temperature, water vapor, and planetary boundary layer (PBL) height, respectively. Quan et al. (2013) provides detailed information regarding these three instruments.

One important challenge is to measure PBL height continuously, which requires to measure detailed temporal and vertical structures of atmospheric PBL. In this study, the micro-pulse lidar (MPL) is used to measure PBL height, which is determined at the altitude where a sudden decrease in scattering coefficients occurs (Boers & Eloranta, 1986; Brooks, 2003; Cohn & Angevine, 2000). The fundamental premise takes an advantage of the large gradient in aerosol concentration that is generally evident between boundary layer aerosols and those found in the free troposphere. The entrainment zone is the transition zone between the PBL and the free troposphere, and, depending on the time of day, it can be highly variable. The top of the PBL, in the idealized case, is therefore taken to be the midway point of the entrainment zone.

For surface aerosol measurements, a detailed size distribution of aerosol concentrations is included. The aerosol number concentrations (with bin size from 10 to 662 nm) were measured using a scanning mobility particle sizer (SMPS, Model 3936, TSI, USA) with a time resolution of 5 min. The SMPS consists of a differential mobility analyzer (DMA, Model 3081) and a condensation particle counter (CPC, Model 3772). The sheath and sample air flows of the DMA were 3 and 0.3 L/min, respectively. The ambient aerosol sample passed through a silica-gel diffusion drier with a relative humidity (RH) maintained below 40%. The aerosol sample then passed into an air-conditioned measurement container with a temperature maintained around 20 °C.

The microwave radiometer (MP), MPL, and SMPS are located at the Baolian site (39.93° N, 116.28° E, while the boundary wind profiler radar (BWPR) is located at the Haidian site (39.98° N, 116.28° E). Both sites are located in the center of Beijing. A detailed geographical distribution of the two sites was recorded (see Fig. 1).

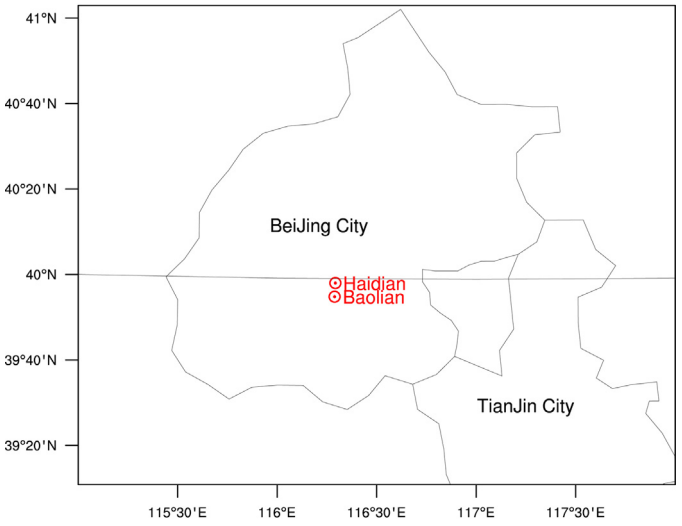

Fig. 1. The detailed geographical distribution of two observation stations (Baolian and Haidian) in Beijing.

Model information

An important objective of this study is to apply a regional chemical/dynamical model to analyze the measurements, to evaluate the model by comparing the model result to the measured data, and to study $PM_{2.5}$ variability in the Beijing region. The model used in this study is a newly developed regional chemical/transport model (WRF-Chem). The weather research and forecasting (WRF) model is a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. Developing WRF has been a collaborative partnership, principally among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA) (which includes the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL)), the Air Force Weather Agency (AFWA), the Naval Research Laboratory (NRL), Oklahoma University, and the Federal Aviation Administration (FAA). The WRF model is a fully compressible and non-hydrostatic Euler model. A detailed description of the parameters used in the WRF model, such as the PBL scheme, the land surface scheme, the microphysics scheme, and the cumulus cloud scheme, can be found on WRF's website (see http://www.wrf-model.org/wrfadmin/docs/arw_v2.pdf).

In addition to dynamical calculations, a chemical model is available online that is coupled with a WRF model (WRF-Chem). Grell et al. (2005) provides a detailed description of WRF-Chem with some modifications in the chemical scheme (Tie et al., 2007). The version of the model, as used in the present study, includes online calculation of dynamical inputs (winds, temperature, boundary layer, clouds, etc.), transport (advection, convection, and diffusion), dry deposition (Wesely, 1989), gas-phase chemistry, radiation and photolysis rates (Madronich & Flocke, 1999; Tie et al., 2003), and surface emissions (including on-line calculation of biogenic emissions).

The chemical precursors of particular matter (PM) in the model are calculated by the RADM2 (Regional Acid Deposition Model, version 2) gas-phase chemical mechanism (Chang et al., 1989), which includes 158 reactions among 36 species.

In this study, the domain of the numerical simulation is 1000 km × 1000 km in the horizontal region, which is centered in Beijing with a resolution of 10 km. The chemical lateral boundary conditions are constrained from the result of a global chemical transport model (MOZART – a model for ozone and related chemical tracers) with aerosol formation modules (Emmons et al., 2010; Tie et al., 2005). The model calculation period from January 15 to 19 in 2013, and the results from January 17 to 19 in 2013 are used for this analysis. The hourly emissions in the region are obtained from a study by Streets et al. (2003, 2008) with 0.16 resolutions, which are linearly interpolated in a horizontal resolution model. Jia and Guo (2012) also have used a WRF-Chem model with these emissions to simulate a fog episode in Beijing, China. According to

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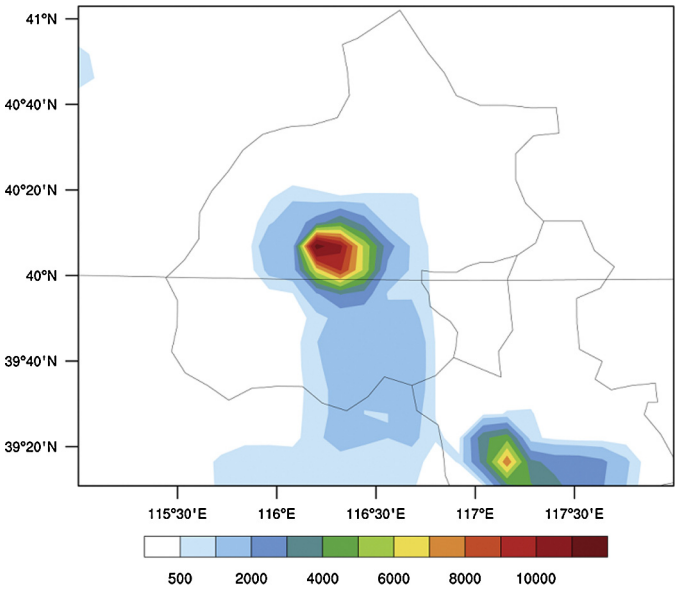

Fig. 2. The average hourly emissions of CO (M/(km^2 h)) in Beijing and its surrounding regions, which are based on a study by Streets et al. (2003, 2008) and fitted to model resolution.

a study by Tie, Brasseur, and Ying (2010), the effect of horizontal resolution on the calculated air pollution in large cities is more sensitive to meteorological calculations than emissions. As a result, the relatively coarse resolution of emissions will not significantly affect the model simulation. Average hourly CO emissions in Beijing city and its surrounding regions were recorded (see Fig. 2). The horizontal distribution of CO emissions shows that there are large emissions in the mega cities of the region (Beijing and Tianjin).

Results and discussion

Model evaluation

The purpose of this study is to investigate the causes of $PM_{2.5}$ variability in the Beijing region. The $PM_{2.5}$ (particular matter with a radius of less than 2.5 μm) concentrations at the Baolian site during the two calculation-periods were calculated and measured (see Fig. 3). The first calculation-period is from 12:00 on January 17 to 12:00 on January 19. During this calculation-period, the $PM_{2.5}$ concentrations were generally low at the beginning of the episode as a concentration of 20–100 μg/kg was recorded from 12:00 on January 17 to 12:00 on January 18. Both the measured and calculated $PM_{2.5}$ concentrations rapidly increased to about 450 μg/kg during the period from 12:00 on January 18 to 00:00 on January 19. After the $PM_{2.5}$ concentrations reached the peak value, $PM_{2.5}$ concentrations rapidly decreased to a low value of 150 μg/kg during the period from 00:00 to 06:00 on January 19. Both the measured and calculated $PM_{2.5}$ concentrations also showed a secondary peak value around 10:00 on January 19. Overall, both the measured and calculated $PM_{2.5}$ concentrations indicated that there was a strong variability with a large peak value of 450 μg/kg. This strong variability provides a good opportunity to study the causes of the heavy haze in Beijing. The second calculation-period is from 02:00 on January 22 to 02:00 on January 24. During this calculation-period, the measured $PM_{2.5}$ concentrations show that there were high values of $PM_{2.5}$ concentrations between 14:00 on January 22 and 00:00 on January 24, ranging in concentration between 180 and 300 μg/kg. During other times of the same period, the concentrations were very low. Although the calculated $PM_{2.5}$ concentrations also increased between 14:00 on January 22 and 00:00 on January 24, the magnitude of the concentrations ranged from 100 to 400 μg/kg. As the first calculation-period had a stronger variability, the calculated results were closer to the measured $PM_{2.5}$ concentrations. In the following studies, we will focus the analysis for the first calculation-period (i.e. between 12:00 on January 18 and 00:00 on January 19).

According to the regulations of the Chinese government, the air quality index (AQI) is used to define the grades of air quality, which has a total of six grades ranging from excellent air quality to serious pollution, respectively. The $PM_{2.5}$ concentration of 450 μg/kg (551 μg/m^3) in this event belongs to the fifth grade of the AQI, which was about 16 times higher than the daily standard value of the U.S. (35 μg/m^3). In this study, we define this as a heavy haze event.

The temporal evolution of the temperature vertical distribution at the Haidian site during the period from 12:00 on January 17 to 12:00 on January 19, 2013 were measured and calculated (see Fig. 4). The measured temperature (Fig. 4(a)) shows that a ground warmer layer occurred at 06:00 on January 18. At 18:00 on January 18, this warm layer was lifted, and formed an inversion layer at a few hundred meters. This inversion layer then disappeared at about 23:00 on January 18 and produced a shallow PBL layer. This led to a weak vertical diffusion. The calculated temperature (Fig. 4(b)) also shows an inversion layer. However, the calculated inversion layer appeared during the period between 12:00 and 23:00 on January 18, which occurred 6 h earlier than the one observed.

The temporal evolution of water vapor vertical distribution at the Haidian site during the period from 12:00 on January 17 to 12:00 on January 19, 2013 was measured and calculated (see Fig. 5). The simulated temporal evolution of water vapor was compared to the observed result. Both the measured (Fig. 5(a)) and calculated (Fig. 5(b)) results show that the water vapor was strongly confined in the lower layer of the atmosphere (below 2 km), and both of them have two peak values in this period. One peak occurred

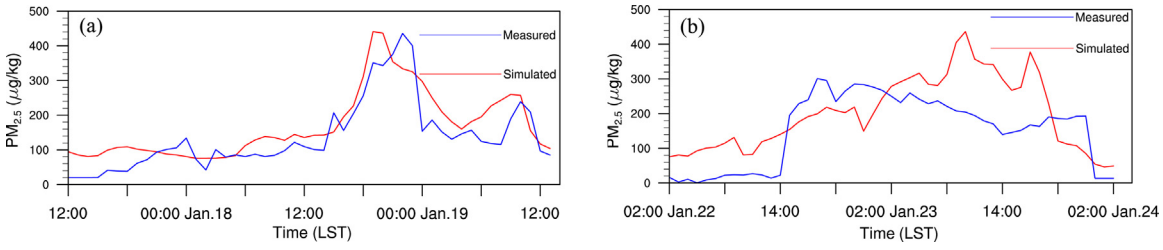

Fig. 3. The measured (blue line) and calculated (red line) $PM_{2.5}$ concentrations (μg/kg) during two periods at the Baolian site: (a) from 12:00 on January 17 to 12:00 on January 19 and (b) from 02:00 on January 22 to 02:00 on January 24. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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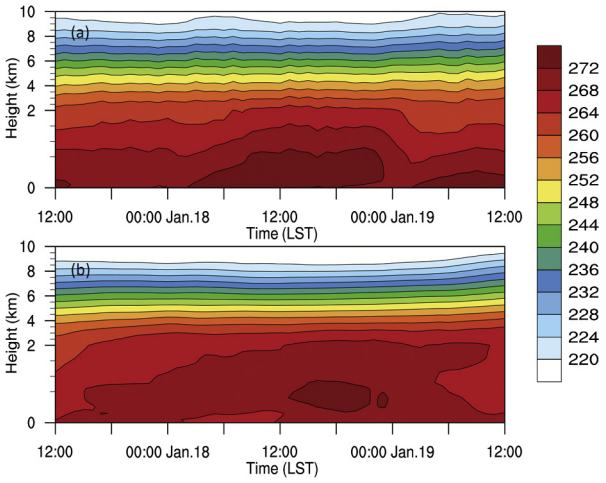

Fig. 4. The temporal evolution of the vertical distributions for measured (a) and calculated (b) temperature (K) at the Baolian site during the period from 12:00 on January 17 to 12:00 on January 19, 2013.

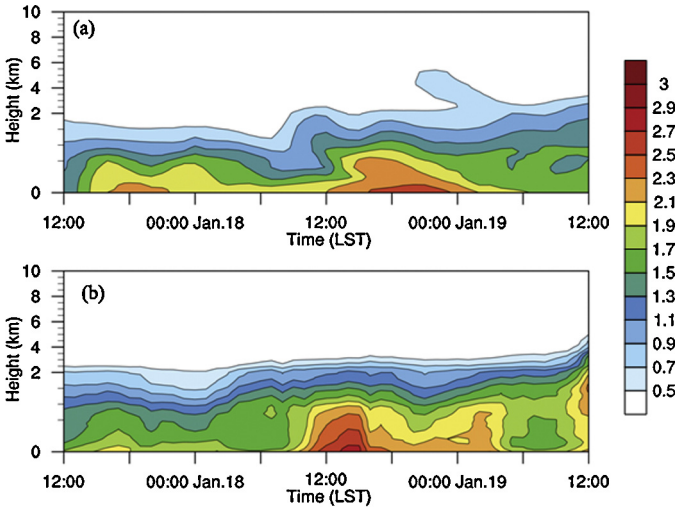

Fig. 5. The temporal evolution of the vertical distributions for measured (a) and calculated (b) water vapor content (g/kg) at the Baolian site during the period from 12:00 on January 17 to 12:00 on January 19, 2013.

approximately between 12:00 on January 18 and 06:00 on January 19, and the other was approximately at 18:00 on January 17. The simulated water vapor content is about 2.5 g/kg, and the observed value is about 2.9 g/kg. The calculated peak value appeared around 2–3 h earlier than the measured result.

The time-height cross sections of the measured (Fig. 6(a)) and calculated (Fig. 6(b)) wind vertical distribution at the Haidian site during the period from 12:00 on January 17 to 12:00 on January 19, 2013 were recorded (see Fig. 6). There are some common features between the measured and calculated wind vertical evolution. For example, both the measured and calculated results show that the wind direction changed from NW to SW at around 18:00 on January 17 at an altitude of 660–1500 m (denoted by the blue circle). It then returned to NW with higher wind speeds at around 12:00 on January 18 (denoted by the black circle). Meanwhile, the wind direction changed to S-ES with low wind speeds between 10:00 and12:00 on January 19 (denoted by the red circle). In addition, during the high pollution period, the wind speeds on the ground surface were very low with a direction of S-SE (denoted by the green circle). With that being said, there were also some discrepancies between the measured and calculated winds. For example, between 12:00 on January 17 and 00:00 on January 18 at an altitude of 100–200 m, the measured winds were in a non-organized state with a strong turbulence in wind directions (denoted by the brown square). In contrast, the calculated wind speeds in the same period appeared with organized north winds. Overall, both the measured and calculated winds nearby the surface were very weak, which had an important impact on the surface concentrations of the aerosols.

Another important parameter in controlling the surface aerosol concentrations is PBL height (Han et al., 2009; Quan et al., 2013). The temporal variation of PBL height between 12:00 on January 17 and 12:00 on January 19 were measured and calculated (see Fig. 7). Both the measured and calculated PBL heights show that PBL heights were relatively high in the beginning of the episode (around 500–800 m) and decreased to a low level (300–400 m) at 00:00

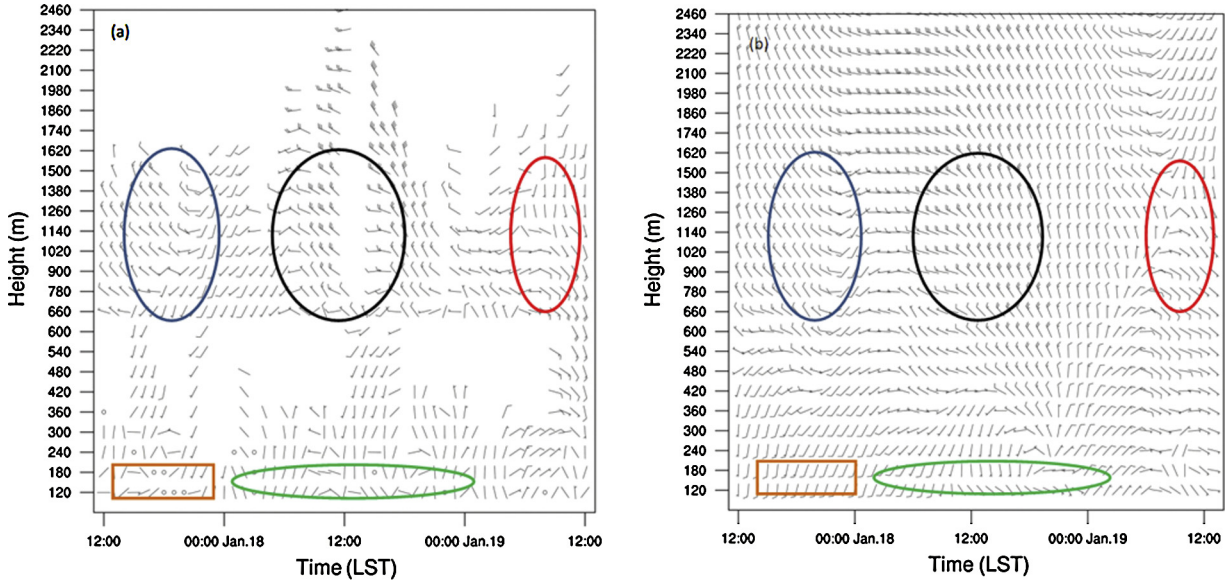

Fig. 6. The temporal evolution of vertical distributions for measured (a) and calculated (b) wind-barb at the Haidian site during the period from 12:00 on January 17 to12:00 on January 19, 2013.

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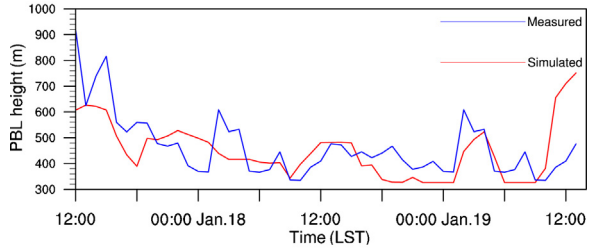

Fig. 7. The calculated (red line) and measured (blue line) PBL height (m) at the Baolian site during the period from 12:00 on January 17 to 12:00 on January 19, 2013. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

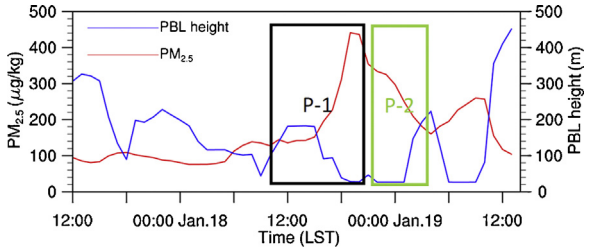

Fig. 9. The calculated (red line) $PM_{2.5}$ concentration (μg/kg) at the Baolian site during the period from 12:00 on January 17 to12:00 January 19, 2013 as well as its correlation with PBL height. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

on January 19. After 00:00 on January 19, PBL height increased to 500–600 m. This large variability of PBL height had an important effect in regulating the variation of the aerosol concentrations. There also were noticeable differences between the calculated and measured PBL heights. For example, the measured variation had a higher frequency than the calculated result. At 00:00 on January 19, the calculated PBL height was around 320 m, while the measured PBL height was about 400 m.

In order to study the causes of the formation and reduction of the high $PM_{2.5}$ pollution event, two periods are defined in the episode. The formation period is denoted by P-1 from 18:00 on January 18 to 00:00 on January 19, and the reduction period is denoted by P-2 from 00:00 to 05:00 on January 19. The P-1 (marked by a black square) indicates the $PM_{2.5}$ concentrations rapidly increased and reached a peak value, and the P-2 indicates the $PM_{2.5}$ concentrations rapidly decreased from the peak value.

Analysis of the causes of the heavy pollution

To better understand the frequent occurrences of a heavy haze in the Beijing region, the causes of the high $PM_{2.5}$ concentrations were analyzed by using the regional chemical/dynamical model (WRF-Chem). As suggested by previous studies (Deng et al., 2008; Tie et al., 2013; Tie, Geng, Peng, Gao, & Zhao, 2009; Zhang et al., 2006), the formation of heavy air pollution events are controlled by two major factors, namely, the high regional emissions and meteorological conditions (such as weak wind speeds).

The calculated $PM_{2.5}$ variation and its correlation with surface wind speed (WS) were recorded (see Fig. 8). The results indicate that the $PM_{2.5}$ concentrations were strongly anti-correlated with surface wind speed. In the beginning of the episode (from 12:00 on January 17 to 12:00 on January 18), the wind speeds were relatively high (varying from 3 to 6 m/s). As a result, the $PM_{2.5}$ concentrations were relatively low, and the concentrations ranged from 80 to 120 μg/kg. At P-1, the wind speeds rapidly reduced from 3 to 1 m/s and maintained low wind speeds (<1 m/s). At P-2,

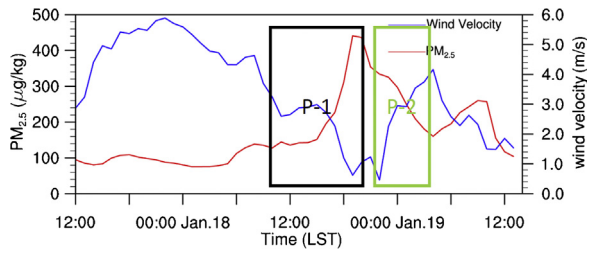

Fig. 8. The calculated (red line) $PM_{2.5}$ concentration (μg/kg) at the Baolian site during the period from 12:00 on January 17 to 12:00 on January 19, 2013 as well as its correlation with wind speed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

the wind speeds increased from less than 1 m/s to about 4 m/s, and the corresponding $PM_{2.5}$ concentrations decreased from the peak value of 450–150 μg/kg. These results suggest that wind speeds were critical for the formation of the heavy haze. The heavy haze events were formed with weak wind speeds. Under weak wind speeds, the horizontal transport of air pollutants almost ceased. As a result, the continuous emissions of air pollution accumulated in the city, causing the heavy haze events. As we will show in the next few sections, vertical transport/diffusion becomes an important factor in controlling the variability of $PM_{2.5}$ concentrations during the heavy haze events in the weak horizontal transport condition.

As we have discussed, one of the important factors in controlling the vertical transport is PBL height. The measurement of the vertical structures of air pollutants showed that the aerosol particles are strongly constrained by PBL in the Beijing region (Quan et al., 2013; Zhang, Ma, Tie, Huang, & Zhao, 2009). Their studies suggest that in an elevated PBL height, aerosol particles are vertically diluted, causing the reduction in surface concentrations. In contrast, in a shallow PBL height, aerosol particles are depressed in a shallow vertical layer, causing the enhancement in surface concentrations. The correlation between PBL heights and surface $PM_{2.5}$ concentrations was recorded (see Fig. 9). The results indicate that the $PM_{2.5}$ concentrations were strongly anti-correlated with PBL heights, especially during the period from low wind speeds. For example, during P-1, with WS being less than 1 m/s, the PBL heights were at the lowest level (less than 50 m), and the $PM_{2.5}$ concentrations were at the peak values (around 450 μg/kg). During P-2, the PBL heights increased from 50 to 250 m, and the corresponding $PM_{2.5}$ concentrations decreased from 300 to 150 μg/kg. This suggests that PBL heights have an important impact on surface $PM_{2.5}$ concentrations. When the horizontal winds were strong (with wind speeds being greater than 4 m/s) during the period between 12:00 on January 17 and 06:00 January 18, the corresponding variation of $PM_{2.5}$ concentrations was not sensitive to the variation of PBL height during this period (see Figs. 8 and 9). In this case, the horizontal transport played an important role in surface $PM_{2.5}$ concentrations. In contrast, when the horizontal transport was weak (with wind speeds being around 1 m/s), such as during the period between 16:00 on January 18 and 06:00 on January 19, the variation of $PM_{2.5}$ concentrations were sensitive to the variation of PBL height during this period, and the vertical diffusion of particles within the PBL heights played an important role in controlling surface $PM_{2.5}$ concentrations.

Effect of regional horizontal transport

In addition to the effects of local factors (wind speeds, PBL heights, etc.), the regional transports could also majorly influence air pollutants (Tie et al., 2010). The regional distribution of $PM_{2.5}$ concentrations in the Beijing region (longitude range from 115° E

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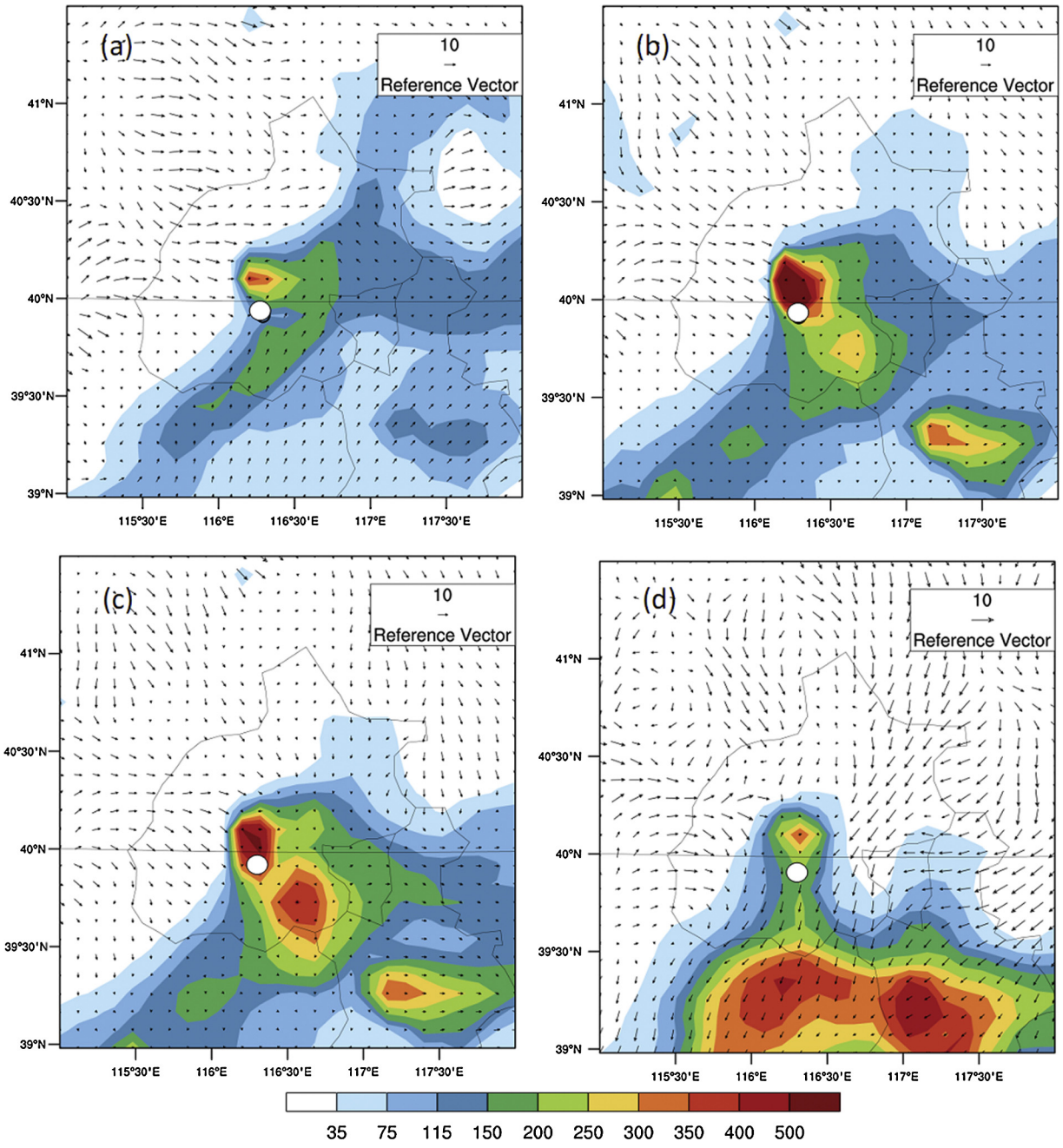

Fig. 10. The calculated surface $PM_{2.5}$ concentrations (μg/kg) and wind (bars) at 06:00 (a), 18:00 (b), and 20:00 (c) on January 18, 2013 as well as 02:00 (d) on January 19, 2013.

to 118° E, and latitude range from 39° N to 42° N) were calculated (see Fig. 10). The results show that at 06:00 on January 18, the wind directions were generally southwestern with the wind speeds of 4 m/s. As a result, the $PM_{2.5}$ pollution largely sped out across the north of Beijing, and the $PM_{2.5}$ concentration at the measurement site was relatively low (about 100 μg/kg). At 18:00 on January 18, the winds were calm with wind speeds around 1 m/s. In addition, there were no organized wind directions. As a result, $PM_{2.5}$ pollution accumulated nearby the large emission areas, such as in Beijing and Tianjin (see Fig. 2). The $PM_{2.5}$ concentrations at the measurement site increased to about 300 μg/kg. At 20:00 on January 18, the winds were continuously at a calm state with wind speeds of less than 1 m/s. Once again, there were no organized wind directions. As a result, $PM_{2.5}$ pollution accumulated deeply in large emission areas nearby, and the $PM_{2.5}$ concentrations reached a peak value of 450 μg/kg at the measurement site. At 02:00 on January 19, the wind speeds increased to about 3 m/s, and the wind direction was northward. As a result, $PM_{2.5}$ pollution was transported from its source region (such as Beijing and Tianjin) to the southern part of the cities. The peak value of the $PM_{2.5}$ concentrations decreased to about 200 μg/kg at the measurement site. The back trajectories were recorded with the source at the measurement site, ending at 18:00 on January 18 and 06:00 on January 19, respectively (see Fig. 11). These two time-periods correspond to high and low $PM_{2.5}$ concentration events in Beijing. The results show that $PM_{2.5}$ was mainly transported from the southwest direction of Beijing when the $PM_{2.5}$ concentration in Beijing was high. In contrast, when the wind turned to the northwest direction, the $PM_{2.5}$ concentration

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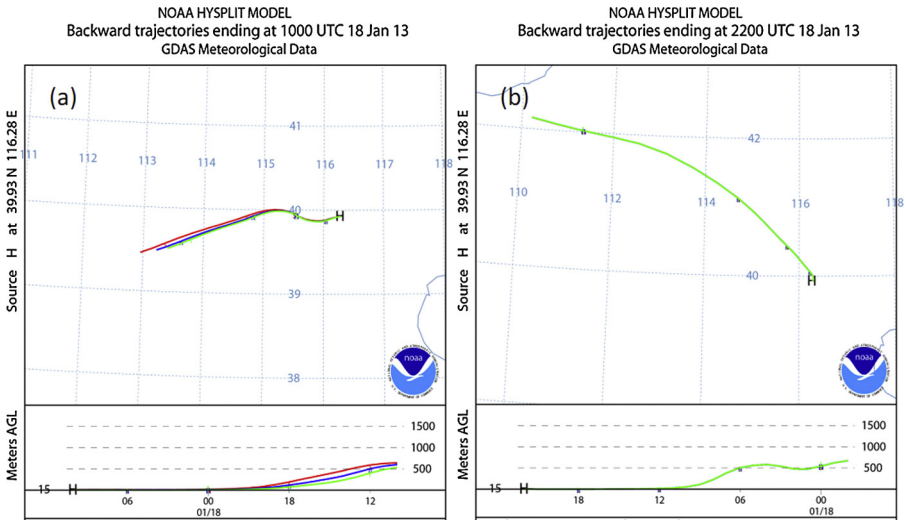

Fig. 11. The back trajectories using the NOAA HYSPLIT model with the source at the measurement site, ending at 18:00 on January 18 (a) and 06:00 on January 19 (b), respectively.

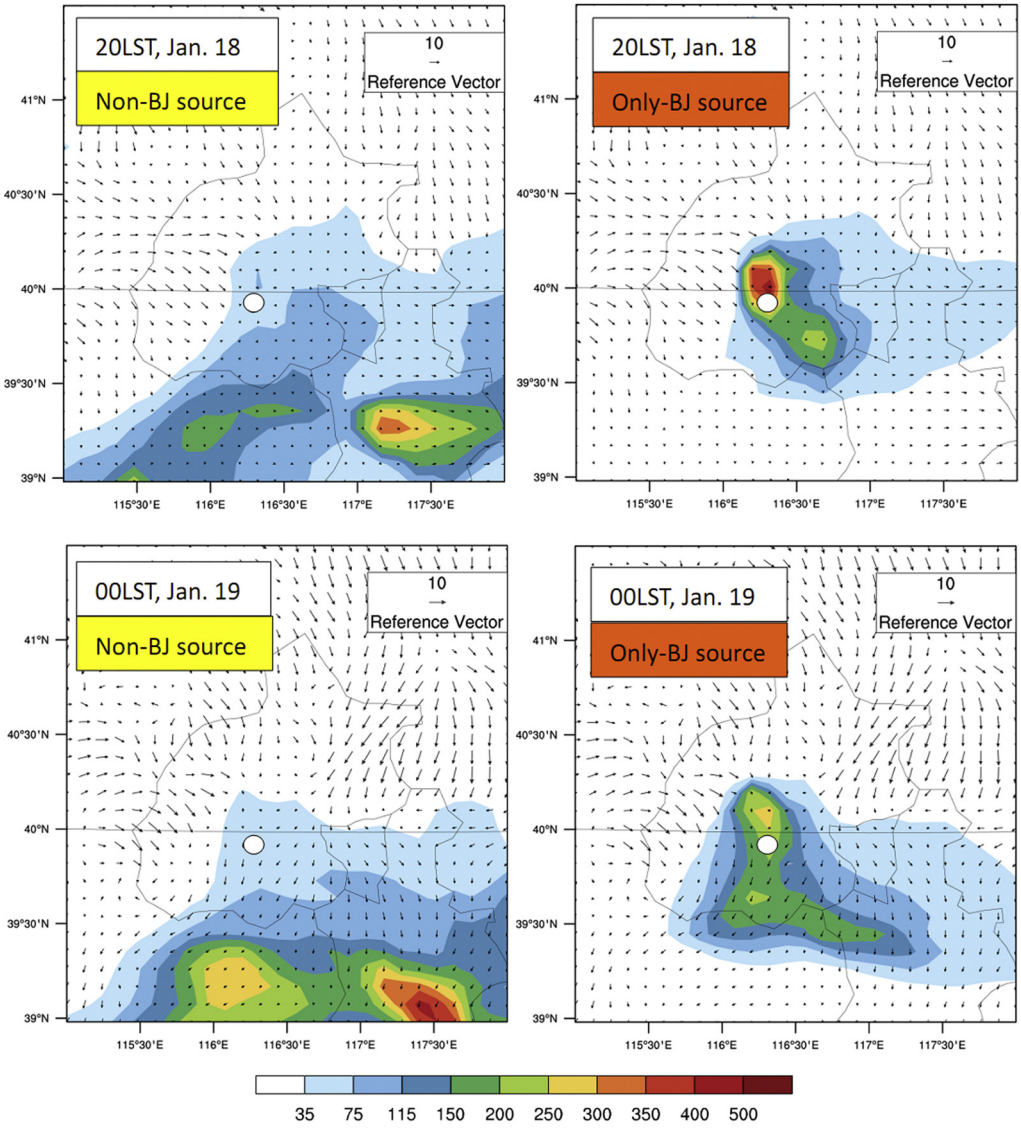

Fig. 12. The calculated surface $PM_{2.5}$ concentration (μg/kg) and wind (bars) at 20:00 (upper panels) on January 18 and 00:00 (lower panels) on January 19, 2013, which is shown without local emissions (left panels) and with only local emissions (right panels).

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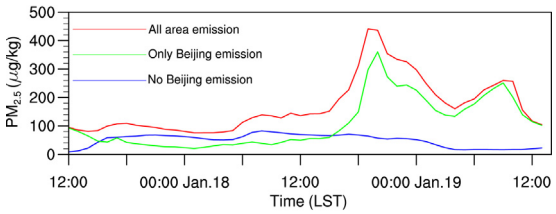

Fig. 13. The calculated $PM_{2.5}$ concentration (μg/kg) shown at the Baolian site during the period from 12:00 January 17 to12:00 January 19, 2013with all emissions (red line), with only local emissions (green line), and without local emissions (blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

was low. These results suggest that regional transport plays an important role in controlling the appearance of heavy haze events in Beijing.

Effect of regional and local emissions

To better understand the individual contribution of local emissions and regional emissions to the occurrence of heavy haze events, sensitive model simulation experiments were conducted. The first experiment was conducted without air pollutant emissions in the Beijing region, and the second experiment was conducted with air pollutant emissions only in the Beijing region.

The distributions of $PM_{2.5}$ concentrations that resulted from the two experiments were recorded (see Fig. 12). The results show that at 20:00 on January 18, the measured $PM_{2.5}$ concentration was at a peak value (450 μg/kg). However, without local emissions in the Beijing region, the calculated $PM_{2.5}$ concentration was less than 100 g/kg. In contrast, with only emissions in the Beijing region, the calculated $PM_{2.5}$ concentration was about 350 μg/kg. These results suggest that local emissions (78%) majorly contribute to the heavy haze, and regional emissions only contribute about 22%. The small contribution from the regional emissions was mainly due to the fact that during the heavy haze period (P-1), the wind speeds were very weak (1 m/s) and the horizontal transport from the surrounding areas was not significant.

At 00:00 on January 19, the measured $PM_{2.5}$ concentration decreased from the peak value (during the P-2). Without the air pollutant emissions in the Beijing region, the calculated $PM_{2.5}$ concentration decreased to about 60 μg/kg (see Fig. 13). In contrast, with only the air pollutant emissions in the Beijing region, the calculated $PM_{2.5}$ concentration was about 220 μg/kg. Given that the wind direction was northeast, the PM pollutions were transported to the south of Beijing. Being the only local emissions case, there was indication that the PM pollutions were sped out across a large area (about 50 km × 100 km) with a diluted distribution in the downwind of Beijing.

Summary

The causes of a heavy haze episode in Beijing were analyzed. During the episode, the $PM_{2.5}$ concentration reached a peak concentration of 450 μg/kg on January 18, 2013, and rapidly decreased to 100 μg/kg on January 19, 2013, characterizing a larger variability of the haze episode. In order to understand the rapid variability of $PM_{2.5}$ concentrations in the episode, the correlation between the measured meteorological data (including winds, PBL heights, etc.) and the measured particle concentrations ($PM_{2.5}$ concentration) were studied. A regional chemical/dynamical model (WRF-Chem) was applied in order to study the causes of the heavy haze. The measurements and the model simulations were compared to evaluate the performance of the model. The results are summarized as follows:

(1) The comparison between the measurements and model results suggests that the WRF-Chem model is capable of reproducing the main feathers of the heavy haze episode, such as the peak concentration and variability of $PM_{2.5}$ concentrations. The simulated PBL height, winds, temperature, and water vapor are generally consistent with the measured results.
(2) The correlation between the meteorological data and $PM_{2.5}$ concentrations shows that there were two major factors in controlling the variability of $PM_{2.5}$ concentrations, namely, surface wind speed and PBL height. During the high wind period, the horizontal transport of aerosol particles played an important role, and a heavy haze was formed when the wind speeds were very low (less than 1 m/s). Under the low wind conditions, the horizontal transport of aerosol particles was weak, and the vertical mixing of aerosol particles played an important role. As a result, the PBL height was a major factor in controlling the variability of $PM_{2.5}$ concentrations. Under the shallow PBL height, the aerosol was strongly confined near the surface, producing high surface $PM_{2.5}$ concentrations.
(3) The sensitivity model study (with and without local emissions) suggests that local emissions (emissions from the Beijing region only) were the major cause for the heavy haze event. Considering only local emissions, the calculated peak value of the $PM_{2.5}$ concentrations was 350 μg/kg, which accounted for 78% of the measured peak value. In contrast, without local emissions, the calculated peak value of the $PM_{2.5}$ concentrations was only 100 μg/kg, which accounted for 22% of the measured peak value.

The results of the study provide useful information in the air pollution control strategy for a seriously aerosol polluted region (i.e. the Beijing region) in China.

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