Response to referee comments on "Modeling study of the 2010 regional haze event in the North China Plain"

We thank the reviewers for valuable comments. This document is organized as follows: the referees' comments are in blue and our responses are in black.

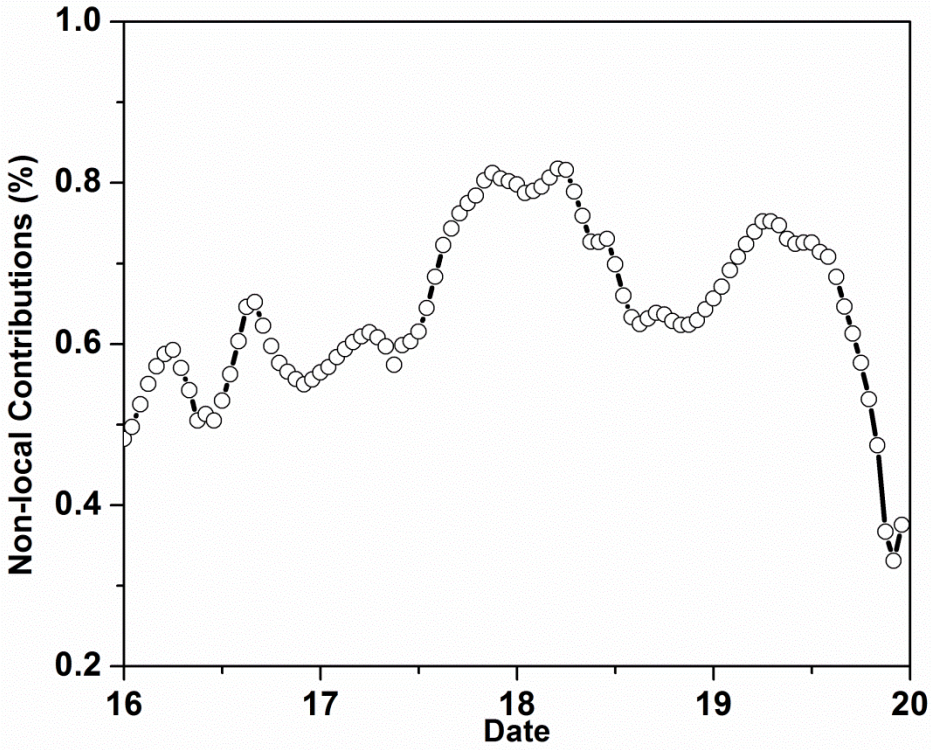
To Referee #1

This manuscript presents a fairly detailed modeling analysis of a haze even in North China in winter. It discusses the chemical composition, transport, and formation mechanism of the haze episode. Using the coupled meteorology-aerosol simulation with WRF-Chem, the paper also estimates the effect of aerosol feedback on meteorology. It concludes that BC contributes to 50% of the overall effect of aerosol feedback on PBL and surface PM2.5 concentrations. This paper confirms many findings from previous analysis of wintertime hazes in North China, including the importance of secondary inorganic aerosols, regional transport, and meteorological conditions. My main concerns are with the validity of using CO as a proxy of regional PM2.5 transport and with the uncertainty in BC simulation. Minor issues are with the presentation clarity and some technical details. I recommend publication after these issues are properly addressed.

Major comments:

1). In Section 4.3, the authors use CO to indicate the source regions of PM2.5 in Beijing. They did a sensitivity analysis by turning off CO emissions in Beijing and used the relative change in CO concentrations to denote the impact of surrounding regions on PM2.5 pollution in Beijing. Although they showed that CO and PM2.5 were highly correlated, CO has a much longer lifetime (~ 3 months) than PM2.5 in winter and also undergoes different loss mechanisms (e.g. CO is not water soluble or lost through deposition). As such the sensitivity simulation using CO may not be appropriate for the sensitivity of PM2.5. Why didn't the authors choose to conduct the sensitivity simulation using PM2.5 directly? They have a model at their disposal. They can turn off primary sources of PM2.5 as well as the emissions of its gaseous precursors over Beijing, the same approach as they did for the CO sensitivity simulation, to evaluate the impact of surrounding areas on Beijing.

Response: Following the referee's suggestion, we have conducted the sensitivity simulation using PM2.5 directly. The temporal variations of non-local contributions are shown below. The average contribution is about 64.5% from January 16 to January 19. The text has been modified and the CO based results have been replaced with these PM2.5 based results.



2). A major conclusion of this paper is that BC is responsible for 50% of the aerosol feedback on meteorology which in turn influence surface concentrations of PM2.5. That conclusion is obviously dependent on the ability of the WRF-Chem model to simulate BC concentrations correctly as well as its relative contribution to the overall PM2.5 composition. Figure 7 clearly shows that the model overestimates BC concentrations at the surface, for example by about a factor of two during the severe haze days (i.e. 18-19 January). Because the model underestimates OC and sulfate at the same time, this means the model has a significant overestimation of the fractional contribution of BC in total PM2.5. These two factors in combination suggest that the simulated absorbing effect of BC on meteorology in this winter episode should be significantly overestimated because of (1) overestimate in BC absolution concentration and (2) underestimate the role of scattering aerosols. This is an important issue that needs to be acknowledged at a minimum, given the emphasis of this manuscript on the simulated role of BC. But the authors did not discuss or even mention any uncertainty of this point. This is a major shortcoming of this paper and should be addressed before acceptation by ACP.

Response: Thanks for this important suggestion. We have added one paragraph to discuss the uncertainty of the BC. We also added some sentences in summary section to mention this point.

The contribution of BC absorption in aerosol feedbacks depends on the model performance in simulating BC and scattering aerosols (sulfate, OC). As shown in Figure 7, BC was overestimated, and sulfate and OC were underestimated in Beijing. The overestimation could be as large as a factor by 2 in some days. As a result, the contribution of BC absorption in aerosol feedbacks may have been overestimated in this study. To explore the uncertainties of the BC

absorption contribution, we conducted simulations by reducing BC emissions by 50%. After this BC emission perturbation, the changes of PBLH and $PM_{2.5}$ concentrations at 2p.m. due to aerosol feedbacks and BC absorption are shown in Figure 14. The domain maximum increases of $PM_{2.5}$ concentrations because of aerosol feedbacks and BC absorption are 19.1μg/m^3 and 10.21μg/m^3, respectively. The domain maximum decreases of PBLH due to aerosol feedbacks and BC absorption are 235.7m and 114.2m, respectively. These numbers are smaller than before because BC emissions were reduced by 50%. Under these conditions of reduced BC concentrations, the contribution of absorption to the feedbacks was still large (50%) This number can be additionally reduced if OC and sulfate concentrations are simulated well. The underestimations of OC and sulfate were because some secondary formation pathways are missing in the current model. In the future, more accurate contribution of BC absorption in aerosol feedbacks can be estimated after the performances of the WRF-Chem model in simulating BC, OC and sulfate are improved.

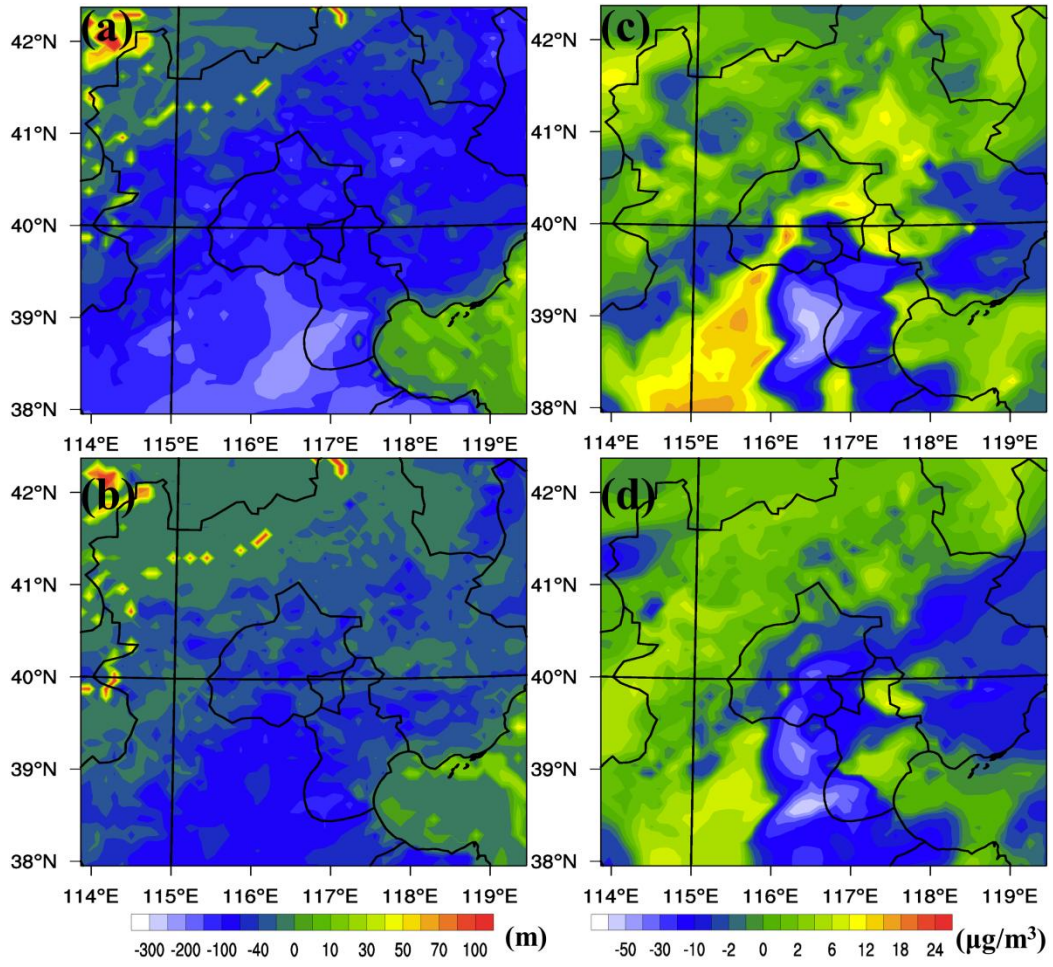


Figure 14. Differences of PBLH (unit: m) and $PM_{2.5}$ concentration (unit: μg/m^3) at 2p.m. between WF and NF scenarios (a, c) when BC emissions were reduced by half; differences of PBLH (unit: m) and $PM_{2.5}$ concentration (unit: μg/m^3) at 2p.m. between WF and NF scenarios (b, d) when BC emissions were reduced by half

Minor Comments

1) pg 22784, l3: add “the time period” before “from 2001 to 2001”.

Response: We have added it.

2) Section 4.1: are the analysis presented in this section based on model simulations or observations? It’s not clear to me.

Response: The analysis is in section 4.1 is based on model simulations. “Simulated” can be found in those figure titles (figure 5, figure 6).

3) Pg 22791, l7: upwards should be northward, since the discussion is on a 2-D surface pattern.

Response: We have corrected it.

4) Pg 22791, l8-l10: the discussion of the high pressure is confusing. First, there is no clear indication of existence of a high pressure on Figure 4. Figure 4 shows only winds, not pressure fields. Second, the authors suggested high pressure would act to disperse pollution and low pressure leads to pollution accumulation. This is contradictory to the common understanding that high pressure is not conducive for pollution dispersion because of the subsidence and stability, and low pressure (e.g. cyclones) usually acts to reduce pollution.

Response: Thanks for this suggestion. Firstly, we plotted the pressure system but did not put it in the paper. Zhao et al. (2013) discussed the pressure system during this haze episode, so we have added the reference in this section. Hope it is not confusing now. The pressure system can be found in Figure 2 of Zhao et al. (2013).

Zhao, X. J., Zhao, P. S., Xu, J., Meng,, W., Pu, W. W., Dong, F., He, D., and Shi, Q. F.: Analysis of a winter regional haze event and its formation mechanism in the North China Plain, Atmos. Chem. Phys., 13, 5685-5696, doi:10.5194/acp-13-5685-2013, 2013.

Secondly, thank you for pointing out this misleading sentence. We agree that high pressure is not conducive for pollution dispersion because of the subsidence and stability, and low pressure usually acts to reduce pollution, but this relationship depends on the relative location to NCP and magnitudes of the pressure system. Actually, this haze event was terminated by the Mongolia anticyclone, which is a high pressure system. We were trying to say that the low pressure during this episode is unfavorable for the dispersion of air pollutants because air flows converged at the surface. To avoid misunderstanding, we have revised this sentence to “The weak high pressure system was replaced by a low pressure system that lasted until January 20, and this weather condition was not conductive for dispersion of air pollutants (Zhao et al., 2013)”. Hope it is better now.

5) Pg 22793, l15-17: Remove the sentence "However, few modeling studies have ….". There have been quit some modeling studies on secondary aerosols during winter haze in China.

Response: We have removed this sentence.

6) Pg 22793, line 24-26: Are these factors from model or observations? If from models, how do they compare with observed factors?

Response: Thanks for this question. I made a mistake in figure 7. The plotted PM2.5 components were hourly data, it should be daily mean. We have corrected the figure. Those factors were from model. We calculated the concentrations and factors again using daily mean. We also compared them with observed factors.

We added one sentence in the manuscript: "The increasing factors for observed primary aerosols and SIA are 2.9 and 6.9, which are close to those factors from simulations."

Table 2. Primary Aerosol, SIA and SOA ($\mu g/m^3$) during Haze Days and Non-haze Days in Beijing

	Primary	SIA	SOA
Haze days	56.4	81.9	1.1
Non-haze days	14.2	10.8	0.3
Ratio	4.0	7.6	3.7

7) Pg 22797, line 23: add "and" before as a result

Response: We have added "and".

8) Pg 22798, line 4: increase of temperature inversion should be changed to decrease of temperature gradient from surface to aloft, because Figure 10e shows only the difference in temperature between the two runs, not temperature profile.

Response: We have corrected.

9) Pg 22798, line 15-17: below Beijing should be changed to south of Beijing.

Response: We have corrected.

To Referee #2

General comments:

This manuscript, using the online coupled Weather Research and Forecasting-Chemistry (WRF-Chem) model, to investigate a haze event in NCP, the contributions of Secondary inorganic aerosols and transportation, particle composition, aerosols' feedback on the local meteorology and PM2.5 itself, and feedbacks associated to Black Carbon. The aim the study is meaningful. The model simulations are in certain agreement with observations. Each point of the paper discussed (cause of haze event, composition, transport, radiative feedback) is important and worth doing. Unfortunately the paper involves too many aspects, but could not concentrate on the one or two targets to study and discuss them in detail. I recommend its resubmission basically in a revision in accordance with the following comments:

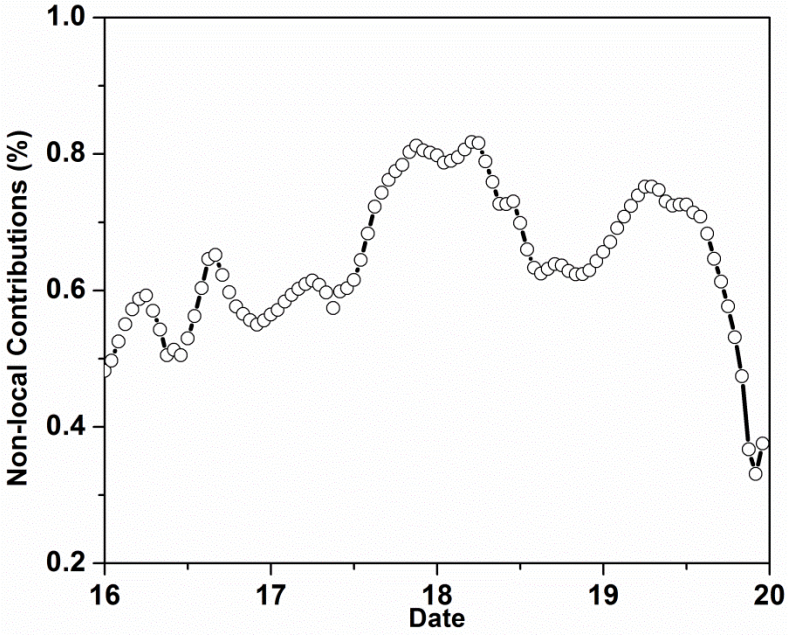
Major comments:

1. Table S1-1 and Figure S2-10 are all supplement files. The authors spend too much space to discuss them in the manuscript which could not be seen by readers in fact and this may lead to misunderstanding. I suggest if they are necessary, please put them into the formal figures and tables in the paper, otherwise reject them and the use texts in the manuscript.

Response: Thanks for this suggestion. We have moved some important figures, like figure S4, figure S7 and S11 from supplement files to manuscript. Although the tables and figures in supplement files are not as important as those in the manuscript, they are still helpful to understand this haze event, so we did not discard them and put them in the supplement files. If the readers are interested in those materials, they can download the supplement file.

2. Though there is a high correlation between CO and PM2.5 concentrations, it is groundless to use the CO transportation contribution as that of PM2.5 directly. It is not difficult to calculate the transportation amount outside Beijing by model output parameters directly.

Response: Following the referee's suggestion, we have conducted the sensitivity simulation using PM2.5 directly. The temporal variations of non-local contributions are shown below. The average contribution is about 64.5% from January 16 to January 19. The text has been modified and the CO based results have been replaced with these PM2.5 based results.



3. AOD is a basic parameter to calculate aerosols direct radiative feedback. The AOD difference between model results and observation (CALIPSO) is obvious (Figure 3) and the model AOD is not good enough to support the aerosols radiative feedback calculation. Further AOD evaluations are needed (MODIS, etc.) for modeling the aerosols radiative feedback reasonably.

Response: Thanks for this suggestion. The difficulty is that during these heavy haze events there is little data available. We analyzed the CALIPSO data as well as AOD from surface sites (Figure S5). The surface sites did not report data during the heavy haze period, but the model well predicted the values before and after. Actually, we did download MODIS data, but most are missing during the study period due to extremely high aerosol loadings. If anything we have probably underestimated the feedback effects due to our underprediction of PM2.5 and AOD based on CALIPSO.

Minor comments

1. Please examine the quota format in the manuscript carefully (different quota format appears in the paper).

Response: We have checked the format and they look fine. The publishing assistant also checked it before publication in ACPD, and I corrected following her instructions.

2. Figure1, 3, 4, 11,12 are not clear and need to be redrawn.

Response: We redrew figure 1,3,4,11 and 12. Hope they are clear now.

3. Figure 4 and its related content (page 22791), wind vectors in the figure needs legend explanation. Pressure system is explained on line 1-10, but it is not drawn in the figure. Please examine the similar questions in other figures (Figure 4, 5, 7, etc.)

Response: Thanks for this suggestion. Firstly, we plotted the pressure system but did not put it in the paper. Zhao et al. (2013) discussed the pressure system during this haze episode, so we have added the reference in this section. Hope it is not confusing now. The pressure system can be found in Figure 2 of Zhao et al. (2013).

Zhao, X. J., Zhao, P. S., Xu, J., Meng,, W., Pu, W. W., Dong, F., He, D., and Shi, Q. F.: Analysis of a winter regional haze event and its formation mechanism in the North China Plain, Atmos. Chem. Phys., 13, 5685-5696, doi:10.5194/acp-13-5685-2013, 2013.

4. Please examine the figure captions under the figure and the explanation in the manuscript. They are not same for some figure.

Response: Thanks for this comment. I have checked all figure titles and made corrections. Although some expressions are different, they denote the same meaning.

Modeling study of the 2010 regional haze event in the North China Plain

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Abstract

The online coupled Weather Research and Forecasting-Chemistry (WRF-Chem) model was applied to simulate a haze event that happened in January 2010 in the North China Plain (NCP), and was validated against various types of measurements. The evaluations indicate that WRF-Chem provides reliable simulations for the 2010 haze event in the NCP. This haze event was~~is~~ mainly caused by high emissions of air pollutants in the NCP and stable weather conditions in winter. Secondary inorganic aerosols also played an important role and cloud chemistry had important contributions. Air pollutants outside Beijing contributed about ~~47.8~~64.5% to the $PM_{2.5}$ levels in Beijing during this haze event, and most of them are from south Hebei, Tianjin city, Shandong and Henan provinces. In addition, aerosol feedback has important impacts on surface temperature, Relative Humidity (RH) and wind speeds, and these meteorological variables affect aerosol distribution and formation in turn. In Shijiazhuang, Planetary Boundary Layer (PBL) decreased about 278.2m and $PM_{2.5}$ increased more than 20μg/m^3 due to aerosol feedback. Feedbacks associated to Black Carbon (BC) account for about 65.7 % of the $PM_{2.5}$ increases and 59.9% of the PBL decreases in Shijiazhuang, indicating more attention should be paid to BC from both air pollution control and climate change perspectives. This contribution decreased from about 60% to 50% after deceasing BC emissions by 50% and the uncertainty can be additionally reduced by improving the model performance in simulating sulfate and OC. ~~300m and $PM_{2.5}$ increased more than 20μg/m^3 due to aerosol feedback. Feedbacks associated to Black Carbon (BC) account for about 50 % of the $PM_{2.5}$ increases and 50% of the PBL decreases in Shijiazhuang, indicating more attention should be paid to BC from both air pollution control and climate change perspectives.~~

1 Introduction

The North China Plain (NCP) is one of the most densely populated areas in the world and it has been the Chinese center of culture and politics since early times. Beijing, the capital of China, Tianjin, Shijiazhuang and other big cities with active economic developments are located in the NCP. This region is experiencing heavy haze pollution with record-breaking high concentrations of particulate matters (Wang et al., 2014b). Haze is defined as an air pollution phenomenon where horizontal visibility is less than 10 km caused by aerosol particles, such as dust and Black Carbon (BC), suspended in the atmosphere (Tao et al., 2012). Its formation is highly related to meteorological conditions, emissions of pollutants and gas-to-particle conversion (Sun et al., 2006; Watson, 2002). Haze has attracted much attention for its adverse impacts on visibility and human health. During haze periods, reduced visibility affects land, sea and air traffic safety and the fine particles can directly enter the human body and adhere to lungs to cause respiratory and cardiovascular diseases (Liu et al., 2013). Moreover, haze affects climate and ecosystems via aerosol-cloud-radiation interactions (Sun, et al., 2006; Liu et al., 2013).

Because haze influences visibility, human health and climate (Gao et al., 2015), numerous studies have used multiple methods to investigate physical, chemical and seasonal characteristics of aerosols during haze. The increase of secondary inorganic aerosols is considered to be an attribute of the haze pollution in east China (Tan et al., 2009; Zhao et al., 2013). Tan et al. (2009) studied the characteristics of aerosols in non-haze and haze days in Guangzhou, China and found that secondary pollutants (OC, $SO4^{2-}$, NO^{3-} and NH^{4+}) were the major components of haze aerosols and they showed a remarkable increase from non-haze to haze days. Similar conclusions were drawn by Zhao et al. (2013) after studying the chemical characteristics of haze aerosols in the NCP. Secondary Organic Aerosol (SOA) formation can also be significant during haze (Tan

et al., 2009; Zhao et al., 2013). Studies of aerosol optical properties show that fine-mode aerosols were dominant during haze (Yu et al., 2011; Li et al., 2013). In addition, contributions of diverse factors to haze formation, such as biomass burning and regional transport, have been investigated. Chen et al. (2007) used MM5-CMAQ to reproduce the haze pollution in September 2004 in the Pearl Region Delta (PRD) region and discovered that sea-land breeze played an important role. Wang et al. (2009) discovered that almost 30-90 percent of the organics during the haze happened in June 2007 in Nanjing were from wheat straw burning. Cheng et al. (2014) concluded that biomass burning could cause haze issues and they found biomass burning contributed 37% of $PM_{2.5}$, 70% of Organic Carbon (OC) and 61% of Elemental Carbon (EC) based upon both modeling and measurement results of case study in summer 2011 in the Yangtze River Delta (YRD) region. These biomass burning events mainly occurred in summer and autumn in east and south China (Cheng et al., 2013; Cheng et al., 2014; Li et al., 2010; Wang et al., 2007; Wang et al., 2009). To evaluate regional contributors to the haze in southern Hebei, Wang et al. (2012) simulated the time period from 2001 to 2010 and concluded that Shanxi province and the northern Hebei were two major contributors, and winter was the worst season, followed by autumn and summer. Han et al. (2014b) pointed out that the haze formation mechanism in winter in Beijing was different from that in summer and mass concentrations of $PM_{2.5}$ in winter were relatively higher and the compositions were different than in summer. The extreme winter haze in the NCP has attracted enormous scientific interests. It has been found the stagnant meteorological conditions (weak surface wind speed and low Planetary Boundary Layer (PBL) height) and secondary aerosol formation are the main causes of winter haze formation (Han et al., 2014a; He et al., 2014b; Huang et al., 2014; Sun et al., 2014; Wang et al., 2014c; Zhao et al., 2013; Zheng et al., 2014a; Zheng et al., 2014b). Other causes proposed include high local emissions (He et al., 2014b; Zheng et al., 2014b), enhanced coal combustion in winter (Huang et al., 2014; Sun et al., 2014), heterogeneous chemistry (He et al., 2014a; Huang et al., 2014b; Quan et al., 2014; Wang et al., 2014c; Wang et al., 2014d; Zheng et al.,2014a; Zheng et al., 2014b) and regional transport (Tao et al., 2014; Sun et al., 2014; Wang et al., 2014b; Wang et al., 2014e; Zheng et al.,2014b). It was also pointed out that fog processing (Huang et al., 2014), aerosol-radiation interactions (Wang et al., 2014a; Wang et al., 2014e; Zhang et al., 2015a) and nucleation events (Guo et al., 2014) may play important roles in winter haze formation.

~~Although previous studies have revealed characteristics and possible causes of winter haze in China,~~The complex haze formation mechanisms ~~still~~ need further studies. Li et al. (2015) emphasized that regional transport of $PM_{2.5}$ is a major cause of severe haze in Beijing, but Zhang et al. (2015b) pointed out that the evidence provided by Li et al. (2015) is insufficient and regional transport should be evaluated using chemical transport models. Furthermore, the contribution of aerosol feedbacks to $PM_{2.5}$ levels ~~is controversial~~remains unquantified. Therefore, the roles of regional transport and aerosol-radiation interactions in haze events need to be better understood. In this study, the online coupled model WRF-Chem, which is capable of simulating aerosols' effects on meteorology and climate, is used to reproduce the severe haze event that happened in the NCP from 16 to 19 January 2010. During this haze event, the highest hourly $PM_{2.5}$ concentration reached 445.6 and 318.1μg/m^3 in Beijing and Tianjin and the areas with low visibility covered most eastern China regions (Zhao et al., 2013). In this study, we address the following important questions: (1) what is the performance of the model configurations in representing the meteorological variables, and the physical and chemical characteristics of the aerosols during the selected study period?; (2) How does the haze build up and dissipate?; (3) How do the chemical species of $PM_{2.5}$ change during haze period?; (4) Does regional transport play an import role in the 2010 haze event in Beijing?; (5) What is the contribution of aerosol feedback mechanisms to $PM_{2.5}$ levels during the haze event?; and (6) What is the role of BC absorption in the feedback mechanism? In section 2, we describe the model we use and model configuration, including emissions and used parameterization schemes. In section 3, surface meteorological, chemical observations, atmospheric sounding products, as well as remote sensing products are used to evaluate the model performance. In section 4, questions from (2) to (6) are answered in detail. Conclusions are provided in the section 5.

2 Model description and configuration

The WRF-Chem model version 3.5.1 was employed to simulate the 2010 haze event in the NCP region and aerosol-radiation interactions were included (Chapman et al., 2006; Fast et al., 2006). Domain settings are the same as those of Jing-Jin-Ji modeled area of Yu et al. (2012). ~~As shown in Figure S1 (see supporting information),~~ T~~t~~hree domains with two-way nesting were used and grid resolutions were 81km × 81km (domain 1), 27km × 27km (domain 2) and 9km × 9km

(domain 3) (see supporting information Figure S1). The number of vertical grids used was 27 and the number of horizontal grids was 81×57, 49×49, and 55×55, respectively. The first domain covers most areas of the East Asia region, including China, Korea, Japan and Mongolia. Beijing was set to be the center of the innermost nested domain. The chemical and aerosol mechanism used was gas-phase chemical mechanism CBMZ (Zaveri and Peters, 1999) coupled with the 8-bin sectional MOSAIC model with aqueous chemistry (Zaveri et al., 2008). MOSAIC treats all the important aerosol species, including sulfate, nitrate, chloride, ammonium, sodium, BC, primary organic mass, liquid water and other inorganic mass (Zaveri et al., 2008). Some of the physics configuration options include Lin cloud-microphysics (Lin et al., 1983), RRTM long wave radiation (Mlawer et al., 1997), Goddard short wave radiation (Chou et al., 1998), Noah land surface model, and the Yonsei University planetary boundary layer parameterization (Hong et al., 2006).

Emissions are key factors in the accuracy of air quality modeling results. The m~~M~~onthly 2010 Multi-resolution Emission Inventory for China (MEIC) (http://www.meicmodel.org/) was used as the anthropogenic emissions. This inventory includes emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), Carbon Monoxide (CO), non-methane volatile organic compounds (NMVOC), NH_3, BC, organic carbon (OC), $PM_{2.5}$, PM_{10}, and carbon dioxide (CO_2) by several sectors (power generation, industry, residential, transportation, etc.). Biogenic emissions were calculated on an online way by the MEGAN model (Guenther et al., 2006). Meteorological initial and boundary conditions were obtained from the National Centers for Environmental Prediction (NCEP) Final Analysis (FNL) data set. Chemical initial and boundary conditions were taken from MOZART-4 forecasts (Emmons et al., 2010). The period from 11 to 24 January 2010 was chosen as the modeling period, covering the 2010 NCP haze period (from 16 to 19 January 2010). To overcome the impacts of initial conditions, three days were simulated and considered as spin-up time.

3 Model Evaluation

3.1 Observation data sets and evaluation metrics

Model evaluation was conducted in terms of both temporal variation and spatial distribution. Table ~~S~~1 ~~(see supporting information)~~ gives a summary of the observation data and variables used in the model evaluation. The meteorological variables, including 2 meter temperature (T2), 2 meter relative humidity (RH2) and 10 meter wind speed (WS10), at four stations (Beijing, Tianjin, Baoding and Chengde) were used. Surface concentrations of $PM_{2.5}$, NO_2, SO_2 at three sites (Beijing, Tianjin and Xianghe, shown in Figure S1), and Aerosol Optical Depth (AOD) at four sites (Beijing city, Beijing forest, Baoding city, Cangzhou city) were also used in the evaluation against measurements. $PM_{2.5}$ and AOD are typical variables to represent severity of haze pollution. To evaluate how model performs in simulating horizontal and vertical distributions of meteorological and chemical variables, soundings of temperature and RH at Beijing, and AODs derived from CALIPSO were used in this study. The statistical metrics calculated include correlation coefficient R, mean bias (MB), mean error (ME), the root mean square error (RMSE), the normalized mean bias (NMB), the normalized mean error (NME), the mean fractional bias (MFB) and the mean fractional error (MFE). The definitions of these metrics can be found in Morris et al. (2005) and Willmott and Matsuura (2005).

3.2 Meteorology simulations

Figure 1 shows the temporal variations of simulated and observed 24-h average temperature (a-d), relative humidity (e-h) and wind speed (i-l) at Beijing, Tianjin, Baoding and Chengde stations. These observations were collected from the China Meteorological Data Sharing Service System (CMDSSS) data set. From normal days to haze days (gray shaded), temperature and relative humidity increased and wind speeds decreased. Generally, the variations of surface temperature, RH and wind speeds are captured by model, although overestimations of wind speed occur at the Chengde station throughout the whole period. Model mean, observation mean, MB, ME and RMSE were calculated and summarized in Table ~~S~~2. The MB and RMSE for surface temperature vary from -2.0 to 2.0 K and from 1.5 to 3.2 K, respectively. The model underestimates temperature at Beijing, Tianjin and Baoding stations, and overestimates temperature at the Chengde station. RH agrees well with observations, with MB varying from -4.4% to 8.1% and RMSE varying from 6.4% to 11.1%. The magnitudes of MB and RMSE are comparable with those of Wang et al. (2014b). The model shows good performance in simulating

wind speed, with RMSE ranging from 1.1 to 1.6 m/s at Beijing, Tianjin and Baoding stations, below the level of "good" model performance criteria for wind speed prediction proposed by Emery et al. (2001). Wind speeds at the Chengde station were overestimated, with RMSE larger than the proposed criteria (2m/s).

Figure ~~S~~2 ~~(see supporting information)~~ compares simulated and observed vertical temperature profiles at 0800 and 2000 (CST) from January 15 to January 20 at Beijing city. These atmospheric sounding data are from the NCAR Earth observing laboratory atmospheric sounding data set. The model captures the vertical profiles of temperature well. Obvious strong temperature inversions existed during the haze period (from 01/16 08:00 to 01/19 20:00) and the lapse rate during this period was about 5-15°C/km, indicating unfavorable conditions for diffusion of pollutants. ~~Figure S3 (see supporting information) shows the vertical profiles of RH.~~ The model captures the general vertical profiles of RH, although the performance is not as good as for temperature (see supporting information Figure S2). Simulated RH deviates largely away from observations on January 18 and 19, when RH was high near the surface.

~~Figure S4~~3(a-c) ~~compares simulated and observed hourly temperature, RH and wind speed at SDZ station (shown in Figure S1) using observations from Zhao et al. (2013). Simulated variations of meteorological variables agree well with observations, despite RH was overestimated on January 19 and 20 (Figure S4~~3(b)) ~~and wind speed was overestimated on January 22 (Figure S4~~3(c)), ~~which is similar to the comparisons shown in Figure 1.~~

3.3 Chemical simulations

Figure ~~S4~~3(d-f) shows variations of simulated and observed hourly $PM_{2.5}$, NO_2 and CO at the SDZ station. The haze event started from 16 January with rapid increase of $PM_{2.5}$, NO_2, and CO concentrations and ended on 20 January. The relationships between meteorological condition and pollution levels are clearly shown. Both the observation and the model show that temperature and relative humidity increase, wind speeds are low, and pollution levels build up (Figure 3). The magnitudes and trends over time of the simulated $PM_{2.5}$, NO_2 and CO are generally consistent

with measurements, although overestimation of $PM_{2.5}$ and underestimations of NO_2 and CO exist during the haze days. Figure ~~2~~ 4 shows the temporal variations of the simulated and observed $PM_{2.5}$, NO_2 and SO_2 at Beijing (a-c), Tianjin (d-f) and Xianghe (g-i) stations. The observations and the model predictions show that the buildups of pollution during the haze event were similar at these three sites, occurring over a large geographical region at the same time. SO_2 was overestimated in Beijing, but other simulations agree well with observations, especially for $PM_{2.5}$. Observation mean, model mean, MB, ME, NMB, NME, MFB, and MFE were calculated for 24-h average simulated and observed $PM_{2.5}$ at these three stations and summarized in Table ~~1~~3. As shown in Table ~~1~~3, the model underestimates $PM_{2.5}$ concentrations at all stations. NMBs for $PM_{2.5}$ are -8.5%, -26.9% and -39.1% at Beijing, Tianjin and Xianghe, respectively. MFBs at these three stations range from -21.8% to 0.4% and MFEs range from 26.3% to 50.7%. They are all within the criteria proposed by Boylan et al. (2006) that model performance is "satisfactory" when MFB is within ±60% and MFE is below 75%. Although the model performance for $PM_{2.5}$ is satisfactory, biases still exist, especially during severe haze days. Reasons for the biases might be errors in meteorological variables, large uncertainties of emission inventory, effects of horizontal and vertical resolutions, and incomplete treatments of atmospheric chemistry. Many atmospheric chemistry reactions have been and are being proposed for PM formation in winter haze. For example, He et al. (2014a) proposed that mineral dust and NO_x could promote the formation of sulfate in heavy pollution days. The sensitivity of the simulations to some of these factors will be discussed in future studies.

3.4 Simulations of optical properties

In WRF-Chem, aerosol optical properties are calculated at four specific wavelengths, 300nm, 400nm, 600nm, and 1000nm, while AOD observations from CSHNET, CALIPSO are not at these four wavelengths. To evaluate model performance of simulating AOD, we derived AOD at observation wavelengths based on Angstrom exponent relation (Schuster et al., 2006). ~~Figure S5 (see supporting information) compares simulated and observed AOD at 500nm in Beijing city (a), Beijing forest (b), Baoding city (c) and Cangzhou city (d).~~ In severe haze days, AOD could not be retrieved , so the observerd AOD data in some days are missing. ~~At all four stations,~~ M~~m~~odel agrees very well with surface AOD observations at all four stations (supporting informaiton

Figure S3). ~~Figure S5 (see supporting information) compares simulated and observed AOD at 500nm in Beijing city (a), Beijing forest (b), Baoding city (c) and Cangzhou city (d).~~

CALIPSO retrievals provide vertical curtains of aerosol and clouds. Figure ~~3~~ 5 shows paths of the CALIPSO satellite, simulated extinction coefficient and observed plume top, and simulated AOD and CALIPSO retrieved AOD at 532nm at three moments: January 14 12:00(CST) (a-c), January 21 02:00(CST) (d-f), and January 21 12:00(CST) (g-i), respectively. There were no retrievals in the NCP during haze days. Figure ~~3~~5(a), (d) and (g) show that the CALIPSO satellite passed over the NCP region at these three moments. Simulated extinction coefficient matches observed plume top (Figure ~~3~~5(b), (e) and (h)), indicating that the model captures the vertical distributions of aerosols. The model also has good performance in simulating AOD at 532nm, although underestimations happen around latitude 36°N (Figure ~~3~~5(c), (f) and (i)).

The model is shown to be capable of simulating the major meteorological and chemical evolution of this haze event. As spatial and vertical profiles of the haze period are incomplete or missing in the satellite retrievals and ground stations only provide point estimates, we can use the model to understand the haze spatial, vertical and temporal evolution, as discussed in the following sections.

4 Results and Discussions

4.1 Meteorological conditions and evolution of air pollutants

The evolution of the spatial distributions of the haze event is shown in Figure ~~4~~6, where the horizontal distributions of $PM_{2.5}$ and wind vectors are plotted every 12 hours from January 14 00:00 to January 21 00:00. In the second plot (January 14 12:00), air flows converged at the NCP surface areas ~~were controlled by a low pressure system and air flows converged~~, resulting in a small increase of $PM_{2.5}$ concentration. From January 14 00:00 to January 16 00:00, $PM_{2.5}$ concentration over the NCP was generally below 120μg/m^3. From January 16 to January 18, Beijing and surrounding areas were controlled by a weak high pressure system (Zhao et al.,

2013). During this period, large amounts of emissions in the NCP accumulated and the persistent southerly winds brought some air pollutants ~~upwards~~ northward to Beijing and southern Hebei areas. The weak high pressure system was replaced by a low pressure system that lasted until January 20, and this weather condition was not conductive for dispersion of air pollutants (Zhao et al., 2013). ~~The weak high pressure system was too weak to disperse air pollutants and the replaced low pressure system aggravated the accumulation of air pollutants.~~ On January 19, the NCP haze was in the worst state, with $PM_{2.5}$ concentrations above 350μg/m^3 in south NCP. From January 20, strong northerly winds dispersed the accumulated air pollutants and the haze ended.

To illustrate the vertical structure of the haze, vertical cross sections of $PM_{2.5}$ concentration and clouds are presented in Figure ~~S7~~ 7 ~~(see supporting information).~~ The cross section location is diagonally cuts the region with the lower left corner of 34N, 110E to the upper corner at 44N, 122E (see supporting information Figure S4).~~shown in Figure S6~~ ~~S4 (see supporting information).~~ There were two highly polluted points (around latitudes 35 and 39) and they started merging as one from January 18 12:00 (Figure ~~S7~~7). At that time, southerly winds blew air pollutants northwards (Figure ~~4~~6) and the polluted region was expanded. On January 19, there were fog and/or clouds near the surface and the impacts of fog and/or clouds will be discussed in section 4.2.

Further details of the evolution of the haze are shown in the temporal variations of $PM_{2.5}$ concentrations in Shijiazhuang, Tianjin and Chengde (marked in Figure S1) in Figure ~~S~~8 ~~(see supporting information)~~. All three sites show similar temporal variations. Around noon of January 15, $PM_{2.5}$ concentrations in Shijiazhuang, Chengde and Beijing increased at nearly the same time, labeled by red arrow in Figure ~~S~~8. Air pollutants started accumulating when the NCP was controlled by the weak and stable weather conditions. Compared to Shijiazhuang and Beijing, the capital city of Hebei province and the capital of China, $PM_{2.5}$ concentrations in Chengde were lower (Figure ~~S~~8). It was estimated that there are more than 8100 coal-fired boilers and industrial kilns in Shijiazhuang city (Peng et al., 2002), resulting in high intensity of emissions in Shijiazhuang. On January 20, Chengde was the first to show sharp decrease of

$PM_{2.5}$ concentrations, followed by Beijing and Shijiazhuang, corresponding to the northerly wind impacts discussed above.

To better understand the relationships between meteorological factors and pollution levels, time series of different pairs of variables are shown in Figure ~~5~~9. CO shows very high correlation with $PM_{2.5}$ (Figure ~~5~~9(a)), which is consistent with the observation and modeling results in Santiago, Chile (Perez et al., 2004; Saide et al., 2011), and shows the large contribution of primary sources (including gaseous precursors) to $PM_{2.5}$. Secondary aerosol formation also plays a role as $PM_{2.5}$ peaks on the 19th while CO peaks on the 18th. RH and wind speed are two important factors affecting the concentrations of aerosols. RH has similar variations as $PM_{2.5}$ concentration (shown in Figure ~~5~~9(a) and 5(b)). The NCP is close to the sea and under the slow southerly flows, temperature and RH increase along with $PM_{2.5}$. During the haze event, RH values were generally above 40% and wind speeds were below 2 m/s (Figure ~~5~~9(b)). Low wind speed is unfavorable for the dilution of air pollutants and high RH would accelerate the formation of secondary species, such as sulfate and nitrate, to aggravate the pollution level (Sun et al., 2006). NO_X concentrations show similar variations as $PM_{2.5}$, indicating the buildup of concentrations during the wind speed stagnation. Ozone shows lower concentrations during haze event (Figure ~~5~~9(c)) because high aerosol loadings produce low photochemical activity due to decrease in UV radiation. The concentrations have an inverse relationship with PBL Height (PBLH) as shown in Figure ~~5~~9(d). Diurnal maximums of PBLHs were mostly below 400m and PBL collapsed at night during the haze event, indicating aerosols were trapped near the surface. On January 21 and 22, PBLHs were between 800 and 1000 meters, which helped diffuse and dilute the air pollutants, resulting in a decrease in concentration. The relationships between these variables are further discussed with respect to the influences of aerosol feedback mechanism in section 4.4.

Figure ~~6~~ 10 shows the temporal variations of vertical profiles of simulated $PM_{2.5}$ concentration (a), temperature (b), RH (c) and wind speeds (d) at the Beijing site. $PM_{2.5}$ was accumulated below 500m and concentrations reached peak values around January 18 00:00 (Figure ~~6~~10(a)), when a strong temperature inversion happened over Beijing (Figure ~~6~~10(b)), which inhibited vertical atmospheric mixing. A strong temperature inversion also happened on January 19

(Figure ~~6~~10(b)). From January 16 to 19, RH was mostly higher than 50% and reached a peak on the night of January 19 (Figure ~~6~~10(c)). As a result, air pollutants released into the atmosphere were trapped in the moist atmosphere and accumulated as near surface horizontal winds were very weak (below 1.5m/s) during the haze period (Figure ~~6~~10(d)). As mentioned above, the high RH enhances the formation of secondary species, which will be discussed in the following section.

4.2 Evolution of aerosol composition during haze

As shown above, during haze events, aerosols build up due to low mixing heights and low wind speeds. An important question is what is the role of secondary aerosol formation during such events? Previous measurement studies have found that the increase of secondary inorganic pollutants could be considered as a common property of haze pollution in East China (Zhao et al., 2013). ~~However, few modeling studies have focused on the chemical characteristics, especially the secondary aerosol formation during haze.~~ The observed and simulated chemical species of $PM_{2.5}$ in Beijing are shown in Figure ~~7~~11(a) and ~~7~~11(b), respectively. Observed secondary inorganic aerosols (SIA) (NH_4^+, SO_4^{2-}, NO^{3-}) increased significantly during the haze episode and accounted for 37.7% of $PM_{2.5}$ mass concentration (Zhao et al., 2013). Primary OC, BC, sulfate, nitrate and ammonium accounted for the major parts of the simulated $PM_{2.5}$ during haze. Table ~~2~~ 4 summarizes the mean concentrations of primary aerosols (primary OC and BC) and SIA (NH_4^+, SO_4^{2-}, NO^{3-}) in non-haze days, and in the most serious haze day. The primary aerosols increased by a factor of ~~11.8~~4.0 from non-haze days to haze days. The SIA also increased from non-haze days to haze days, which agrees with the observation (Tan et al., 2009; Zhao et al., 2013). The SIA increased by a factor of ~~33.4~~7.6 from non-haze days to haze days. The increasing factors for observed primary aerosols and SIA are 2.9 and 6.9, which are close to those factors from simulations. However, the amounts of sulfate are underestimated by WRF-Chem, compared with the observation in Figure ~~7~~11(a) from Zhao et al. (2013). Tuccella et al. (2012) pointed out that the underestimation of simulated sulfate could be due to the underestimation of SO_2 gas phase oxidation, errors in nighttime boundary layer height predicted by WRF-Chem, and/or the uncertainties in aqueous-phase chemistry. It could also be caused by the missing heterogeneous sulfate formation in current model (He et al., 2014a; Wang et al., 2014d; Zheng et al., 2014a). As

discussed earlier, the SO_2 gas phase concentrations at this site were overestimated. Adding reaction pathways to produce sulfate aerosol would improve both the predictions of sulfate (increase) and SO_2 (decrease) (He et al., 2014a; Wang et al., 2014c; Zheng et al., 2014a).

We investigated the role of aqueous phase chemistry during the haze event. ~~Figure S9 (see supporting information) shows the contribution of aqueous chemistry to $PM_{2.5}$ (calculated as the difference between with and without cloud chemistry scenarios).~~ The aqueous phase pathway can reach a level of over 50 μg/m^3 around the Beijing area, accounting for a significant part (about 14.3%) of total $PM_{2.5}$ concentration (see supporting information Figure S5). As shown in Figure ~~S~~7, fog/clouds existed near the surface on January 19 and this corresponds to the $PM_{2.5}$ difference on that day ~~in Figure S9~~due to aqueous phase pathway. The sulfate production in aqueous phase may be higher than shown ~~here~~ in this study ~~due to~~after adding missing aqueous-phase reactions. The impacts of heterogeneous reactions on sulfate production will be investigated in future studies.

As shown in Figure ~~7~~11(a) and 7(b), the model underestimates OC. To evaluate the formation of Secondary Organic Aerosol (SOA) during the haze event, the RADM2/MADE-SORGAM model was used. The CBMZ/MOSAIC version used is not capable of simulating SOA formation because CBMZ was hard-wired with a numerical solver in WRF-Chem and thus SOA condensable precursors could not be directly added into it (Zhang et al., 2012). RADM2 is an upgrade of RADM1 and it gives more realistic predictions of H_2O_2 (Stockwell et al., 1990), and Schell et al., (2001) incorporated SOA into the Modal Aerosol Dynamics Model for Europe (MADE) (Ackermann et al., 1998) by means of the Secondary Organic Aerosol Model (SORGAM). SORGAM treats anthropogenic and biogenic aerosol precursors separately and eight SOA compounds are considered, of which four are anthropogenic and the other four are biogenic (Schell et al., 2001). Predicted Anthropogenic SOA (ASOA), biogenic SOA (BSOA) and Primary Organic Aerosol (POA) in Beijing are shown in Figure ~~7~~11(c). SOA indeed shows a marked increase from non-haze days to haze days, but the amount of SOA is very small compared with POA. The highest SOA concentrations in China are usually found in summer and in Central China (Jiang et al., 2012). In addition, almost all of the simulated SOA are ASOA. Jiang et al. (2012) also concluded that in winter, the fractions of ASOA are larger than 90% in

north China. Biogenic emissions are usually controlled by solar radiation and temperature, and solar radiation is weaker and temperature is lower in winter compared with summer. Moreover, the high isoprene, API (a-pinene and other cyclic terpenes with one double bond) and LIM (limonene and other cyclic diene terpenes) emissions are located below 30 °N and in Northeast China (Jiang et al., 2012), not in the NCP, so the SOA concentrations are not high in this winter haze event period in the NCP. As shown in Table ~~2~~4, the mean SOA concentration in non-haze days is 0.15μg/m^3 and in the most serious haze day is 8.2μg/m^3. The factor increase of SOA from non-haze days to haze day is 8.2, which is lower than that of primary aerosols and much lower than that of SIA. The SOA formation in winter has not been well studied and it might be underestimated by the model as it could have missing pathways to SOA formation. Further work is needed to improve the underestimation of SOA formation in the winter.

4.3 Impacts of surrounding areas on haze in Beijing

Previous studies found that both local emissions and regional transport have significant contributions to the high fine particle levels in Beijing (Yang et al., 2011). ~~In section 4.1, we mentioned that there exists a high correlation between CO and $PM_{2.5}$ concentrations. Figure S10 (see supporting information) shows the correlations of $PM_{2.5}$ and CO concentrations in Beijing (a) and SDZ (b). The correlation coefficients are 0.91 and 0.96, respectively. According to these high correlations, we can use CO transport to represent $PM_{2.5}$ transport to quantify the local and regional contributions to the Beijing haze. CO tracer tests~~Two~~A~~ sensitivity simulation~~s~~ ~~were~~ was conducted ~~in two simulations~~to quantify the contributions of surrounding areas to haze in Beijing~~:~~. ~~one with~~when Beijing local ~~CO~~ emissions ~~on and the other one with Beijing local emissions~~were turned off. The ratio of $PM_{2.5}$ ~~CO~~ in Beijing when Beijing emissions are turned off to $PM_{2.5}$ ~~CO~~ in Beijing when Beijing emissions are on represents the non-local contributions. It can reach above 8~~7~~0% during haze (see supporting information Figure ~~S11~~S6) and the average contribution is about 6~~4.5~~47.8% from January 16 to January 19. ~~These contribution values can be used to represent the non-local contributions to the $PM_{2.5}$ levels in Beijing during haze.~~

To figure out the dominant transport paths, FLEXPART-WRF (Stohl et al., 1998; Fast and Easter, 2006) was used to generate 72-hour backward dispersions around the Beijing area. 50000 particles were released backwards from a box (1 degree×1 degree×400m), the center of which is

Beijing urban area, from January 19 00:00. The number concentrations of particles were plotted at 6 hours before, 12 hours before, 24 hours before and 48 hours before the released time (Figure 812). For 12 hours, Beijing was influenced by sources to the south, including sources from south Hebei, Tianjin and Shandong. For 2 days, more sources contributed to the haze buildup in Beijing, including sources from Henan and Inner Mongolia. A number of coal mines are located in Hebei, Shandong and Henan provinces and Inner Mongolia areas have high emissions of primary aerosols.

4.4 The impact of aerosol feedback

Aerosols affect weather and climate through many pathways, including reducing downward solar radiation through absorption and scattering (direct effect), changing temperature, wind speed, RH and atmospheric stability due to absorption by absorbing aerosols (semi-direct effect), serving as cloud condensation nuclei (CCN) and thus impacting optical properties of clouds (first indirect effect), and affecting cloud coverage, lifetime of clouds and precipitation (second indirect effect) (Zhang et al., 2010; Forkel et al., 2012). The feedback mechanisms are complex and many aspects of them are not well understood. Although previous studies have investigated aerosol-radiation-meteorology interactions (Y. Zhang et al., 2010; R. Forkel et al., 2012), the studies on short time scale events with high aerosol loadings, such as haze events, are limited. This section focuses on evaluating the impacts of aerosol feedback mechanism on meteorology and air quality. The feedback discussed in this paper only includes aerosols' direct and semi-direct effects.

4.4.1 Impact of feedback on meteorology and $PM_{2.5}$ distribution

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Figure 913(a) shows the observed daily maximum surface solar radiation and simulated surface solar radiation in for the with feedback (WF) and without feedback (NF) scenarios in Beijing. Simulated daily surface maximum surface shortwave radiation values in for the NF feedback scenario are higher than observations and the overestimations are reduced by implementing aerosol feedback (Figure 913(a)). In For the NF scenariocase, the correlation coefficient R between simulated and observed daily maximum surface shortwave radiation is 0.84 in Beijing;

for the WF scenario, the correaltin coefficient increased to R=0.93, and the haze reduced the shortwave radiation values by 30 to 80%. ~~in WF scenario, simulated and observed surface shortwave radiation are highly correlated, with 0.93 R value in Beijing, proving that high concentrations of aerosols can significantly affect radiative transfer. Ding et al. (2013) investigated the influence of aerosols on weather during biomass burning episodes using radiation measurements and drew similar conclusions. However, their study did not include the evaluation of aerosol feedbacks from a modeling perspective.~~

The changes in radiation have impacts on the environment. Simulated PBLH and $PM_{2.5}$ concentration at Shijiazhuang ~~in~~ for the WF and NF scenarios are shown in Figure ~~9~~13(b) and ~~9~~13(c). In non-haze days, PBLH differences between the two scenarios are negligible due to low aerosol loadings. In haze days, PBLHs in the WF scenario are generally lower (by up to 60%) than in the NF scenario. As shown in Figure ~~9~~13(c), $PM_{2.5}$ concentration at Shijiazhuang in WF scenario is higher than it in the NF scenario and the difference reaches about 50μg/m^3 on January 19. Aerosols affect PBLHs in two ways: (1) radiation is scattered back to sky and absorbed, and as a result, radiation reaching the surface is reduced (Figure ~~9~~13(a)) and so ~~is~~ temperature is lowered; and (2) suspended aerosols like BC absorb radiation to heat the upper PBL (Ding et al., 2013). Both of these ways increase temperature inversion and atmospheric stability, and thus exacerbate $PM_{2.5}$ pollution.

Figure ~~10~~ 14 shows temporal variations of vertical profiles of (a) $PM_{2.5}$ (c) RH (e) temperature (g) wind speeds differences in Beijing between WF and NF scenarios. When aerosol feedback is included, $PM_{2.5}$ concentrations near Beijing surface are mostly increased, except on the morning of January 17, on the afternoon of January 18 and on January 19 (Figure ~~10~~14(a)). The increases of $PM_{2.5}$ are caused by the above mentioned ~~increases of temperature inversion~~decrease of temperature gradient from surface to aloft (shown in Figure ~~10~~14(e)) and atmospheric stability. Apart from these, $PM_{2.5}$ concentrations are also affected by RH and wind speeds. In WF scenario, RH is generally increased near the surface, especially on January 19 (Figure~~.~~ ~~10~~14(c)), while horizontal wind speeds are also increased on January 19, which is the main cause of decreases of $PM_{2.5}$ concentrations in Beijing.

To evaluate the impact of aerosol feedback on horizontal meteorological fields and $PM_{2.5}$ distributions, averaged differences of $PM_{2.5}$ concentrations, temperature, PBLHs and horizontal winds between WF and NF scenarios at 2p.m. and 2a.m. in haze days (from January 16 to 19) were calculated and are shown in Figure ~~11~~15. Figure ~~11~~15(c) shows that PBLHs are reduced in almost all NCP areas when aerosol feedbacks are considered at 2p.m.. At 2p.m., $PM_{2.5}$ concentrations are increased about 20μg/m^3 at Shijiazhuang (114.53°E, 38.03°N). In a few locations (the areas ~~below~~ to the south of Beijing (Figure ~~11~~15(a))), PM levels are decreased, although PBLHs are suppressed in those areas. The decreases of $PM_{2.5}$ concentrations in the areas ~~below~~ south of Beijing are due to big horizontal wind changes, shown in Figure ~~11~~15(g). When aerosol feedback is included, surface temperature is reduced in areas where there are high aerosol loadings (Figure ~~11~~15(e)). Figure ~~11~~15(d) shows that PBLHs are enhanced in east and southwest NCP areas at 2a.m. with aerosol feedback. Aerosol feedback mechanism at night time is more complex compared to it at day time. At night, there is no incoming shortwave radiation from the sun and major radiation is the long wave radiation emitted from the earth. The presence of clouds and some kinds of aerosols can trap outgoing long wave radiation, and as a result, the surface atmosphere is warmed. Different aerosols show different effects on long wave radiation. Greenhouse gases (GHGs) absorb long wave radiation, while large particles like dust scatter long wave radiation. As a result, the upper atmosphere temperature is likely to be warmer or cooler than surface atmosphere temperature. If the upper atmosphere is warmer than the surface, a stable PBL will form. This can explain why aerosol feedbacks increase PBL heights in some regions and decrease in some other regions of NCP. Changes of $PM_{2.5}$ concentrations at 2a.m. are mainly caused by changed PBLHs (Figure ~~11~~15(b)), showing decreasing trends in areas where PBLHs are enhanced, because changes of winds are relatively small (Figure~~.~~ ~~11~~15(h)). Temperature changes at 2a.m. are similar to it at 2p.m., but the magnitudes are smaller.

4.4.2 Impact of BC absorption on meteorology and $PM_{2.5}$ distribution

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To investigate BC's influence on meteorology and air quality, sensitivity tests were conducted by removing BC absorption in WRF-Chem (i.e., imaginary refractive index set to zero). Figure ~~10~~ 14 shows temporal variations of vertical profiles of (b) $PM_{2.5}$ (d) RH (f) temperature and (h) wind speeds differences in Beijing between WF and NBCA scenarios. The differences between

WF and NBCA can be used to represent impacts of BC absorption since in WF scenario both scattering and absorbing are considered while in the NBCA scenario only scattering is considered. It is obvious from Figure ~~10~~14(f) that the upper atmosphere is heated by BC, especially at 1.5km, which increases temperature inversion and atmospheric stability. BC absorption's impacts on $PM_{2.5}$, RH and wind speeds are similar to the impacts of both scattering and absorption, but the magnitudes are smaller (Figure ~~10~~14(b), (d) and (g)).

Figure ~~12~~ 16 is similar to Figure ~~11~~ 15 except that the differences are between WF and NBCA scenarios. At 2p.m., $PM_{2.5}$ concentration is increased about 10μg/m^3 in Shijiazhuang (114.53°E, 38.03°N), accounting for about 50% of $PM_{2.5}$ changes due to the total aerosol feedback (Figure ~~12~~16(a)). At 2p.m., PBL heights are decreased about 40-150m (Figure ~~12~~16(c)), accounting for about 50% of those changes in Figure ~~11~~15(c). At 2p.m., surface temperature in high aerosol loading areas are decreased about 0-2 °C (Figure ~~12~~16(e)), while the temperature decreases in the same areas are above 2°C in Figure ~~12~~16(e). At 2a.m., changes of $PM_{2.5,}$ PBLHs, surface temperature and wind speeds are similar to Figure ~~11~~15, with smaller magnitudes.

The contribution of BC absorption in aerosol feedbacks depend on the model performance in simulating BC and scattering aerosols (sulfate, OC). As shown in Figure ~~7~~11, BC was overestimated, and sulfate and OC were underestimated in Beijing. The overestimation could be as large as a factor by 2 in some days. As a result, the contributions of BC absorption in aerosol feedbacks ~~may have been overestimated in this study~~are uncertain. To explore the uncertainties of the BC absorption contribution, we conducted a simulation~~s~~ by reducing BC emissions by 50%. The changes of PBLH and $PM_{2.5}$ concentrations at 2p.m. due to aerosol feedbacks and BC absorption after BC emission changes are shown in Figure 1~~3~~7. The domain maximum increases of $PM_{2.5}$ concentrations because of aerosol feedbacks and BC absorption are 19.1μg/m^3 and 10.21μg/m^3, respectively. The domain maximum decreases of PBLH due to aerosol feedbacks and BC absorption are 235.7m and 114.2m, respectively for the base and 50% BC emission cases. These numbers are smaller than before because BC emissions were reduced by 50%. Due to 50% perturbation in BC emissions, the contribution of BC absorption in aerosol feedbacks decreased from about 60% to 50%. This number can be additionally reduced if OC and sulfate concentrations are simulated well. ~~The underestimations of OC and sulfate were because some secondary formation pathways are missing in the current model.~~ In the future, we can get more

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accurate estimations of BC absorption in aerosol feedbacks after the performances of simulating BC, OC and sulfate are improved.

5 Conclusions

In this study, the online coupled WRF-Chem model was used to reproduce the haze event happened in January, 2010 in the NCP. The model was evaluated against multiple observations, including surface observations of meteorological variables and air pollutants, atmospheric sounding products, surface AOD measurements, and satellite AOD measurements. The correlation coefficients between simulated and observed $PM_{2.5}$ concentrations in Beijing, Tianjin and Xianghe stations are 0.77, 0.75 and 0.69, indicating that WRF-Chem provides reliable representation for the 2010 haze event in the NCP.

This haze event is mainly caused by high emissions of air pollutants in the NCP region and stable weather conditions in winter. The haze built up almost simultaneously in major cities in the NCP and dissipated from north to south. During haze days, horizontal wind speeds and mixing heights were low, temperature inversion happened above surface and RH values were above 40%. Photochemistry was not significant during haze days due to weak UV radiation. In addition, secondary inorganic aerosols played an important role in the haze event. The role of cloud chemistry in this haze event cannot be ignored.

The contribution of non-local sources to $PM_{2.5}$ in Beijing was also studied. ~~CO was used to represent $PM_{2.5}$ to quantify non-local contributions to $PM_{2.5}$ in Beijing based on high correlations between them.~~ The average contribution is about ~~47.8~~64.5% in haze days. The FLEXPART model was implemented to investigate the sources of the non-local contributions and results show that air pollutants from south Hebei, Tianjin city, Shandong and Henan provinces are the major contributors to the $PM_{2.5}$ in Beijing.

Impacts of high aerosols in haze days on radiation, boundary layer heights and $PM_{2.5}$ have been demonstrated. When aerosol feedback is considered, simulated surface radiation agrees well with observations. In haze days, aerosol feedback has important impacts on surface temperature, RH and wind speeds, and these meteorological variables affect aerosol distribution and formation in turn. The role of BC in aerosol feedback loop has also been investigated. It can account for about as high as 65.7% of the $PM_{2.5}$ increases, and 59.9% of the PBLH decreases in Shijiazhuang. More attention should be paid to BC from both air pollution control and climate change perspectives. Due to the underestimation of sulfate and OC, and overestimation of BC in the current model, the contribution of BC absorption in aerosol feedbacks may have been overestimated. We decreased the BC emission by 50%, and found that the contribution decreased from about 60% to 50%. The uncertainty of this contribution can be additionally reduced by improving the model performance in simulating sulfate and OC.

~~50 % of the $PM_{2.5}$ increases and 50% of the PBLH decreases in Shijiazhuang. More attention should be paid to BC from both air pollution control and climate change perspectives.~~

~~This study still has some limitations. First, underestimation of sulfate and OC is a problem of WRF-Chem model. Further studies are needed to improve the simulation of sulfate and organic aerosols. Second, emissions have large uncertainties in Asia, which affect air quality simulations determinedly. Some advanced techniques, such as data assimilation, can be applied to reduce uncertainties in the future.~~

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chemical data are available at http://www.acd.ucar.edu/wrf-chem/mozart.shtml. Contact M. Gao (meng-gao@uiowa.edu) or G.R. Carmichael (gcarmich@engineering.uiowa.edu) for data requests.

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Table 1. **Observation Data and Variables Used in This Study.**

Data sets [a]	Variables [b]	Data frequency	Number of sites used	Data sources
CMDSSS	T2, RH2, WS10	Daily	4	http://cdc.cma.gov.cn/home.do
Atmospheric Sounding	T, RH	12 hours	1	http://weather.uwyo.edu/upperair/sounding.html
CARE-China	$PM_{2.5}$, NO_2, SO_2	Hourly	3	
CSHNET	AOD	Hourly	4	
SDZ	T1.5, RH1.5, WS10, $PM_{2.5}$, NO_2, CO	Hourly	1	Zhao et al. (2013)
CALIPSO	AOD	N/A	N/A	http://www-calipso.larc.nasa.gov/
MODIS	AOD	Daily	N/A	http://ladsweb.nascom.nasa.gov/data/search.html

[a]CMDSSS—China Meteorological Data Sharing Service System; CARE-China—Campaign on the atmospheric Aerosol Research network of China; CSHNET—Chinese Sun Hazemeter Network; SDZ—Observation data at

Shangdianzi site are extracted from paper Zhao et al. (2013); CALIPSO—The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation; MODIS—the Moderate Resolution Imaging Spectroradiometer. [b]T2— temperature at 2m; RH2—relative humidity at 2m; WS10—wind speed at 10m; T1.5—temperature at 1.5m; RH1.5—relative humidity at 1.5m; AOD—Aerosol Optical Depth.

Table 2. **Performance Statistics for Meteorological Variables.**

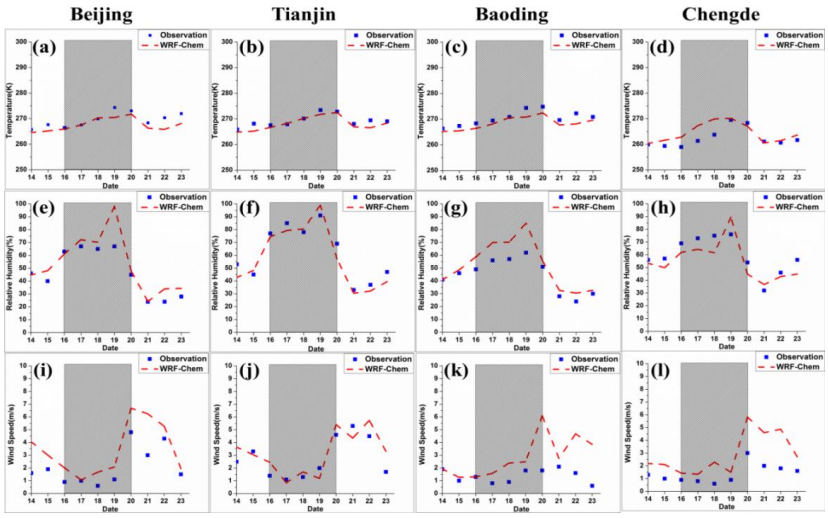
Variables	Beijing					Tianjin					Baoding					Chengde				
	Obs.	Mod.	MB	ME	RMSE	Obs.	Mod.	MB	ME	RMSE	Obs.	Mod.	MB	ME	RMSE	Obs.	Mod.	MB	ME	RMSE
T2(K)	269.5	267.6	-1.9	2.0	2.5	269.3	268.1	-1.1	1.2	1.5	270.4	268.5	-2.0	2.0	2.3	262.5	264.5	2.0	2.4	3.2
RH2 (%)	46.9	53.4	6.6	7.2	11.1	61.5	58.4	-3.1	5.9	6.4	44.4	52.5	8.1	8.1	10.4	59.4	55.0	-4.4	8.0	8.8
WS10(m/s)	2.1	3.4	1.3	1.3	1.6	2.8	3.2	0.4	1.0	1.1	1.4	2.8	1.4	1.4	2.1	1.4	2.9	1.5	1.5	1.8

Table ~~1~~3. Performance Statistics of $PM_{2.5}$

	Obs. ($\mu g/m^3$)	Model ($\mu g/m^3$)	R	MB ($\mu g/m^3$)	ME ($\mu g/m^3$)	NMB (%)	NME (%)	MFB (%)	MFE (%)
Beijing	111.7	122.1	0.77	-10.4	30.4	-8.5	24.9	0.4	26.3
Tianjin	103.3	141.2	0.75	-37.9	56.1	-26.9	39.7	-7.8	49.6
Xianghe	93.0	152.6	0.69	-59.7	68.0	-39.1	44.5	-21.8	50.7

Table ~~2~~4. Primary Aerosol, SIA and SOA (μg/m^3) during Haze Days and Non-haze Days in Beijing

	Primary	SIA	SOA
Haze days	56.4~~81.3~~	~~137.6~~81.9	~~1.23~~1.1
Non-haze days	14.2~~6.9~~	~~4.1~~10.8	~~0.15~~0.3
Ratio	4.0~~11.8~~	~~33.4~~7.6	~~8.2~~3.7



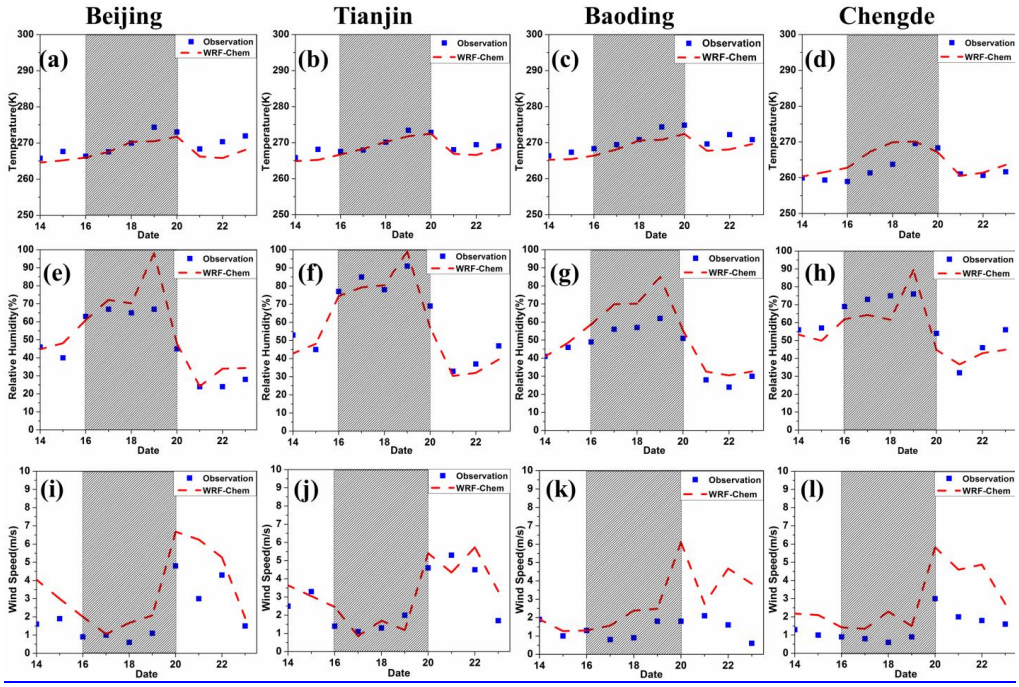


Figure 1. The temporal variations of observed and simulated 24-h average temperature (a-d), relative humidity (e-h) and wind speed (i-l) in the Beijing, Tianjin, Baoding, and Chengde stations.

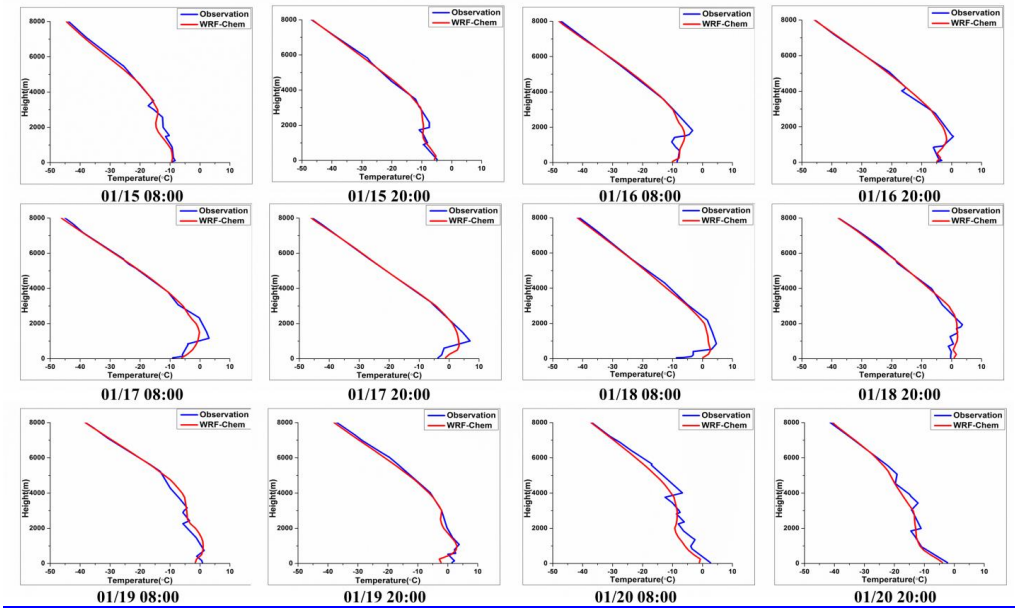


Figure 2. Simulated and observed vertical temperature profiles at 0800 and 2000 (China Standard Time, CST) from 15 January to 20 January.

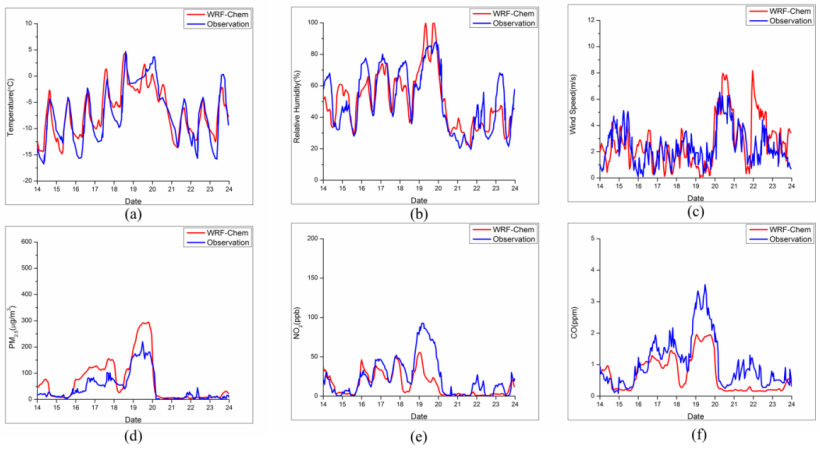


Figure 3. Simulated and observed hourly temperature, RH, wind speed, $PM_{2.5}$, NO_2 and CO in the Shangdianzi (SDZ) station.

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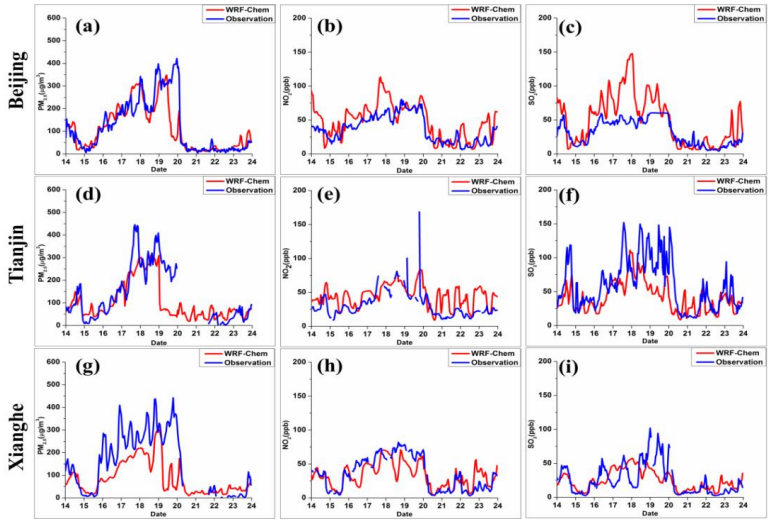
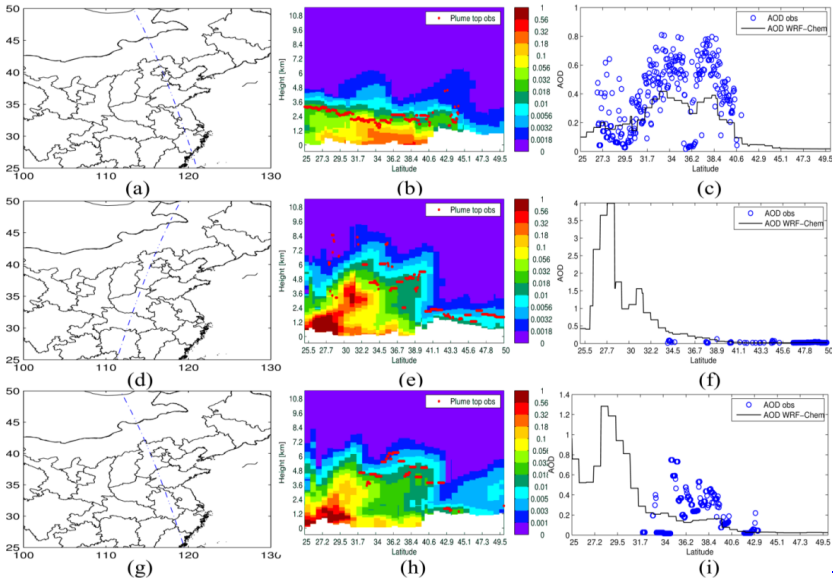


Figure ~~2~~4. Temporal variations of the simulated and observed $PM_{2.5}$, NO_2 and SO_2 at Beijing (a-c), Tianjin (d-f) and Xianghe (g-i) stations.


Plume top obs
AOD obs
AOD WRF–Chem
Height [km]
AOD
Latitude
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)

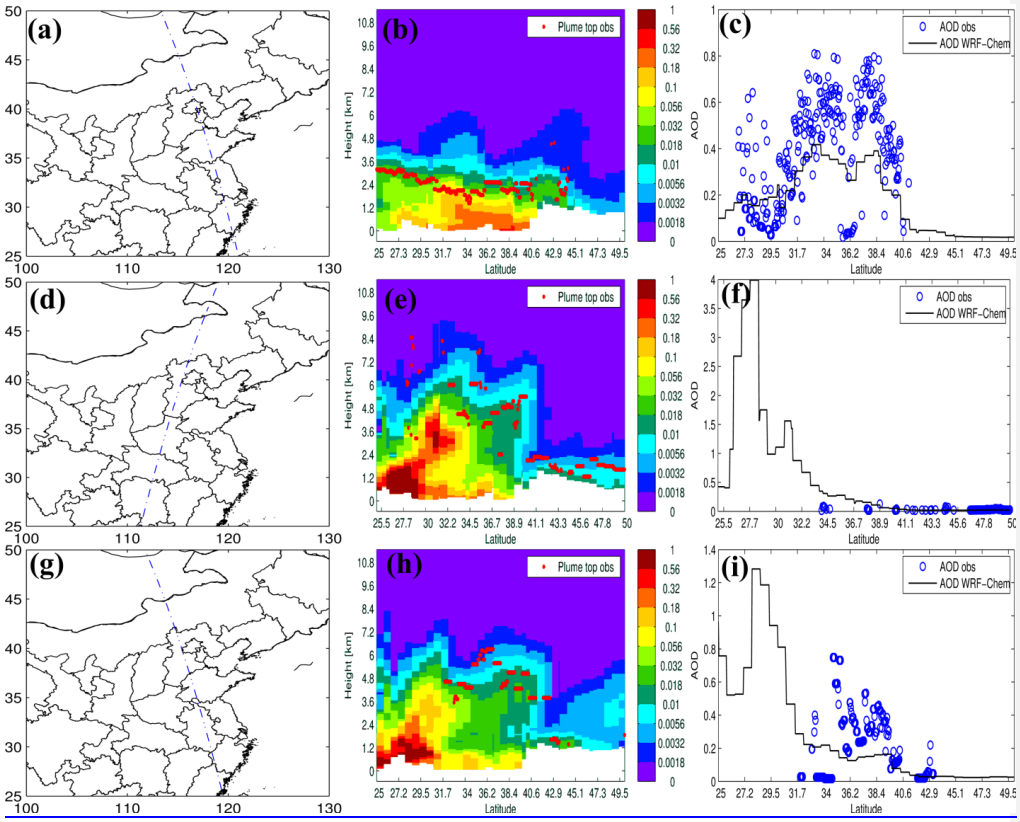


Figure ~~3~~5. Routes of CALIPSO satellite, simulated extinction coefficient and observed plume top, and simulated AOD and CALIPSO retrieved AOD at 532nm at three moments: January 14 12:00(CST) (a-c), January 21 02:00(CST) (d-f), and January 21 12:00(CST) (g-i).

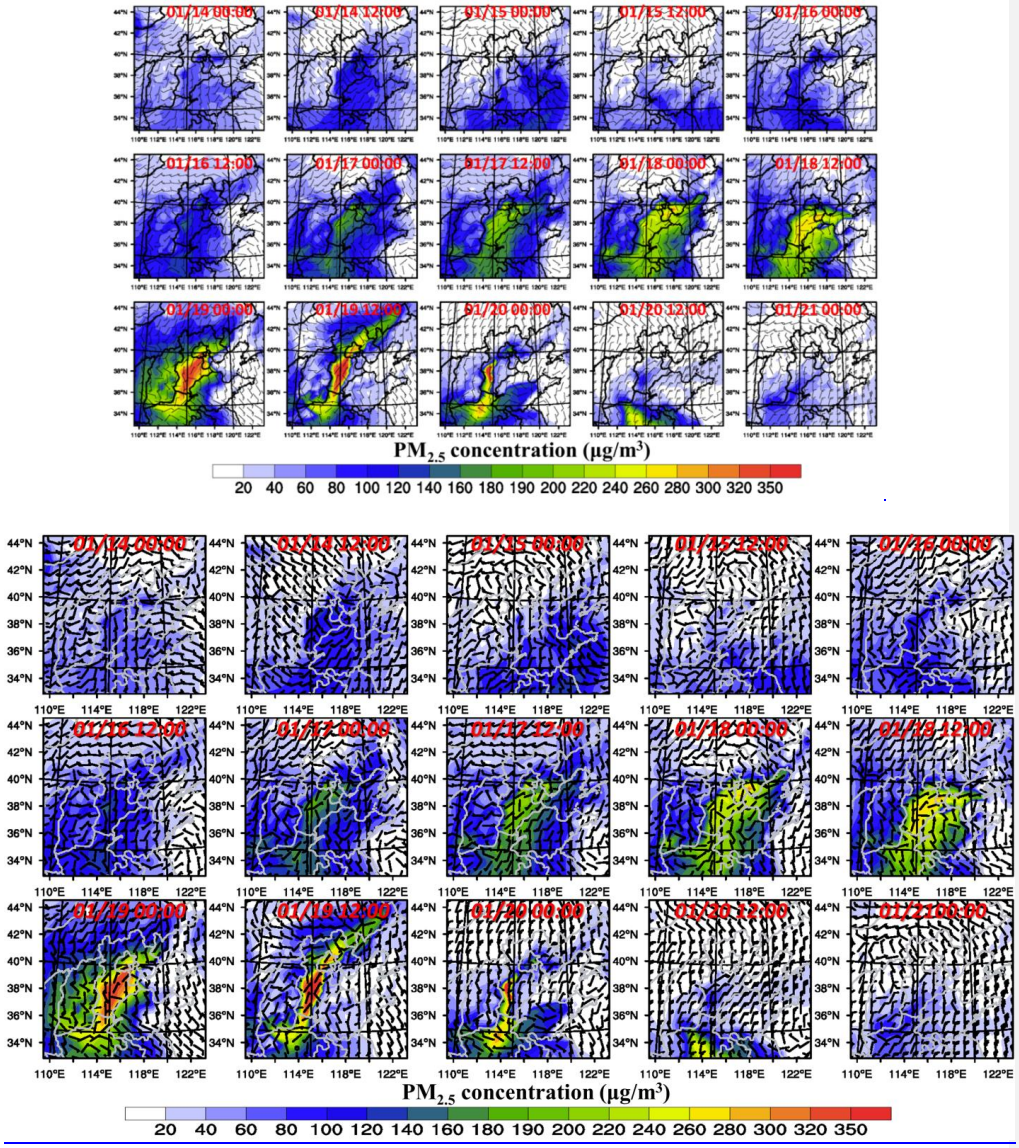


Figure 64. $PM_{2.5}$ concentration from 14 January 00:00 to 21 00:00 January, plotted every 12 hours.

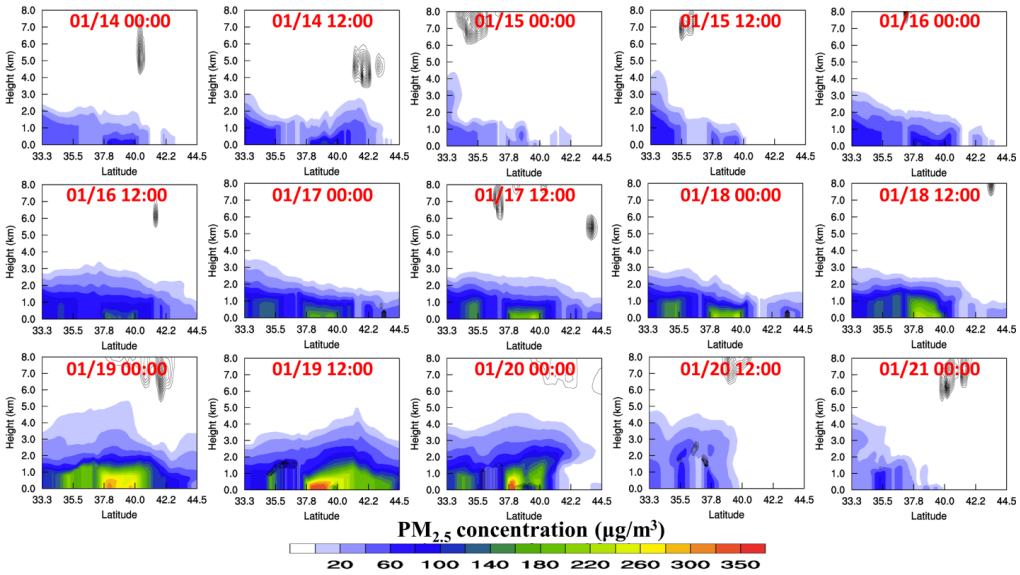


Figure 7. Cross section plots of $PM_{2.5}$ concentration and clouds from 14 January 00:00 to 21 00:00 January every 12 hours.

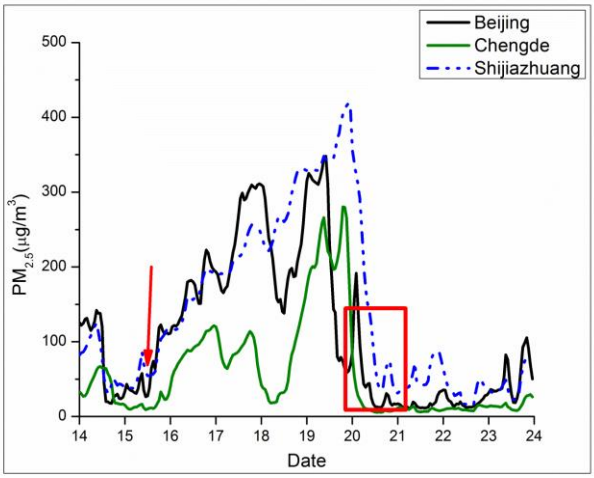


Figure 8. Temporal variations of simulated $PM_{2.5}$ at Shijiazhuang, Beijing and Chengde.

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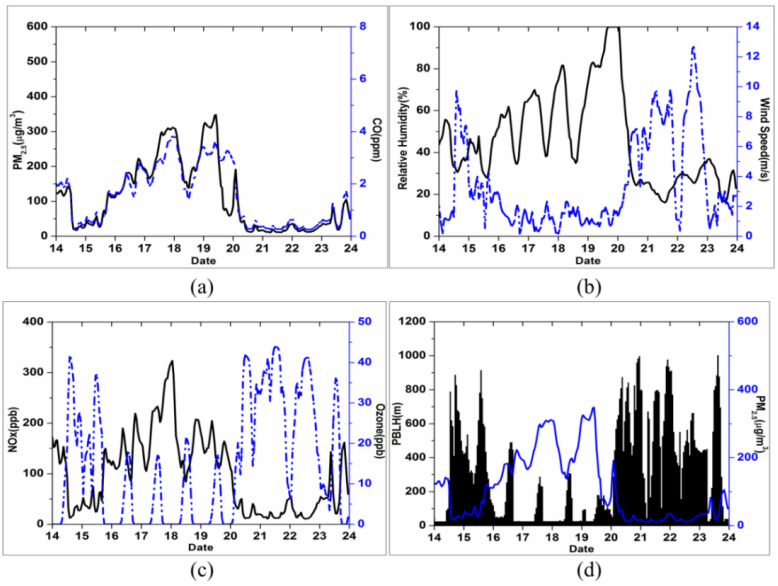


Figure 5~~9~~. Simulated temporal variations of meteorological and chemical variables in Beijing.

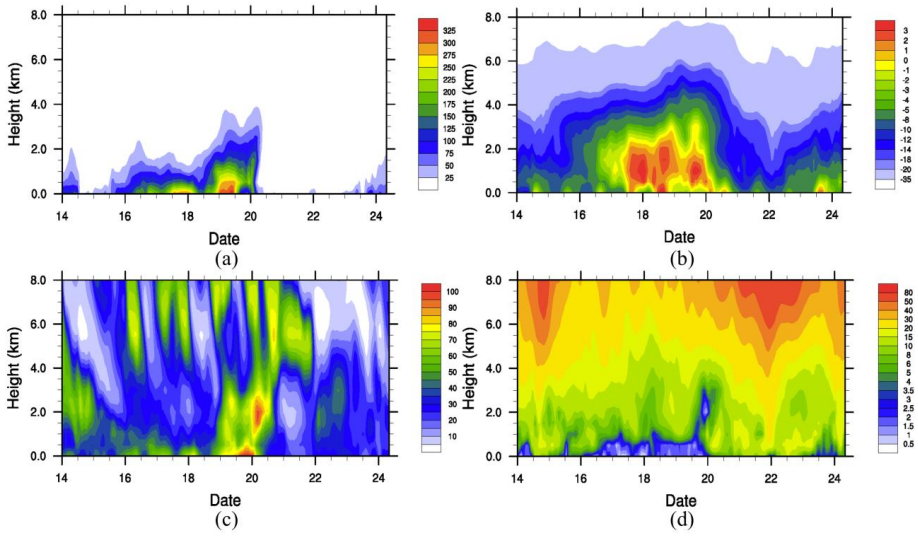
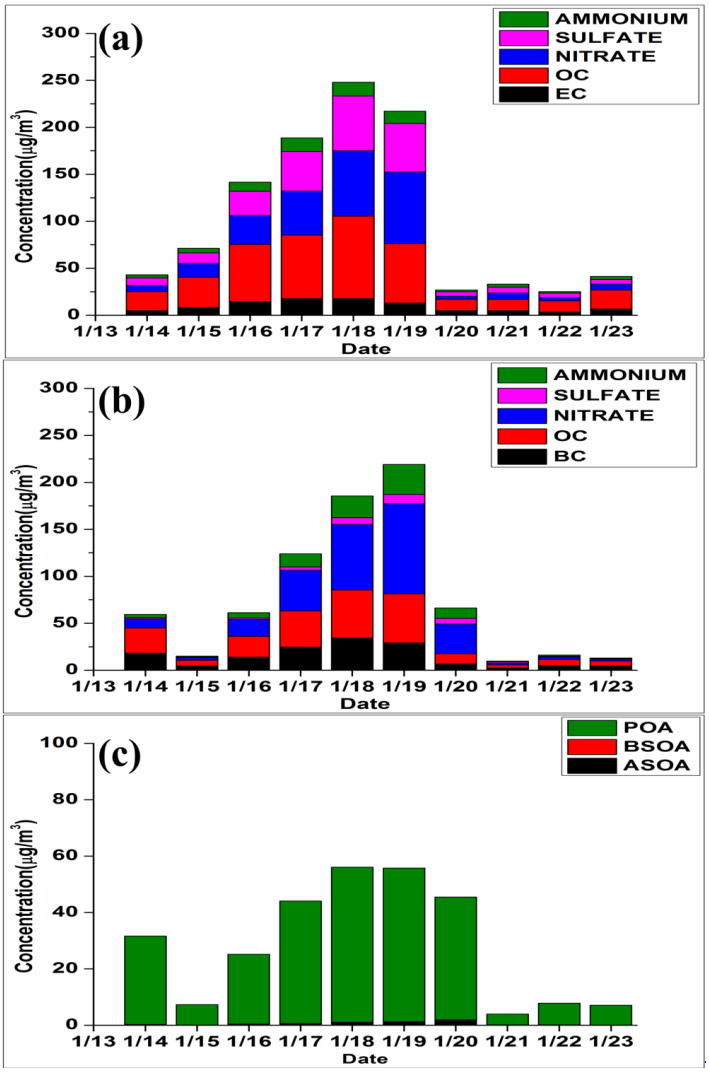


Figure ~~6~~10. Temporal variations of vertical profiles of simulated (a) $PM_{2.5}$ (unit: $\mu g/m^3$) (b) temperature (unit: °C) (c) RH (unit: %) (d) wind speeds (unit: m/s) in Beijing.



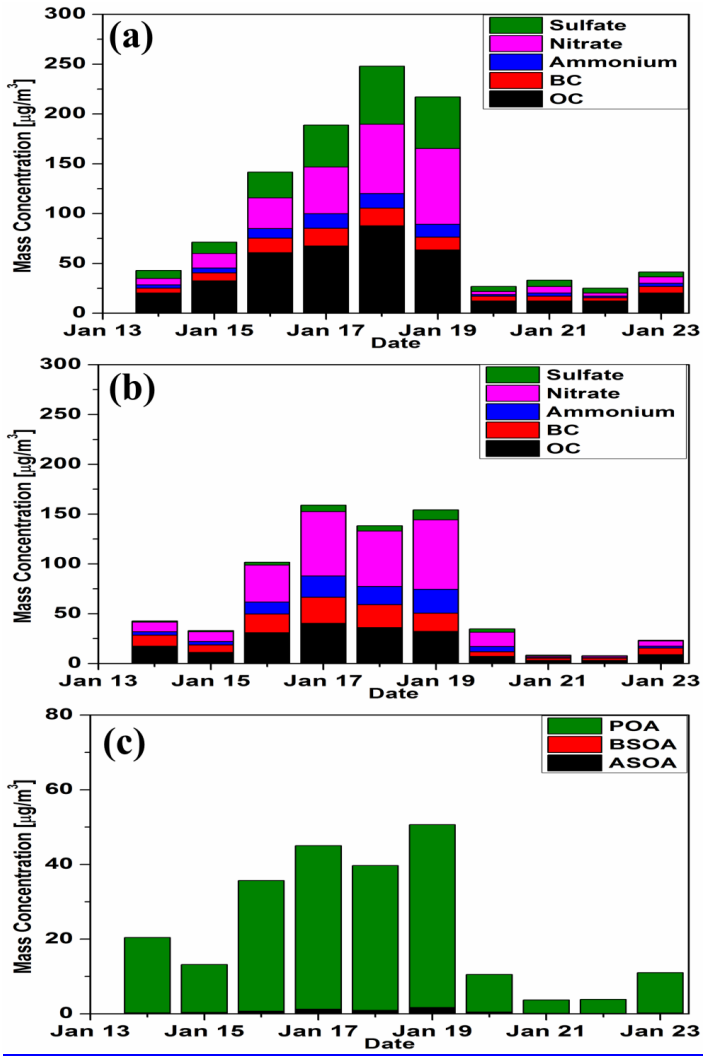
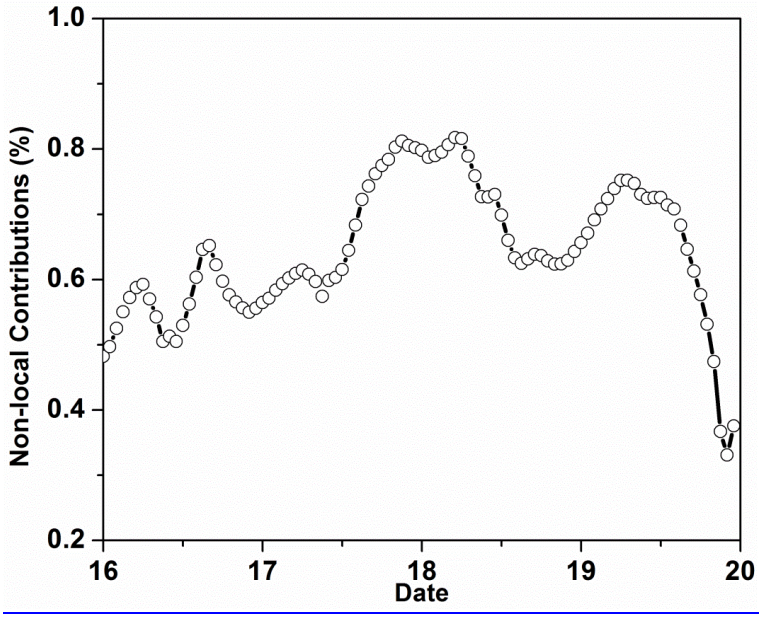


Figure ~~7~~11. Observed (a) and simulated (b) chemical species of $PM_{2.5}$ and simulated SOA (c) in the Beijing site.


Non-local Contributions (%)
1.0
0.8
0.6
0.4
0.2
16
17
18
19
20
Date

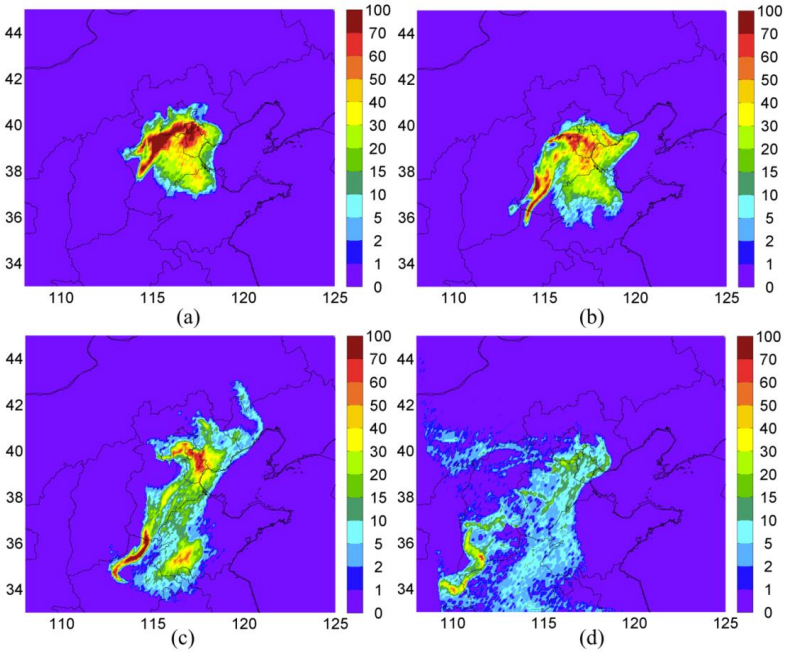

(a)
(b)
(c)
(d)
100
70
60
50
40
30
20
15
10
5
2
1
0
44
42
40
38
36
34
110
115
120
125

Figure ~~8~~12. Backward dispersion of particles released on January 19 00:00, plotted 6, 12, 24, and 48 hours before being released (unit: number/grid cell).

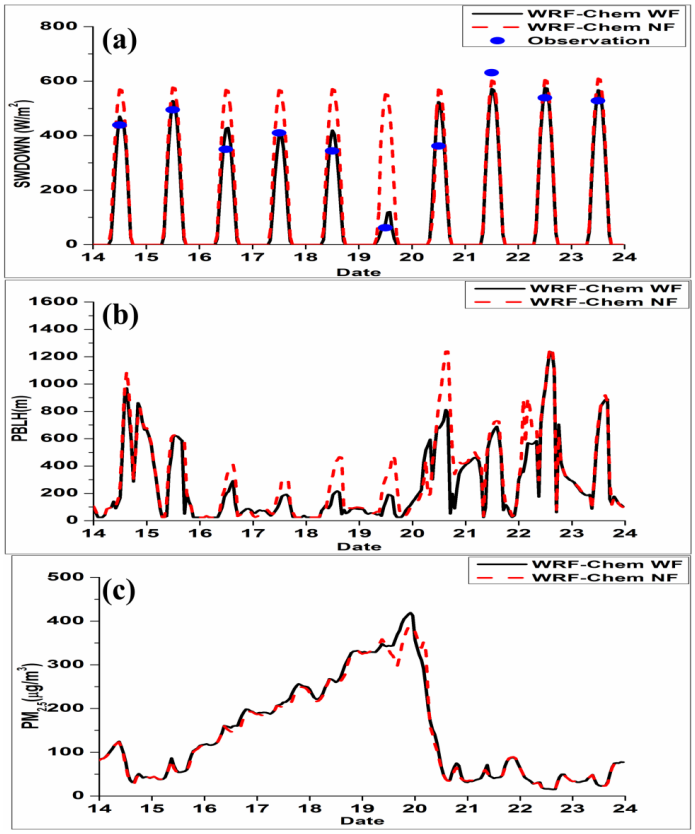


Figure ~~9~~13. Observed daily maximum surface solar radiation and simulated surface shortwave radiation in with feedback (WF) and without feedback (NF) scenarios in Beijing (a), simulated PBLH (b) in WF and NF scenarios at Shijiazhuang, and simulated $PM_{2.5}$ concentration (c) in WF and NF scenarios at Shijiazhuang.

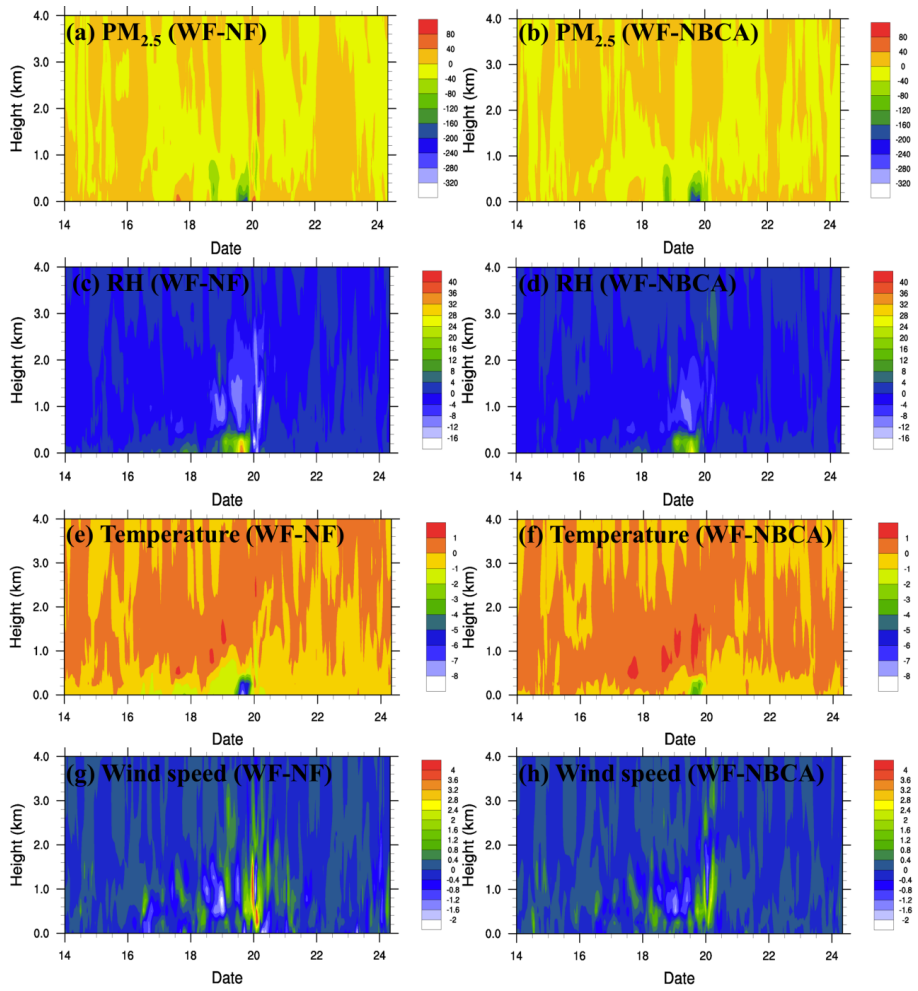
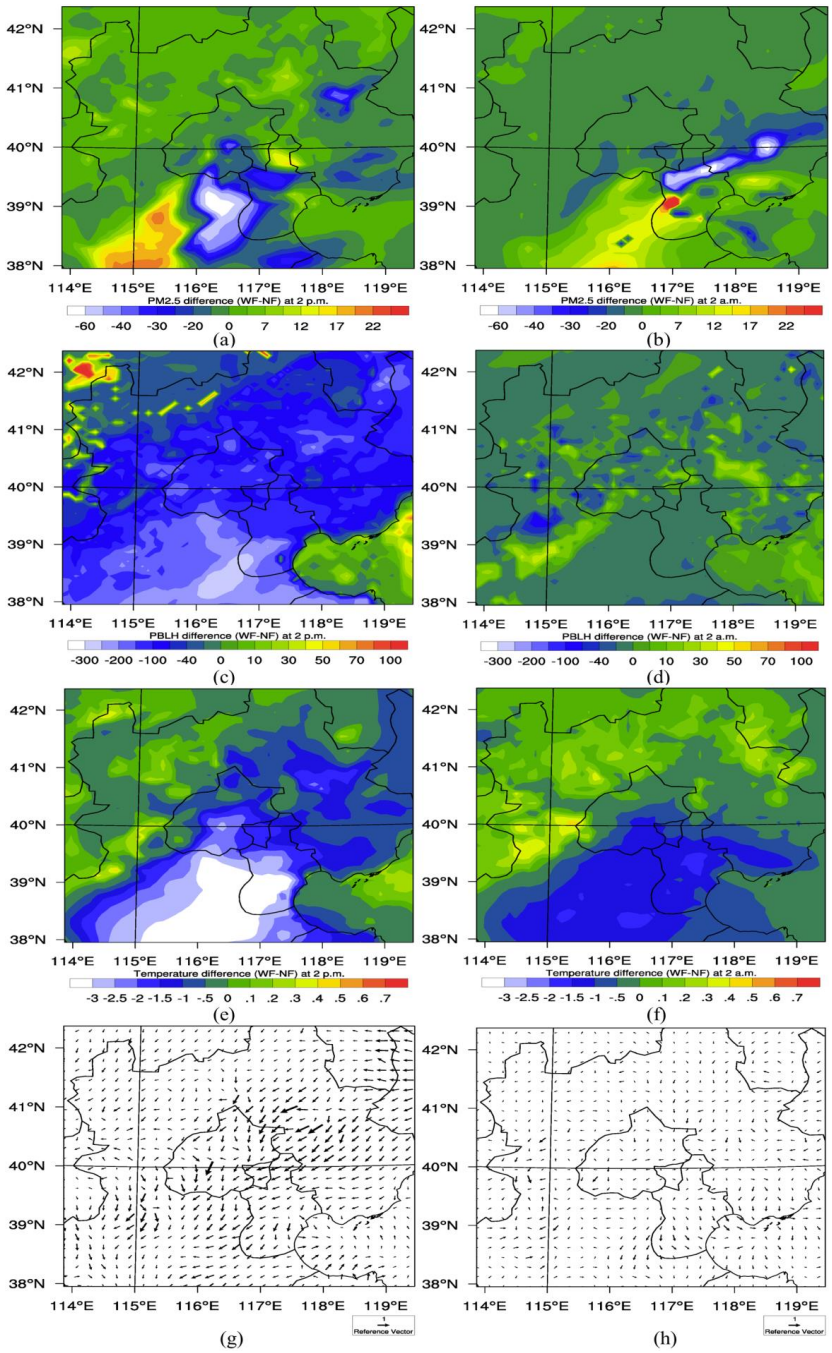


Figure ~~10~~14. Temporal variations of vertical profiles of (a) $PM_{2.5}$ (unit: μg/m^3) (c) RH (unit: %) (e) temperature (unit: °C) (g) wind speeds (unit: m/s) differences in Beijing between WF and NF scenarios; (b), (d), (f) and (h) are $PM_{2.5}$, RH, temperature and wind speeds differences in Beijing between WF and NBCA (BC absorptions are teased out) scenarios.


42°N
41°N
40°N
39°N
38°N
114°E 115°E 116°E 117°E 118°E 119°E
PM2.5 difference (WF-NF) at 2 p.m.
-60 -40 -30 -20 0 7 12 17 22
(a)
PM2.5 difference (WF-NF) at 2 a.m.
-60 -40 -30 -20 0 7 12 17 22
(b)
PBLH difference (WF-NF) at 2 p.m.
-300 -200 -100 -40 0 10 30 50 70 100
(c)
PBLH difference (WF-NF) at 2 a.m.
-300 -200 -100 -40 0 10 30 50 70 100
(d)
Temperature difference (WF-NF) at 2 p.m.
-3 -2.5 -2 -1.5 -1 -.5 0 .1 .2 .3 .4 .5 .6 .7
(e)
Temperature difference (WF-NF) at 2 a.m.
-3 -2.5 -2 -1.5 -1 -.5 0 .1 .2 .3 .4 .5 .6 .7
(f)
Reference Vector
(g)
Reference Vector
(h)

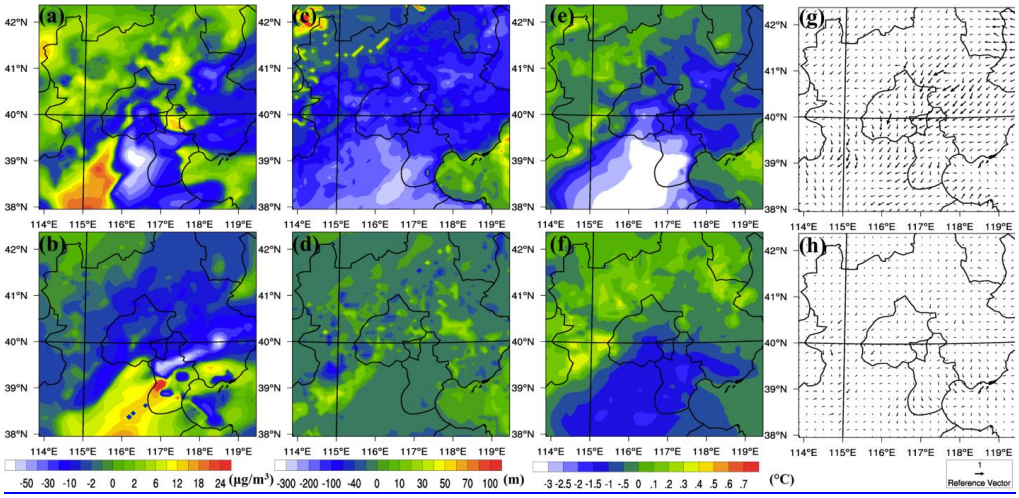
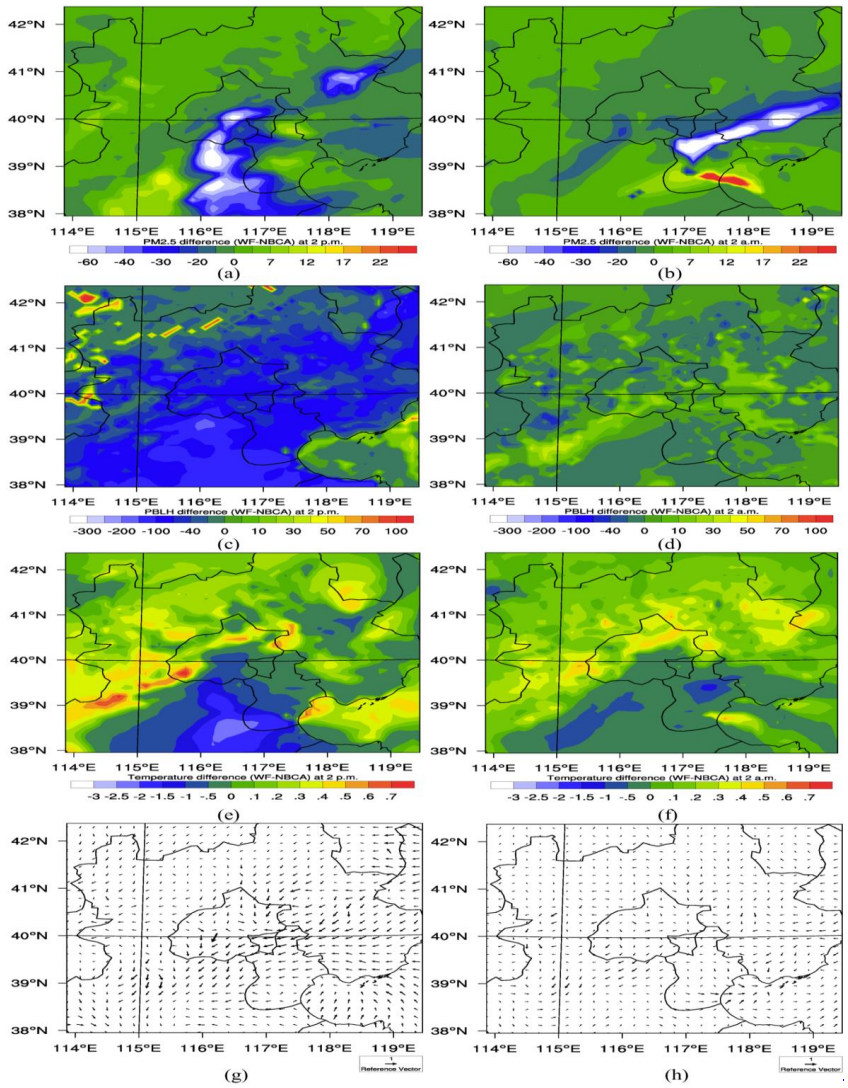


Figure ~~11~~15. Differences of $PM_{2.5}$ concentration (unit: μg/m^3), temperature (unit: °C), PBLH (unit: m) and horizontal wind (unit: m/s) at 2p.m. (a, c, e, g) and 2a.m. (b, d, f, h) between WF and NF scenarios.


42°N
41°N
40°N
39°N
38°N
114°E 115°E 116°E 117°E 118°E 119°E
PM2.5 difference (WF-NBCA) at 2 p.m.
-60 -40 -30 -20 0 7 12 17 22
(a)
PM2.5 difference (WF-NBCA) at 2 a.m.
-60 -40 -30 -20 0 7 12 17 22
(b)
PBLH difference (WF-NBCA) at 2 p.m.
-300 -200 -100 -40 0 10 30 50 70 100
(c)
PBLH difference (WF-NBCA) at 2 a.m.
-300 -200 -100 -40 0 10 30 50 70 100
(d)
Temperature difference (WF-NBCA) at 2 p.m.
-3 -2.5 -2 -1.5 -1 -.5 0 .1 .2 .3 .4 .5 .6 .7
(e)
Temperature difference (WF-NBCA) at 2 a.m.
-3 -2.5 -2 -1.5 -1 -.5 0 .1 .2 .3 .4 .5 .6 .7
(f)
1
Reference Vector
(g)
1
Reference Vector
(h)

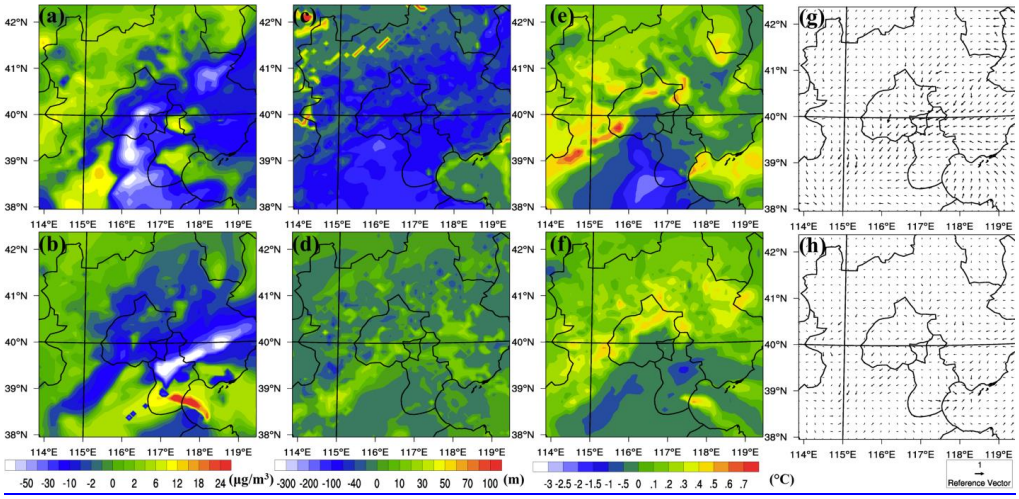


Figure ~~12~~16. Differences of $PM_{2.5}$ concentration (unit: μg/m^3), temperature (unit: °C), PBLH (unit: m) and horizontal wind (unit: m/s) at 2p.m. (a, c, e, g) and 2a.m. (b, d, f, h) between WF and NBCA scenarios.

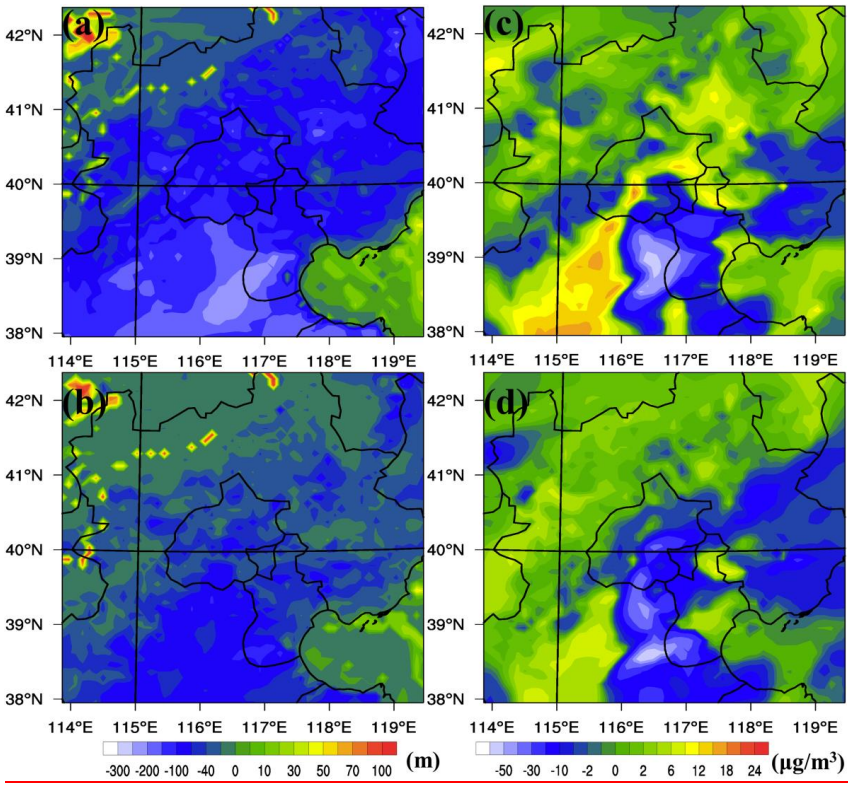


Figure 17. Differences of PBLH (unit: m) and $PM_{2.5}$ concentration (unit: μg/m^3) at 2p.m. between WF and NF scenarios (a, c) when BC emissions were reduced by half; differences of PBLH (unit: m) and $PM_{2.5}$ concentration (unit: μg/m^3) at 2p.m. between WF and NF scenarios (b, d) when BC emissions were reduced by half