Dear editor and referees,

We thank you for your time on our paper. The comments and suggestions are useful to improve the quality of the manuscript. Herein we present the replies to all the comments on our manuscript named "Effects of black carbon and boundary layer interaction on surface ozone in Nanjing, China"

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Referee#1

(1) The address for 5th institution should be 'Tropical and Marine Meteorology'.

Reply: Follow the referee's comment. We have rechecked the address of the 5th institution and corrected
10   it in the revised manuscript.

(2) The conclusions in abstract are a little messy, please reorganize your findings.

Reply: Thank you for your comment. Our main conclusion of our study is that, with the impacts of BC, the surface ozone reduced before noon which is primarily caused by the changes in the ozone
15   contribution from chemical and physical processes. Among the changes in these processes, the change in vertical mixing process takes major responsibility for the reduction of surface ozone. We have adjusted the conclusions in abstract. And we believe that the conclusion will be more clear and easy to following. Please check the new abstract in the revised manuscript.

20   (3) Page 9 line 17: Please define how you calculate the ozone gradient.

Reply: Follow this comment. The vertical gradient of ozone is the difference of the ozone concentration between every two adjacent vertical layers. Because of the sigma coordinate in vertical direction in WRF-Chem, the ozone concentration is firstly interpolated in vertical direction with height interval of 50m. And then, the vertical gradient of ozone concentration is calculated as the Equation:

25   $vertical\ gradient = O_3(h_{i+1}) - O_3(h_i)\ \ (i = 1, 2, 3 \ldots\ldots)$

where h_i and h_{i+1} are the heights of layer i and $(i + 1)$. The h_{i+1} equals to $h_i + 50$. $O_3(h_i)$ is the ozone concentration at the height of h_i. The definition of ozone gradient and the equation have been added

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into the revised manuscript. Please check them in page 9 (lines from 31 to 34) and page10 (lines from 1 to 3).

(4) Page 10: the less ozone near the surface is very likely caused by less ozone production aloft (Figure 6d), not weakened turbulence. Please provide a more comprehensive explanation for this.

Reply: Thank you for your comment. The less ozone chemical production aloft will influence the surface ozone. For example, the reduction of chemical contribution will change the ozone vertical gradients which could influence the vertical mixing of ozone which occurs in the BL and finally reduce the surface ozone. However, according to our results, the CHEM_DIF aloft occurred one hour later than the reduction of surface ozone did. In addition, the value of CHEM_DIF was small whereas the value of VMIX_DIF in the BL was large (-18 - -8 ppb h^{-1}) which suggested that the less chemical production aloft impacted limitedly on vertical mixing and surface ozone. Besides ozone gradients, VMIX is closely related to the turbulence. As Figure 7b shows, the turbulence exchange coefficient with the impacts of BC was much smaller than that without the impacts of BC. It suggested that, when ozone gradients in the two cases were similar with each other in the morning, the much weaker turbulence would entrain much less ozone down to surface and made the ozone reduction. Thus, it could be concluded that the reduction of surface ozone was primarily caused by the weakened turbulence. We have added more detailed discussion of this section and please check the details in pages from 8 to10 in the revised manuscript.

(5) Please be careful when interpret the surface VMIX term, because it also includes information of chemical production above surface. For example, if chemical production above surface larger and higher ozone above surface, it will lead to a positive VMIX term at the surface.

Reply: Thanks, we agree with your comment. The contribution from VMIX at surface is related to the turbulence and ozone vertical gradient above surface. Chemical production above surface will influence ozone vertical gradient. Thus, ozone exchanging in vertical direction, the VMIX at surface is surly includes the information of chemical production above surface. In our study, we primarily talked about the changes in processes contributions caused by BC. In figure 6d, with the impacts of BC, chemical

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contribution aloft decreased (with decreased rate between -9.4 and -2.1 ppb h^{-1}) from 11:00 to 14:00. This reduction would change the vertical gradients of ozone and further influence the vertical mixing of ozone. However, the significant change in vertical mixing in the BL (-18 to -8 pph h^{-1}) suggested that the changes in chemical process cause limited influence on the changes in vertical mixing process.

5 According to our discussion, the weakened turbulence and the suppressed BL, which being caused by the impacts of BC, were more important to the change of VMIX.

Referee#2

(1) Fig. 2 is too crowded. In order to better evaluate the model simulation in details, the authors should

10 enlarge the figure. I suggest it can be separated to 2 figures. One figure only contains meteorological parameters (Fig. 2a) and another is for chemical species (Fig. 2b).

Reply: Follow the referee's comment. The figure 2 is separated to 2 parts, Figure 2a only contains the meteorological parameters and Figure 2b only contains the chemical species. Please check the new Figure 2 in the revised manuscript.

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(2) Fig. 3 has a similar problem. The Fig. 3C is impossible to read. It should be an individual panel.

Reply: Follow the referee's comment. Figure 3 is rearranged, Fig. 3a and 3b are set as a panel and Fig. 3c is set as an individual panel. Please check the new Figure 3 in the revised manuscript.

20 (3) Why there is a consistent heating by BC around 1.2 km, especially at 10am. If it is due to residual layer of BC, the authors should explain it in more details.

Reply: Thank you for your comment. The consistent heating above BL is exactly due to the impacts of BC in the residual layer. We have added the explanation in the revised manuscript and please check the details in page 7 lines from 15 to 22.

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(4) In the introduction, the authors should reference the work by Tie et al. (2005). Although it used a global model, it is an early work to discuss the effect of aerosols (including BC) on photochemistry and

Reply: Thanks. These references are very helpful to our study. They have been cited in the introduction. Please check the details in the revised manuscript.

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Reply: Thank you for your comment. The photochemical production of ozone is not only related to the photolysis rate, but also related to the concentrations of ozone precursors (NO_x and VOCs). Since the suppression of BL, the concentrations of NO_x and VOCs increased at surface (figure S2). It should be noted that, the ratios of VOCs/NO_x also increased which suggested that VOCs increased more significantly than NOx did. In addition, the little changes of the ratio of HCHO/NO_y indicated that ozone still formed under the VOC-limited conditions. In this case, the increase of VOCs was favorable for ozone chemical formation. In our study, ozone contributions from chemistry were enhanced with the impacts of BC from 10:00 to 12:00. During this period, the photolysis rate was reduced which showed the reduce effect to the chemical production. Thus, the enhancement of ozone chemical production was more likely related to the increase of ozone precursors. In order to interpreting this problem, we have added a figure (Figure S2) in the supplement and the relevant discussion has been added into the revised manuscript. Please check the relevant information in page 7 (lines from 24 to 28) page 8 (lines from 31 to 34) and page 9 (lines from 1 to 2).

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Effects of black carbon and boundary layer interaction on surface ozone in Nanjing, China

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Abstract. As an important solar-radiation absorbing aerosol, the effect of black carbon (BC) on surface ozone, via reducing ~~by influencing~~ photolysis rate, has been widely discussed by "offline" model studies. However, BC-boundary layer (BL) interactions also influence surface ozone. Using the "online" model simulations and processes analysis, we demonstrate the

20 significant impact of BC-BL interaction on surface ozone in Nanjing. The absorbing effect of BC heats the air above the BL, ~~above the BL and~~ suppresses and delays ~~the BL~~ development of BL, which eventually leads to changes in surface ozone via changing the contributions ~~of~~ from ~~ozone through~~ chemical and physical processes (~~photochemistry~~photochemistry, vertical mixing~~, and advection~~ and advection). For chemical process, ~~Different from previous "offline" model studies, BL~~ the suppression of BL leads to large amounts of ozone precursors being confined below the BL which has the increased effect on

25 ozone chemical production and offset~~ting~~ the ~~influence~~ decrease effect ~~from~~ caused by the reduction of photolysis rate, thus enhancing ozone ~~photo~~chemical formation ~~before noon~~from 10:00 to 12:00. Furthermore, the changes in physical process, especially the vertical mixing process, show a more significant influence on surface ozone.~~Furthermore T~~, the changes in ~~physical process show a more significant influence on surface ozone. The weakened~~he weakened turbulence, caused by the suppressed BL, entrains much less ozone aloft ~~from the overlying ozone-rich air~~ down to surface.~~. As a result~~ Finally, by

30 summing-up the changes in the processes, ~~, the net contribution of ozone from physical and chemical processes leads to~~ surface ozone reduces~~reduction~~ before noon and t.~~ T~~he maximum reduction reaches to 16.4 ppb at 12:00. In ~~the~~ afternoon, the changes in chemical process are small which influence inconspicuously to surface ozone. However, the change in vertical mixing process ~~physical process~~ still influences ~~the~~ surface ozone significantly. Due to the delayed development of the BL, there are less ~~vertically mixed BL continues to show an~~ obvious ozone gradients ~~near~~ around the top of ~~the~~ BL.

35 Therefore, high concentrations of ~~more~~ ozone aloft still can be entrained down to the surface which ~~,~~ offsets~~ting~~ the ~~surface~~

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~~ozone~~ reduction of surface ozone. Comparing ~~all~~ the changes in the ~~contributions of~~ processes, the change in ~~the contribution of~~ vertical mixing plays ~~a more~~ the most important role in impacting surface ozone. Our results ~~show~~ highlight the great impacts of BC-BL interactions on surface ozone ~~.~~ via influencing the ozone contribution from physical process which suggests that ~~And~~ more attention should be paid on the mechanism of ~~mechanism of~~ aerosol-BL interactions when ~~we~~

5   controlling ~~deal with~~ the ozone pollution ~~control in China~~.

1 Introduction

Black carbon (BC) aerosol, also known as soot, is primarily formed by incomplete combustion of carbonaceous fuels, diesel fuels, and biomass (Bond et al., 2004). BC accounts for a small fraction, less than 15%, of the total mass concentration of aerosol particles in atmosphere over urban areas (Yang et al., 2011). However, it is of great interest because of its significant

10   influences on global radiation balance (Chameides and Bergin, 2002), both directly, by absorbing solar radiation (Liao and Seinfeld, 2005; Ramanathan and Carmichael, 2008), and indirectly, by affecting cloud formation (Lohmann and Feichter, 1997; Fan et al., 2015). Owing to such impacts on radiation, BC plays an important role in global and regional climate change (Jacobson, 2001; Bond et al., 2013), weather (Qian et al, 2003; Saide et al., 2015), and the atmospheric environment (Li et al., 2005; Ding et al., 2016; Peng et al., 2016). In addition, the BC aging mechanism (Qiu et al., 2012), the

15   performance of BC in heterogeneous reactions (Lei et al., 2004; Li et al., 2012), and its impact on human health (Atkinson et al., 2012) have been the focus of significant research in recent years.

Tropospheric ozone is a typical secondary air pollutant (Crutzen, 1973). It has important environmental effects on the atmosphere (Monks et al., 2015) especially in the boundary layer (BL). The impact of aerosols, especially BC, on surface ozone has been attracting much attention from researchers. Dickerson et al. (1997) reported that BC decreases surface ozone

20   concentration by reducing photolysis rates. Jacobson (1998) suggested that aerosols containing BC cores reduced photolysis rates and resulted in a decrease of ozone concentration by 5%–8% at ground level in Los Angeles. Castro et al. (2001) found a strong reduction in photolysis rate (10%–30%) due to BC-containing aerosols. They also reported that this photolysis rate reduction led to a decrease of surface ozone in Mexico City. Similar results have been found in other studies simulating the effects of BC on surface ozone in other places around the world (Li et al., 2005; Tie et al., 2005; Li et al., 2011).

25   In addition to reducing photolysis rates, the global warming effect of BC is significant, preceded only by CO_2 (Jacobson, 2002). Incident solar radiation is absorbed by BC in the atmosphere, leading to the air aloft being heated and the temperature being raised. Conversely, air at low levels is cooled and the temperature is decreased. Under this condition, atmospheric stability is increased and the development of BL is suppressed during the daytime. Using an atmospheric model, Ding et al. (2016) demonstrated this effect and suggested that such BC-BL interactions will enhance the occurrences of haze pollution

30   episodes. Tie et al. (2017) also discussed the relationships between aerosol (including BC) and BL. Moreover, they highlighted the serious impacts of this mechanism on air qualities in winter. Owing to the close relationship between ozone

and BL development during the daytime (Zhang and Rao, 1999; Zhu et al., 2015), BC-BL interactions may also influence surface ozone; however, relevant studies on this phenomenon are still lacking.

As one of the most developed regions in China, the Yangtze River Delta (YRD) has reported severe haze (Ding et al., 2013a) and ozone pollution (Tie et al., 2013) in recent decades. Nanjing is the capital of Jiangsu province, which is an important industrial and economic centre in the YRD region. Previous studies have reported that the BC (Zhuang et al., 2014) and ozone (Ding et al., 2013b) concentrations are relatively high in Nanjing in October. In this study, measured data of BC and ozone, which were obtained in Nanjing in October 2015, were used to show variations in surface ozone under the conditions of high BC concentration and low BC concentration during daytime. Furthermore, the fully coupled "online" model system Weather Research and Forecasting with Chemistry (WRF-Chem) was applied to simulate the air pollutants (ozone, $PM_{2.5}$, and BC) in YRD in October 2015. With the consideration of the aerosol-BL feedback mechanism in the model system, we demonstrate the mechanism of the BC-BL interaction affecting surface ozone in Nanjing.

2 Model setting and data description

The Weather Research and Forecasting (WRF) model coupled with Chemistry (WRF-Chem), which is widely used to evaluate the impacts of aerosols on radiation (Zhang et al., 2010; Forkel et al, 2012), is a fully coupled online 3D Eulerian chemical transport model considering both chemical and physical processes. We used version 3.4 in this study, and detailed descriptions of the meteorological and chemical aspects of WRF-Chem can be found in Skamarock et al. (2008) and Grell et al. (2005). Regarding simulation settings, two nested domains (Figure 1) were set up with horizontal resolutions of 36 km and 12 km, and grids of 99 × 99 and 99 × 99 for the parent domain (D1) and nested domain (D2), respectively. The parent domain (D1), centred at (119.0°E, 31.5°N), covered most of China and the surrounding countries and ocean. The corresponding simulations provided meteorological and chemical boundary conditions for the nested domain (D2), which covered most of Eastern China.

There were 38 vertical layers from the surface up to a pressure limit of 50 hPa, of which 12 levels were located below the lowest 2 km to fully describe the vertical structure of the BL. Carbon-Bond Mechanism Z (CBM-Z), which includes 133 chemical reactions for 53 species and extends the framework to function for a longer time and at larger spatial scales than its predecessor; Carbon-Bond IV, was used as the gas-phase chemical mechanism (Zaveri and Peters, 1999). The corresponding aerosol chemical mechanism was the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC) with 8 bins (Zaveri et al., 2008), which is extremely efficient and does not compromise accuracy in aerosol model calculations. Other major model configuration options are listed in Table 1.

The National Centres for Environment Prediction (NCEP) final (FNL) Operational Global Analysis data files were used to provide the initial and boundary meteorological conditions for our simulations. The initial and boundary chemistry conditions were provided by the output of the Model of Ozone and Related Chemical Tracers (MOZART-4; Emmons et al., 2010). Both anthropogenic and natural emissions were inputted into the model system. Anthropogenic emissions were

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derived from the Multi-resolution Emission Inventory for China (MEIC) database (http://www.meicmodel.org/). MEIC contains both gaseous and aerosol species, including SO_2, NO_X, NH_3, CO, VOCs (volatile organic compounds), BC, OC (organic carbon), PM_{10}, and $PM_{2.5}$. Biogenic emissions were calculated using the Model of Emission of Gas and Aerosols from Nature (MEGAN; Guenther et al., 2006).

5   Two parallel experiments were conducted to investigate our subject: (1) simulation with aerosol feedback considering both the direct and indirect radiation effects from all chemical species (Exp_WF), in which aerosol optical properties were calculated at each time step and then coupled with the radiative transfer model for both short and long wave radiation (Iacono et al, 2008); (2) simulation with aerosol feedback, excluding BC (Exp_WFexBC), in which only the optical property of BC was subtracted when calculating the shortwave radiation and optical properties of all other aerosols were retained and

10   calculated in the same manner as in experiment EXP_WF (Wang et al., 2016). The two experiments started at 00:00 UTC on 1 October 2015 and ended at 00:00 UTC on 26 October 2015. In order to reduce the influence of initial conditions, the first 9 days were designated as the spin-up period.

We collected observational data on both meteorology (temperature, wind direction, and wind speed) and air pollutants (Ozone, NO_2 and $PM_{2.5}$) in five cities (Hefei, Maanshan, Nanjing, Zhejiang, and Wuxi, Figure 1) in October 2015 to evaluate

15   the model performance. Temperature, wind direction, and wind speed, with a temporal resolution of 3 h, were obtained from Meteorological Information Comprehensive Analysis and Process System (MICAPS). And these data were measured by the national surface observation network operated by the China Meteorological Administration (CMA). Data on the hourly concentrations of Ozone, NO_2, and $PM_{2.5}$ were downloaded from the publishing website of China National Environmental Monitoring Centre (http://113.108.142.147:20035/emcpublish). These air pollutants and three other pollutants (SO_2, PM_{10},

20   and CO) were measured by the national air quality monitoring network operated by the Ministry of Environmental Protection of China. The China National Environmental Monitoring Centre is responsible for ensuring data quality. More information of the air pollution measurements ~~are~~ is available in Wang et al. (2014). In addition, measurements of shortwave irradiance and BC concentrations in the northern suburb of Nanjing (near the ozone monitoring site) were taken. Shortwave irradiance was measured using a Pyranometer (MS-802F of EKO instrument, Japan). The measurement accuracy is 1 W m^{-2}

25   and the temporal resolution is 1 min. More information is available in the instrument manual (https://eko-eu.com/files/PyranometerManual20160926V11.pdf). Hourly concentrations of BC were measured by using an Aethalometer (model AE-33 of Magee Scientific, USA). The sampling time interval was set to 1 min and the inlet flow was set to 5 L min^{-1}. More information is available in Drinovec et al. (2015).

3 Result and Discussions

3.1 Model evaluation

To evaluate model performance, the measured and simulated variables from 10 to 26 October 2015 were compared (Figure 2a and 2b). In addition, shortwave and BC concentration data observed in Nanjing were used to evaluate the corresponding model predictions.

3.1.1 Meteorology evaluation

Regarding meteorological factors (Figure 2a), which highly impact transport, deposition, and transformation in the atmosphere (Li et al., 2008), a good performance of meteorological conditions will guarantee accuracy in the air pollutant simulations. In this study, the observed temperature, wind direction, and wind speed were used for evaluating the meteorological model. In addition, the shortwave irradiance measured in Nanjing was also used to evaluate the simulation of shortwaves. Model performance statistics, including index of agreement (IOA), mean bias (MB), and the root mean square error (RMSE), are shown in Table 2, along with benchmarks derived from Emery et al. (2001). The IOA of wind direction (WD) was based on the calculation suggested by Kwok et al. (2010), which considers the nature of WD, and others were calculated following the approach of Lu et al. (1997).

WD showed similar patterns between the simulation and observations, but MB values of WD in Zhenjiang, Hefei, and Wuxi were beyond the benchmark. However, the high values of IOA showed good agreement, indicating that the simulation successfully captured the wind direction during the period. Wind speed (WS) showed a slight over-estimation in Hefei and Wuxi with positive MBs of 0.72 and 0.87. Furthermore, the WS statistics are acceptable, especially IOAs and RMSEs, which are within the scope of the benchmarks. The negative MBs of temperature at 2 m above the surface (T2) indicate that the model predictions slightly underestimated T2. High values of IOAs in these cities indicate acceptable agreements between measurements and simulations. The short-wave radiation (SW) time series showed similar patterns between the simulation and measurements in Nanjing. The high IOAs and low biases (MB and RMSE) suggest satisfactory model performance on SW, which is very important for the determination of photochemistry and BC feedback mechanism.

3.1.2 Air pollutant evaluation

Measured hourly concentrations of O_3, NO_2, and $PM_{2.5}$ in the five cities were collected to evaluate the model performance on air pollutants. In addition, hourly BC concentrations measured in Nanjing were also used for evaluating the BC simulation. Statistical metrics on air pollutants, which include IOA, mean normalized bias (MNB), and mean fractional bias (MFB), are shown in Table 3, along with benchmarks derived from EPA (2005, 2007) .

For ozone, MNBs in Nanjing and Wuxi were slightly beyond the benchmarks. However, the time series shows similar patterns between the simulation and measurements (Figure 2b), reflected by the high values of IOA. As an important ozone precursor, a good model performance on NO_2 is necessary. More than 0.7 of IOA values reflect the good agreement between

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measurements and simulations. The values of MNBs and MFBs are close to those of other studies in this region in October (Hu et al., 2016). Owing to its complex chemical composition, accurate simulation of PM$_{2.5}$ was difficult. The IOA values of PM$_{2.5}$ were lower than those of O$_3$. However, MFBs were within the benchmarks, indicating that the model predictions of PM$_{2.5}$ are acceptable. For the BC time series, similar patterns were found between the simulation and observation.

5 Considering that the MFB was within the benchmarks for PM$_{2.5}$ and the relevant high value of IOA (0.67), the model predictions of BC were deemed acceptable.

In general, based on the comparisons between measurements and simulations of both meteorology and air pollutants, the similar time series patterns and acceptable statistical results demonstrate the good simulation capability of the model system in capturing the meteorological and chemical features. In this case, the meteorological and chemical features in Eastern

10 China from 10 to 26 October 2015 were well reproduced, which is favourable for our analysis and discussions.

3.2 Observational and model results of BC and ozone

Analysing relevant observation data, ozone and BC concentrations on sunny days were selected. Subsequently, ozone concentrations were distributed into two sets ~~(Figure 3a)~~ based on the daytime mean BC concentrations being higher (black) and lower (red) than the monthly mean concentration (~3 μg m^{-3}). When BC concentration was higher (Figure 3a), the

15 increase in ozone concentrations occurred later than when BC was lower during 10:00 to 14:00. At 12:00, the difference between the two patterns of ozone concentrations reached to the maximum value. Because of the limited measurements, the formation of changes in ozone and the relationship between the BC-BL interaction and surface ozone could not be validated. In this case, numerical simulations using the online-coupled chemistry transport model WRF-Chem provides an effective method to analyse and discuss this subject.

20 With the application of WRF-Chem, Ding et al. (2016) reported the suppression of BL development induced by the warming effects of BC. By analysing our model outputs, the maximum changes in ~~mean~~ BL-Height~~~~ (ΔBLH_MAX) over Nanjing were calculated. ΔBLH_MAX is defined as the maximum difference of hourly mean BLH over Nanjing between Exp_WFexBC and Exp_WF during morning~~morning and noon~~ [Equation (1)].

$$\Delta BLH_{MAX} = \max(\overline{BLH}_{WFexBC}^{t=10:00} - \overline{BLH}_{WF}^{t=10:00}, \ldots \ldots, \overline{BLH}_{WFexBC}^{t=12:00} - \overline{BLH}_{WF}^{t=12:00}), \tag{1}$$

25 In Eq. (1), $\overline{BLH}$ is the mean boundary layer height over Nanjing. The simulated mean BC columns (from the surface to 2 km) over Nanjing, during the occurrence of ΔBLH_MAX, were also calculated. The relationship between the two variables is shown in Figure 3b. Similar to Ding's study, the positive values suggest that BL development is suppressed by the warming effect of BC. This effect is more significant at higher BC concentrations. For example, the BC column was more than 9 mg m^{-2} on 17 October and the ΔBLH_MAX was more than others (more than 400 m). Owing to the significant impact, we took

30 the model result of 17 October as an example to study the relationship among surface ozone, BC, and BL development. From 10:00 to 14:00 on 17 October, the average distribution (Figure 3c) of BC concentrations was inhomogeneous due to the inhomogeneous distribution of BC emissions (Qin and Xie, 2012) and wind fields at ground level. The northern areas were controlled by southerly winds, whereas northeast winds blew over the southern areas. In the central areas (most parts of

Jiangsu and Anhui), winds were weak, which is favourable for the accumulation of air pollutants. BC was therefore mainly concentrated in Nanjing and the surrounding areas. Conversely, surface ozone showed low concentration over this region, suggesting that BC and ozone at ground level showed opposite distributions over Nanjing.

3.3 The BC-BL interaction and its effects on photolysis rate and ozone precursors

5 ~~At high concentrations~~Because of the solar-radiation absorption of BC in the atmosphere, the incident shortwave radiation is attenuated ~~by BC~~. Consequently, other meteorological elements are affected. Figure 4a presents the vertical profiles of BC concentration (black solid line) and changes in related meteorological elements (Exp_WF−Exp_WFexBC) induced by BC at 10:00, 12:00, and 14:00. Since being emitted from surface (Qin and Xie, 2012), BC concentration in boundary layer is normally higher than which above boundary layer where named the residual layer in the morning. However, the lower 10 concentrations of BC aloft could also influence the meteorological elements significantly. The vertical profiles of the atmospheric attenuation of shortwave radiation ($\triangle$SW; blue solid line), which is defined as the gradual vertical loss in intensity of the incident solar radiation induced by BC, ~~shows~~ showed a small reduction above 1.2 km ~~where BC concentrations are low. .~~ ~~With BC increasing downwards,~~And $\triangle$SW ~~becomes~~ became larger with BC increasing downwards. A greater reduction in shortwave radiation could be observed at a height of 1 km than at the lower adjacent level. This 15 suggests that, when BC concentrations are similar in adjacent layers, solar-~~ ~~radiation absorption ~~by~~ of BC is more efficient at higher altitudes than that at lower altitudes (Ferrero et al., 2014; Ding et al., 2016). It also should be noted that when BC concentration ~~is~~ was sufficiently high, large amounts of BC ~~will~~ would absorb more shortwave radiation; hence, the attenuation of shortwave radiation displayed a second peak below the height of 600 m. Because of the absorption of solar radiation induced by BC, the heating rate of shortwave increased correspondingly. ~~More~~ The significant shortwave 20 absorption in the residual layer ~~leads~~ leaded to a great~~er~~er increase in heating rate (magenta solid line), which ~~will lead to~~caused a consistent heating effect on air aloft (Figure 4a 10:00 and 12:00). In this case, it was favourable to form the temperature inversion which showed that ~~a more rapid rise in temperature above the BL than in the upper BL (Figure 4a 10:00 and 12:00). Under the influence of BC (in Exp_WF),~~ the Equivalent Potential Temperature (EPT; grey solid line) in Exp_WF ~~exhibited a lower value~~was lower at the top of the BL (black dashed line) than that ~~at higher altitudes~~in the residual 25 layer. ~~which suggested the temperature inversion was formed above the BL.~~ The temperature inversion ~~This will~~ increased the atmospheric stability, ~~and~~ suppressed and delayed the development of the BL (black dashed line) at 10:00 and 12:00. Conversely, the EPT in Exp_WFexBC (orange solid line) did not exhibit this property and the BL (red dashed line) ~~could~~ developed rapidly, reaching 1 km altitude by 12:00. ~~At~~ At~~Till~~ 14:00, the BL in Exp_WFexBC was almost fully developed, whereas the BL in Exp_WF was still developing and rising close to the BL in Exp_WFexBC.

30 As one of the most important ozone precursors, the photolysis of NO_2 directly contributes to the ~~photo~~chemical formation of tropospheric ozone. Due to the attenuation of incident solar radiation induced by BC, the photolysis rate of NO_2 was reduced in the daytime ($\triangle J[NO_2]$; brown solid line in Figure 4b), and this is consistent with the results of previous studies (Dickerson et al., 1997; Li et al., 2005). NO_2 in the atmosphere is primarily formed through chemical production or directly emitted from

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surface sources (e.g. industry, transportation, and soil) and is usually confined in BL. As a result of BL suppression caused by BC, more NO_2 is confined below the BL, as shown in Figure 4b (ΔNO_2; green solid line). Similar to NO_2, other ozone precursors (e.g. NO, VOCs) also showed the same variations in vertical distribution (figure~~s are not shown~~S1). The chemical production of tropospheric ozone is affected by both photolysis rate and the concentrations of precursors (Crutzen, 1973; Tie et al., 2009). When only considering the photolysis rate, the reduction of $J[NO_2]$ will weaken the photochemistry and reduce ozone concentration. However, when considering the mechanism of ~~the chemical production of ozone is not only related to the photolysis rate, but also closely related to ozone precursors. Using the online model system, with~~ the ~~aerosol~~BC-BL ~~feedback~~interactions at the same time ~~mechanism~~, the concentrations of ozone precursors will change which also influence the ozone chemical production and the results ~~the influence of ozone precursors' changes will be observed and the change in chemical production of ozone~~ may be different from previous ~~offline model~~ studies that only considering the effects of photolysis rate reduction. In addition, the ~~changes in~~suppressed -BL ~~development~~ could also affect ~~the relevant~~ physical process~~es~~es in the BL, which will also influence surface ozone. Quantitative changes in ozone contributions from chemical and physical processes will be discussed in the following section.

3.4 Changes in surface ozone resulting from BC-BL interaction

~~Because v~~Since variations in ozone concentration ~~are~~ are directly caused by physical and chemical processes (Zhu et al., 2015), it can be discussed with process analysis that ~~the mechanism of~~ BC-BL interactions affect the~~ing~~ ozone concentration ~~can be determine through process analysis (Zhu et al., 2015)~~. The following processes were considered in this work: (1) advection (ADV) caused by transport, which is highly related to winds and ozone concentrations gradients from upwind area to downwind area; (2) vertical mixing (VMIX) caused by atmospheric turbulence and vertical ~~ozone~~ gradients of ozone concentration, which is closely related to the development and variations of the BL (Zhang and Rao, 1999; Gao et al., 2017); and (3) chemistry (CHEM), which is the ~~net value~~result of chemical calculation~~s~~ including ozone chemical production and chemical reduction. ~~The contribution of c~~Convection process, i.e. the ozone contribution ~~of ozone~~caused by convection ~~dynamic and thermodynamic effects~~movements, was negligible in this case~~,~~, ~~and~~ is not mentioned herein ~~in this study~~. Complete details on the process analysis ~~in~~of WRF-Chem are available in Zhang et al. (2014), Gao et al. (2016), and the WRF-Chem user guide.

As shown in Figure 5a, ~~The~~the simulated surface ozone concentrations in Exp_WF and Exp_WFexBC were similar, below 20 ppb before 10:00, and ~~are shown in Figure 5a. As shown in the figure, surface ozone~~ increased slowly ~~from 08:00 to 09:00, and the concentrations were below 20 ppb~~. From 10:00, the surface ozone concentrations in both cases started to increase rapidly. However, with the impacts of BC, ozone in Exp_WF increased slower than that in Exp_WFexBC which formed the ozone reduction. At 12:00, the ozone reduction reached to the maximum value of 16.4 ppb. From 12:00 to 14:00, the increase trend of ozone in Exp_WFexBC slowed down which shrunk the differences of ozone between the two cases. After 14:00, there were not significant differences between the two ozone patterns.~~, especially in Exp_WFexBC. Based on~~ By analysing the processes contribution~~s~~ of ozone in Exp_WFexBC (Figure 5b), VMIX contributed the most whereas ADV

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contributed the least to surface ozone from 10:00 to 14:00. ~~VMIX contributed more than CHEM during the period from 10:00 to 14:00. Overall, the contribution of ADV was much less than those of VMIX and CHEM.~~ The result of the three processes, also denoted as the net contribution of ozone (NET), shows the hourly variation of the ozone concentration. In figure 5b, the significant positive contributions of VMIX and the consistence in the variations of VMIX and NET~~The

5 process contribution~~ suggest~~ed~~s that vertical mixing process took major responsibility for the ~~the~~ increase ~~in~~ of ozone in Exp_WFexBC ~~is highly related to the contribution of ozone by vertical mixing~~. Because of ~~the impacts of~~ BC, ~~the~~ ozone contributions from chemical and physical process~~es~~ ~~contributions also~~ changed at surface which. ~~Differences in the contributions of the processes~~ (Exp_WF−Exp_WFexBC) are presented in Figure 5c. From 10:00 to 12:00, changes in chemical contribution (CHEM_DIF) increased ~~surface ozone~~ at a rate of 3.1 ppb h^{-1}. However, changes in VMIX

10 contribution (VIMX_DIF) decreased ~~surface ozone~~ more significantly with ~~and at~~ a greater rate of ~~approximately~~ -8.2 ppb h^{-1}. NET_DIF in this study indicated the hourly change of ozone concentration caused by the impacts of BC. Thus, the negative values of NET_DIF from 10:00 to 12:00 suggested that surface ozone reduced continuously. ~~. Changes in all the processes, as a result of the impacts of BC, further decreased surface ozone (Exp_WF) from 10:00 to 12:00 with the maximum reduction of 16.4 ppb at 12:00 (Figure 5a).~~ In the afternoon (13:00 to 14:00), the CHEM_DIF was near to zero

15 which ~~shows~~ showed little influence to the change of ~~the variation of~~ surface ozone. ~~However, t~~However, VMIX in Exp_WF was enhanced (VMIX_DIF is positive) which leaded to the NET_DIF change from negative to positive. Further, the positive NET_DIF indicated that reduction of surface ozone was offset which is because the increase trend of surface ozone in Exp_WFexBC slowed down during this period.

~~he reduction of ozone became weaker and it was mainly because the effects of VMIX with BC is larger than those without

20 BC (VMIX_DIF is positive), which offsets the reduction of surface ozone. After 14:00, there were no significant differences between the two ozone patterns.~~

Among all the changes in the contributions from processes ~~caused by BC~~, VMIX_DIF accounted for more than 50% of NET_DIF ~~the net contribution variation (NET_DIF)~~, indicating that change~~s~~ in the ozone contribution from vertical mixing ~~are~~was the ~~primary~~key ~~means~~factor in impacting~~of BC impacting~~ surface ozone in this study. In addition, ~~although~~ J[NO$_2$]

25 ~~was~~ reduced ~~by the impacts of~~induced by BC~~,~~ but changes in CHEM at ~~the~~ surface increased before noon. The reduction ~~in~~in photolysis rate should reduce the chemical production of ozone; however, changes in ozone precursors will also influence the chemical production of ozone. As figure S2 shows, ~~Under~~ ~~in Nanjing~~since the suppression of BL, the concentrations of both NO$_x$ and VOCs increased at surface. The ratios of VOCs/NO$_x$ also increased which suggested that VOCs increased more significantly than NO$_x$ did. In addition, the little change of the ratio of HCHO/NO$_y$ indicated that ozone still formed

30 under the VOC-limited condition. In this case, the increase of more significant increase of VOCs was favourable for ozone chemical production.~~would lead to increase of~~might the influence of BC on the atmosphere, more ozone precursors (i.e. NO$_2$) are confined below the BL due to the suppression of BL development (Figure 4b). With the photolysis of a large amount of NO$_2$ at the surface,~~ ~~As a~~Thus~~result,~~ it~~it~~can~~could be concluded that ~~it showed that the increase of ozone precursors leaded to the enhancement of the contributions from chemistry was highly related to the increase of ozone precursors~~ozone chemical

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~~production will be enhanced and may offset the influence of the reduction in photolysis rate.~~ ~~Thus, an enhanced positive CHEM_DIF was shown near the surface (3 ppb h^{-1}) from 10:00 to 12:00.~~

The development of the BL directly affects vertical mixing process and the distribution of ozone in the BL (Zhang and Rao, 1999). Herein, the distributions of ~~we present~~ VMIX ~~distributions~~ contributions with ~~(Figure 6a)~~ and without ~~(Figure 6b)~~ the effects of BC are shown in Figure 6a and 6b ~~to discuss the impacts of BC-BL interactions on surface ozone~~. The BLH with (black line) and without (red line) the ~~effects~~ impacts of BC are also presented in Figure 6. In general, ozone concentration ~~is higher~~ increases with height ~~in upper layers is higher than which in lower layer~~ before sunrise and in the early morning over polluted regions (Wang et al., 2015). When the BL ~~develops~~ developed in the morning, ozone was ~~turbulence exchanges~~ exchanged by turbulence ~~ozone~~ in the ~~the~~ vertical direction, resulting in the entrainment of the abundant ozone aloft down to the surface and the increase of surface ozone concentrations. Therefore, VMIXs in both cases showed positive values in lower layer and negative values in upper layer. ~~(Figure 6a and b).~~ Differences in VMIX (VMIX_DIF) between Exp_WF and Exp_WFexBC showed the changes ~~in~~ in ~~the~~ ozone contribution ~~of~~ from ~~ozone from~~ vertical mixing caused by ~~the effects of BC and .~~ ~~T~~the vertical distribution of VMIX_DIF is shown in Figure 6c. W~~Under~~ith the effects of BC, the ~~slowly developing~~ suppressed BL weaken~~eds~~ turbulence ~~and mixing height,~~ which ~~leads~~ leaded to ~~decreased~~ reduced vertical exchange ~~downward entrainment~~ of ozone ~~(-8.2 ppb h^{-1})~~ from 10:00 to 12:00. Thus, the VMIX_DIF showed negative value in the lower layer and positive values in the upper layer. After 12:00, BL in Exp_WFexBC was fully developed and VMIX became weak. By contrast, BL in Exp_WF was still developing during this period. In this condition, VMIX was not weakened or even larger than which in Exp_WFexBC. Thus, VMIX_DIF showed positive values in lower layer and negative values in upper layer. ~~Differences in VMIX (VMIX_DIF) between Exp_WF and Exp_WFexBC showed the changes in the contribution of ozone from vertical mixing caused by the effects of BC. The vertical distribution of VMIX_DIF is shown in Figure 6c.~~

Similar to VMIX_DIF, changes in ~~in the~~ ozone contribution ~~of~~ from ~~ozone from~~ chemistry (CHEM_DIF) are presented in Figure 6d. The ~~photo~~chemical production of ozone is related to both photolysis rate and ozone precursors. As discussed above, the BC-BL interaction leads to reduced photolysis rates ~~and~~ but more accumulation of ozone precursors ~~under the BL~~ at surface. ~~The photochemical production of ozone is related to both photolysis rate and ozone precursors.~~ The reduction of photolysis rate will surely decrease photochemical rate. However, the ~~photolysis of a large amount of NO$_2$~~ increase of ozone precursors at the surface may offset the influence of the reduction in photolysis rate and enhance the chemical production of ozone. Thus, enhanced ~~CHEM~~ chemical contribution could be ~~shown~~ seen near the surface (with positive CHEM_DIF of 3 ppb h^{-1}) from 10:00 to 12:00. In the residual layer, different from the situation near the surface, ~~In upper layers,~~ less ~~NO$_2$~~ ozone precursors ~~is~~ being ~~mixed~~ transported up owing to the suppression of BL (Figure 4b and S1) and ~~the~~ reduction of photolysis ~~, leading~~ rate (Figure 4b) leaded to a decreased ~~CHEM~~ chemical contribution (with negative CHEM_DIF between -9.4 and -2.1 ppb h^{-1}) ~~at a height of 500-1000 m~~ from 11:00 to 14:00. Under the effects of BC, the contribution of ADV ~~decreases~~ decreased slightly within the BL before noon (Figure 6e). In Figure 6f, NET_DIF, the result

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of VMIX_DIF, CHEM_DIF and ADV_DIF, ~~the difference of the net contribution of all processes (NET_DIF)~~ represents the ~~variation~~ hourly change of ~~in~~ ozone concentrations ~~caused by the~~ ~~effects~~ impacts of BC. Comparing Figures from 6c to 6f, the similar distributions and the significant ratio of VMIX_DIF to NET_DIF suggest that the change in the ozone contributions from vertical mixing induced by BC ~~has~~ had the greatest influence on surface ozone.

5 Due to BC-BL interactions, VMIX in Exp_WF is weakened before noon but enhanced in the afternoon (Figure 7a). The contribution of VMIX depends on the vertical gradients (the difference of ozone concentrations between every two adjacent vertical layers) of ozone and the turbulent exchange coefficient. In Figure 7b, ~~Vertical~~ vertical gradients of ozone (solid lines ~~in Figure 7b~~) showed similar profiles in both experiments during the early stage of BL development before noon. In the afternoon, the ozone gradient (red solid line in Figure 7c) decreased significantly without the effects of BC in the mature

10 stage of BL development, whereas the ozone gradient remained large ~~at~~ around the top of the BL ~~under~~ with the effects of BC (black line in Figure 7c). The effects of BC can lead to a significantly smaller turbulence exchange coefficient (black line with square in Figure 7b), lowering the entrainment of ozone from higher altitudes to the surface, which ~~indicates~~ indicated that ~~the contribution of~~ VMIX in Exp_WF ~~is~~ was smaller before noon. In the afternoon, the faster developing BL without the effects of BC ~~forms~~ formed a uniformly mixed ozone profile, with very small vertical gradients. As a result, the contribution

15 of VMIX in Exp_WFexBC ~~is~~ was smaller, although the turbulence exchange coefficient ~~is~~ was still large. In contrast, with the impacts of BC, larger ozone gradients ~~at~~ around the top of the BL result~~ed~~ in stronger entrainment of ozone down to the surface which ~~leads~~ leaded to the ozone contribution of VMIX in Exp_WF became larger at surface.

4 Conclusions

In this study, measured data of BC and ozone in Nanjing, an important industrial and economic centre in the YRD region of

20 China, showed that ozone concentration ~~increases~~ increased slowly from 10:00 to 14:00 when the BC concentration ~~is~~ was relevant high. With the application of ~~Because of the limited of measurement, the~~ WRF-Chem model, we studied ~~was applied to study~~ the impacts of BC-BL interactions on surface ozone in Nanjing. Acceptable agreement was achieved between observed and simulated results for both meteorological and chemical variables, suggesting that the WRF-Chem model has the capability to accurately reproduce meteorological factors and air pollutants in this study.

25 The model results show~~ed~~ that, when high concentrations of BC ~~are~~ were confined over Nanjing, the incident solar radiation ~~is~~ was absorbed. The absorbed radiation heated the air above the BL, ~~and~~ suppressed and delayed the development of the BL. Because of the BL suppression, it caused the changes in the ozone contribution~~s~~ ~~of~~ from chemical and physical processes ~~to ozone~~ (photochemistry, vertical mixing and advection) ~~will change correspondingly~~. In particular, BL suppression ~~leads~~ leaded more ozone precursors (e.g. ~~NO₂~~ NO$_x$ and VOCs) being confined below the BL. Although the photolysis rate ~~is~~ was

30 reduced as a result of the solar-radiation absorption induced by BC, more ozone precursors enhanced the contributions from ~~chemical~~ chemistry production of surface ozone before noon. However, as a more significant ~~impact~~ factor, the suppressed BL weakened the turbulence and entrained ~~very little~~ less ozone aloft down to the surface which reduced the contributions

from vertical mixing process. As a result, surface ozone decreased before noon, with the maximum reduction reaching 16.4 ppb at 12:00. In the afternoon, the changes in ~~chemical production~~chemistry process were small which influenc~~ing~~e inconspicuously to surface ozone. However, ~~physical process~~vertical mixing process still influences the surface ozone significantly. Due to the delay of the BL development, the vertical ozone structure showed ~~larger~~ obvious vertical gradients ~~near~~ around the top of the BL, and ~~more~~ high concentration of ozone aloft could be entrained down to the surface to offset the surface ozone reduction before noon.

Comparing ~~all~~ the changes in the contributions ~~of~~ from the chemical and physical processes induced by the effects of BC, the change in vertical mixing process which was caused by BL suppression ~~plays~~ played a more important role in influencing surface ozone ~~on surface ozone~~. Our results highlight ~~enhance~~ the great impacts of BC-BL interactions on surface ozone via influencing the ozone contribution from physical process which suggests that more attention should be paid on the mechanism of aerosol-BL interactions when controlling the ozone pollution in China.~~. The aerosol-BL-gas relationship will provide new insights in ozone pollution control in China.~~

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Table 1: Major model configuration options used in the simulations

Item	Selection
Long wave radiation	RRTMG
Shortwave radiation	RRTMG
Microphysics scheme	Lin scheme
Boundary layer scheme	Yonsei University (YSU) scheme
Land surface option	Noah land-surface model
Photolysis scheme	Fast-J Photolysis
Dry deposition	Wesely scheme

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Table 2: Statistical metrics for meteorological variables from 10 to 26 October 2015. The benchmarks follow the recommended values reported by Emery et al. (2001). The values that not meet the criteria are denoted in bold.

Variables		Nanjing	Zhenjiang	Maanshan	Hefei	Wuxi	Criteria
WD (°)	IOA	0.94	0.95	0.91	0.92	0.94	
	MB	-0.54	**-11.72**	-5.83	**-15.29**	**-11.39**	$\leq \pm 10$
	RMSE	42.53	39.83	53.78	52.43	45.03	
WS (m s^{-1})	IOA	0.72	0.76	0.66	0.65	0.63	≥ 0.6
	MB	0.26	-0.4	0.01	**0.72**	**0.87**	$\leq \pm 0.5$
	RMSE	1.11	1.2	1.43	1.21	1.49	≤ 2
T2 (°C)	IOA	0.93	0.87	0.95	0.91	0.92	≥ 0.8
	MB	**-1.71**	**-1.93**	-0.33	**-2.03**	**-0.88**	$\leq \pm 0.5$
	RMSE	2.44	2.8	1.79	2.5	2.31	
SW ($\times 10^3$ W m^{-2})	IOA	0.96					
	MB	0.01					
	RMSE	0.09					

Table 3: Statistical metrics for air pollutants from 10 to 26 October 2015. Criteria for ozone and PM$_{2.5}$ are suggested by EPA (2005) and EPA (2007). The values that do not meet the criteria are denoted in bold.

Variables		Nanjing	Zhenjiang	Maanshan	Hefei	Wuxi	Criteria
O$_3$ (ppb)	IOA	0.91	0.85	0.84	0.93	0.84	
	MNB	**-0.32**	0.02	-0.09	0.05	**0.24**	≤ ±0.15
	MFB	-0.59	-0.61	-0.52	-0.10	-0.31	
NO$_2$ (ppb)	IOA	0.81	0.77	0.70	0.73	0.79	
	MNB	-0.13	0.05	0.51	-0.17	-0.32	
	MFB	-0.25	-0.05	0.15	-0.34	-0.49	
PM$_{2.5}$	IOA	0.62	0.76	0.77	0.59	0.67	
(μg m^{-3})	MNB	0.12	0.13	0.10	0.11	0.10	
	MFB	-0.04	-0.01	-0.01	-0.02	-0.02	≤ ±0.6
BC	IOA	0.67					
(μg m^{-3})	MNB	0.76					
	MFB	0.38					
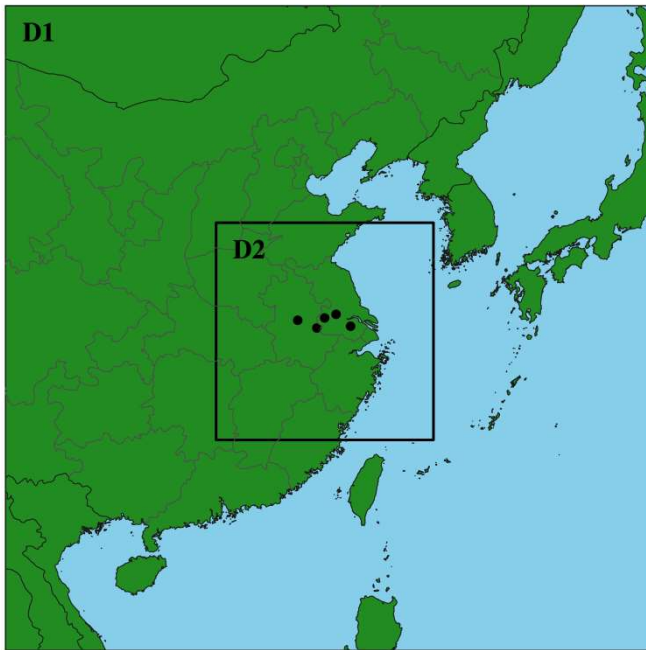
Figure 1: Map of the two model domains. The locations of the observation sites used for model evaluation are presented as dots. From west to east, the sites are located in Hefei, Maanshan, Nanjing, Zhenjiang, and Wuxi.

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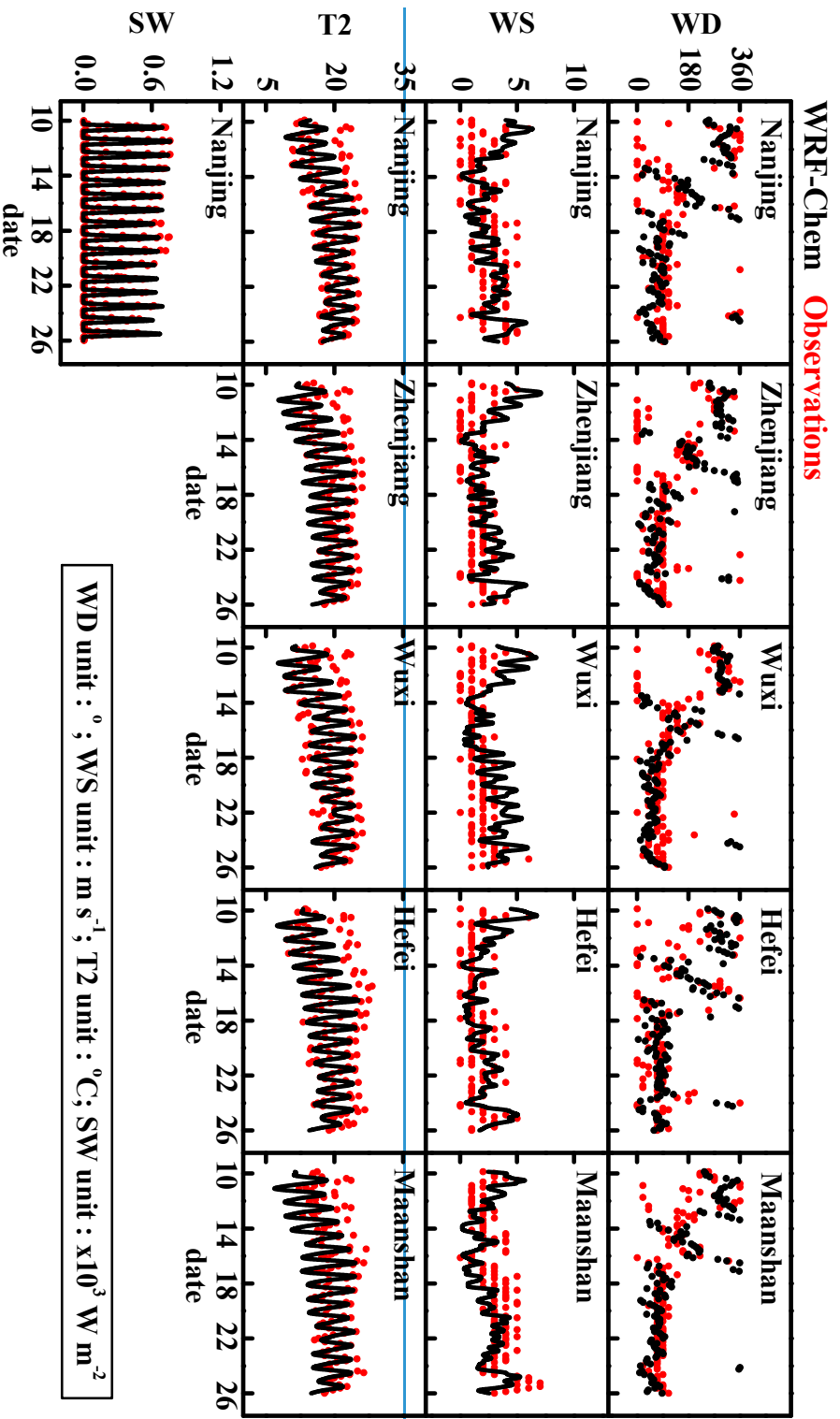
Figure 2a: Time series comparisons of meteorological variables between observations and simulations from 10 to 26 October 2015. (WD = Wind Direction; WS = Wind Speed; T2 = Temperature at 2m above the surface; SW = Short Wave)
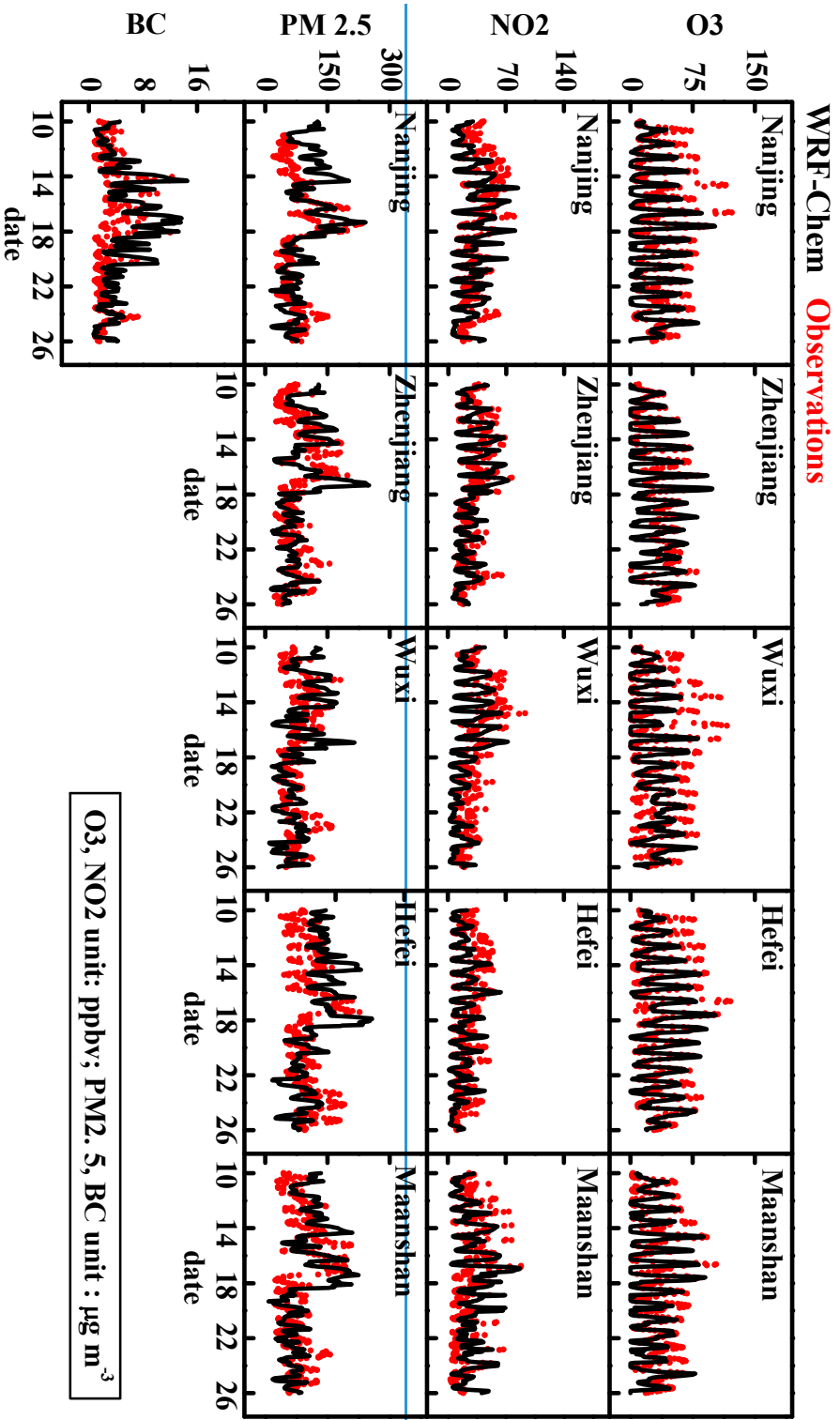
WD unit : ° ; WS unit : m s^{-1}; T2 unit : °C; SW unit : x10^3 W m^{-2}

Figure 2b: Same to figure 2a but for chemical variables (O3 = Ozone; NO2 = Nitrogen dioxide; PM2.5 = Particulate Matter with diameter less than or equal to 2.5 μm; BC = Black Carbon)

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WRF-Chem **Observations**
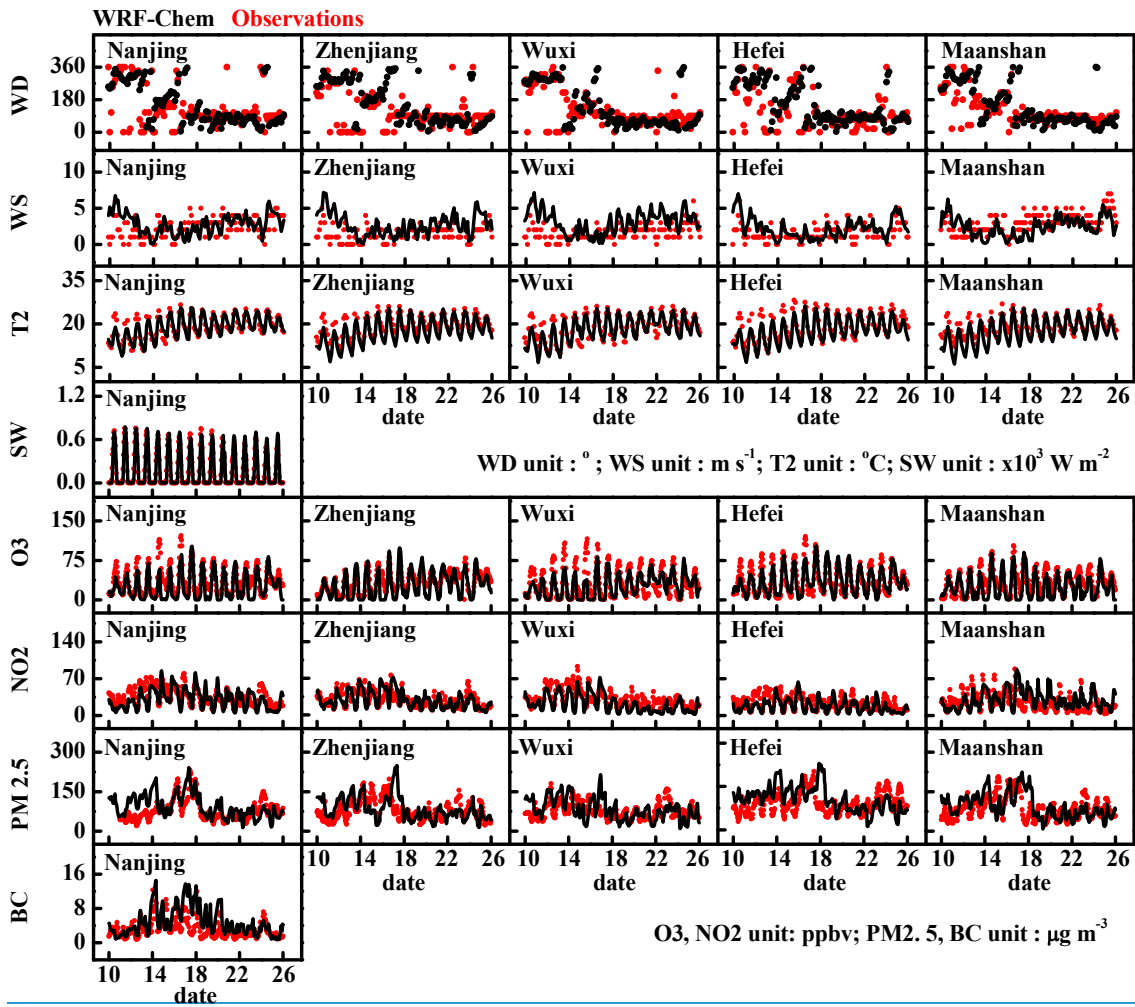
Figure 2: Time series comparisons between observed and simulated variables from 10 to 26 October 2015. (WD = Wind Direction; WS = Wind Speed; T2 = Temperature at 2 m above the surface; SW = Shortwave; O3 = Ozone; NO2 = Nitrogen dioxide; PM2.5 = particulate matter with diameter less than or equal to 2.5 μm; BC = Black Carbon)

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(a)
— Ozone when BC > 3μg m⁻³
— Ozone when BC < 3μg m⁻³

(b)
□ Δ BLH_MAX
— fitting line y=45.6x+12.6

(c)
— BC (μg m⁻³)
■ Ozone (ppb)

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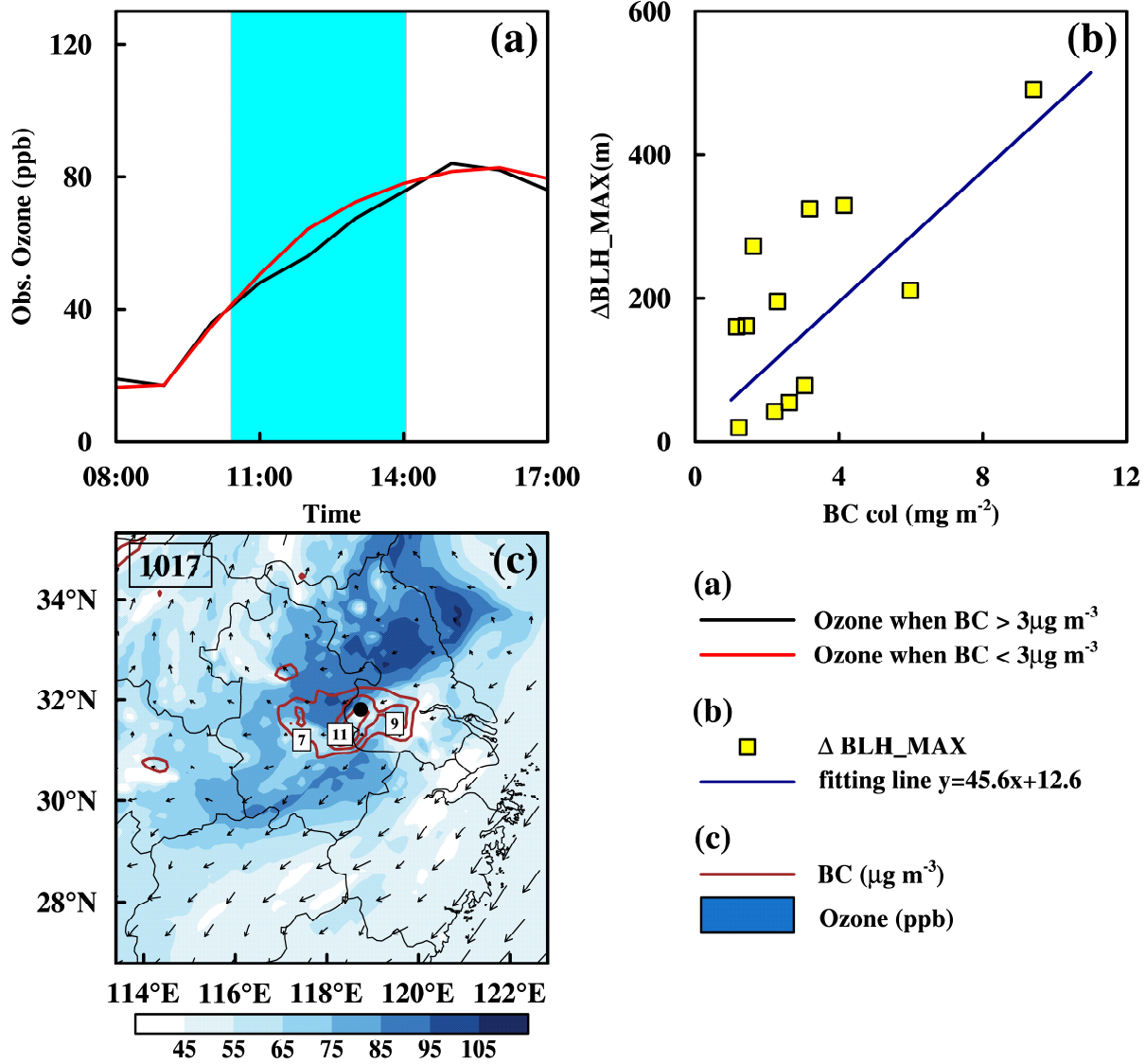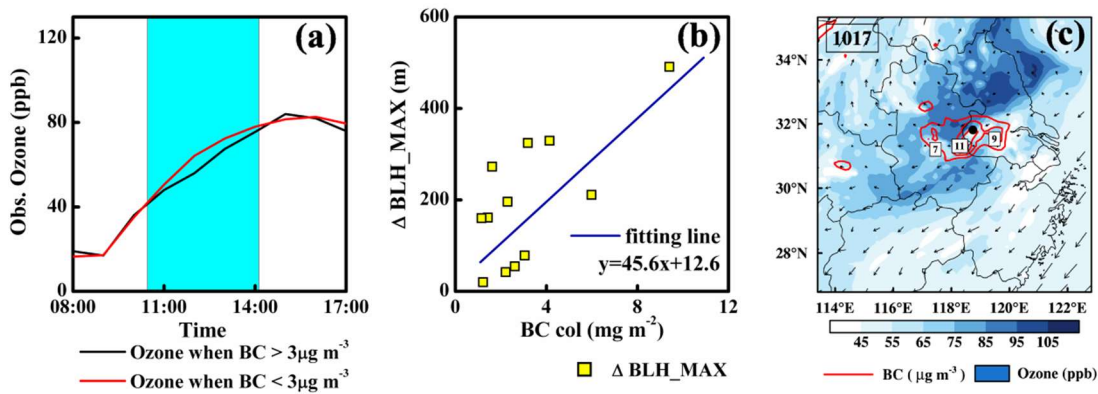
Figure 3: (a) Observational averaged ozone concentrations with BC concentrations lower (red) and higher (black) than the monthly mean value during October 2015; (b) simulated maximum BLH changes (yellow square) induced by BC; (c) Average distribution of surface BC (red contour) and ozone concentrations (blue colour fill), showing wind fields from 10:00 to 14:00 local on 17 October 2015. Black dot denotes the location of the observation site.

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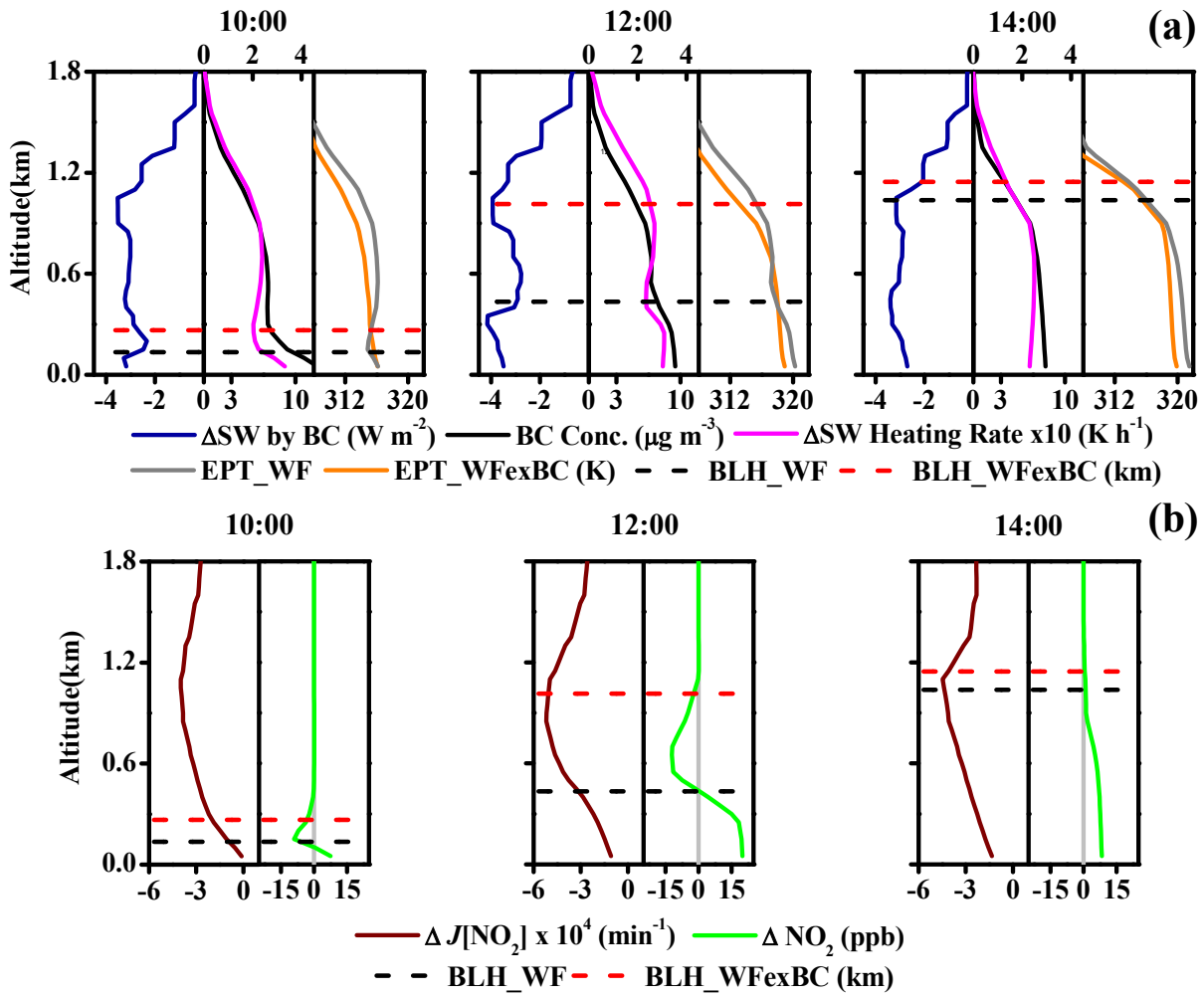
Figure 4: Vertical distributions of (a) averaged BC concentrations (black line; unit: µg m^{-3}), attenuation of incident shortwave radiation induced by BC (blue line; unit: W m^{-2}), change of shortwave heating rate induced by BC (magenta line: unit: K h^{-1}), Equivalent Potential Temperature (EPT; unit: K) of the two experiments (dark grey line for Exp_WF and orange line for Exp_WFexBC); (b) average changes in J[NO$_2$] (brown line; unit: min^{-1}) and NO$_2$ (green line; unit: ppb) induced by BC in Nanjing at 10:00, 12:00 and 14:00. BLHs of the two experiments (black and red dashed line denotes BLH in Exp_WF and Exp_WFexBC, respectively) are presented in (a) and (b).
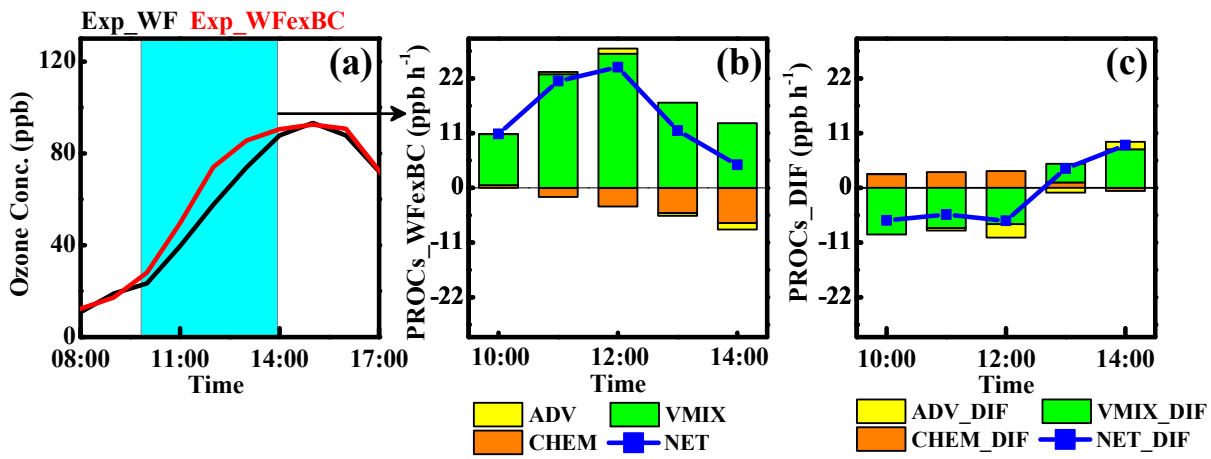
Figure 5: (a) Time series of simulated ozone concentration (unit: ppb) from 08:00 to 17:00; (b) hourly process contributions in the Exp_WFexBC experiment from 10:00 to 14:00; and (c) variations in process contributions caused by BC-BL interactions (Exp_WF−Exp_WFexBC) from 10:00 to 14:00. Cyan shades in (a) highlight the ozone differences induced by BC. In (b): ADV is advection, VMIX is vertical mixing, and CHEM is chemistry; the blue line with squares denotes the net value of the processes (NET); Variations in each process and the net contribution are denoted by ADV_DIF, VMIX_DIF, CHEM_DIF and NET_DIF. Units in (b) and (c) are ppb h^{-1}.
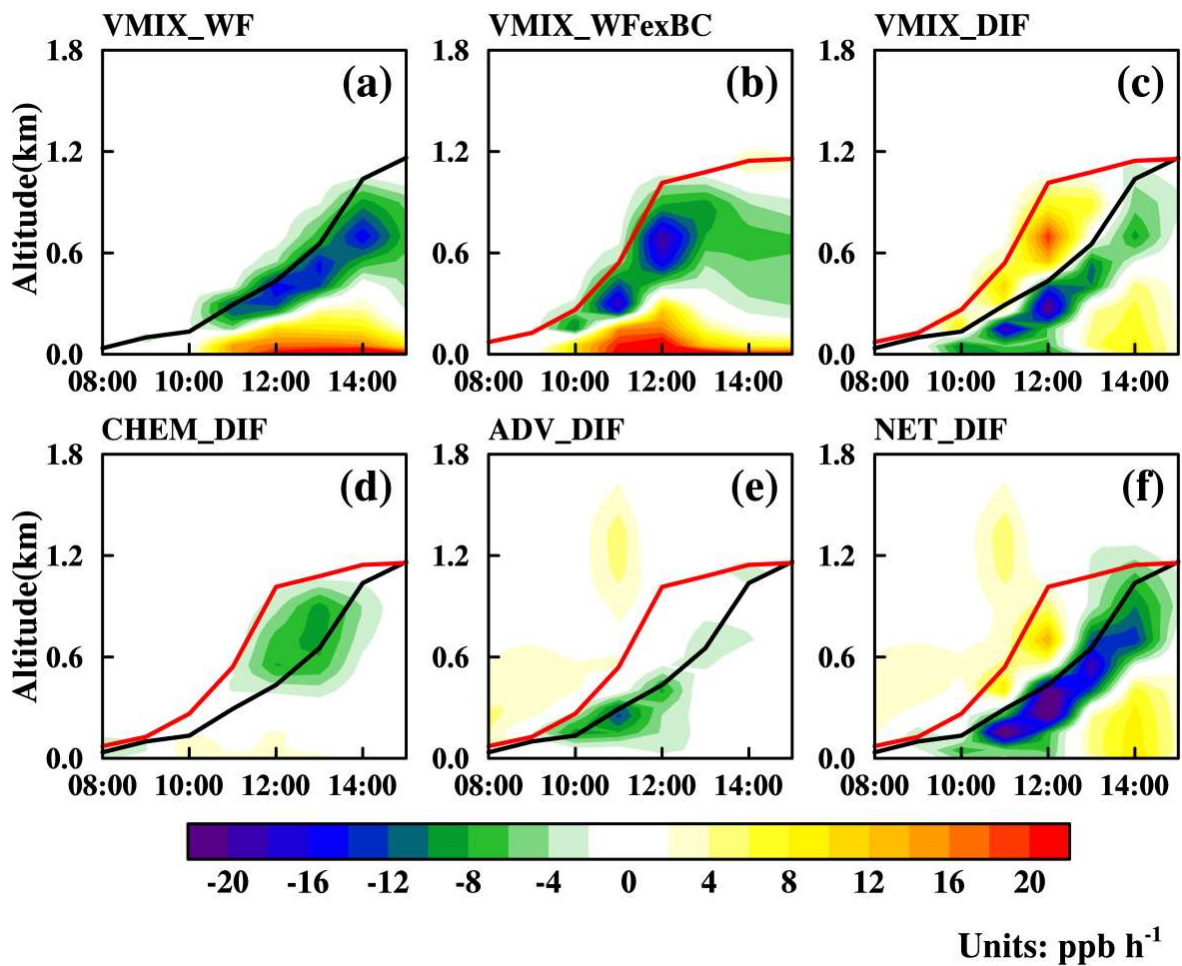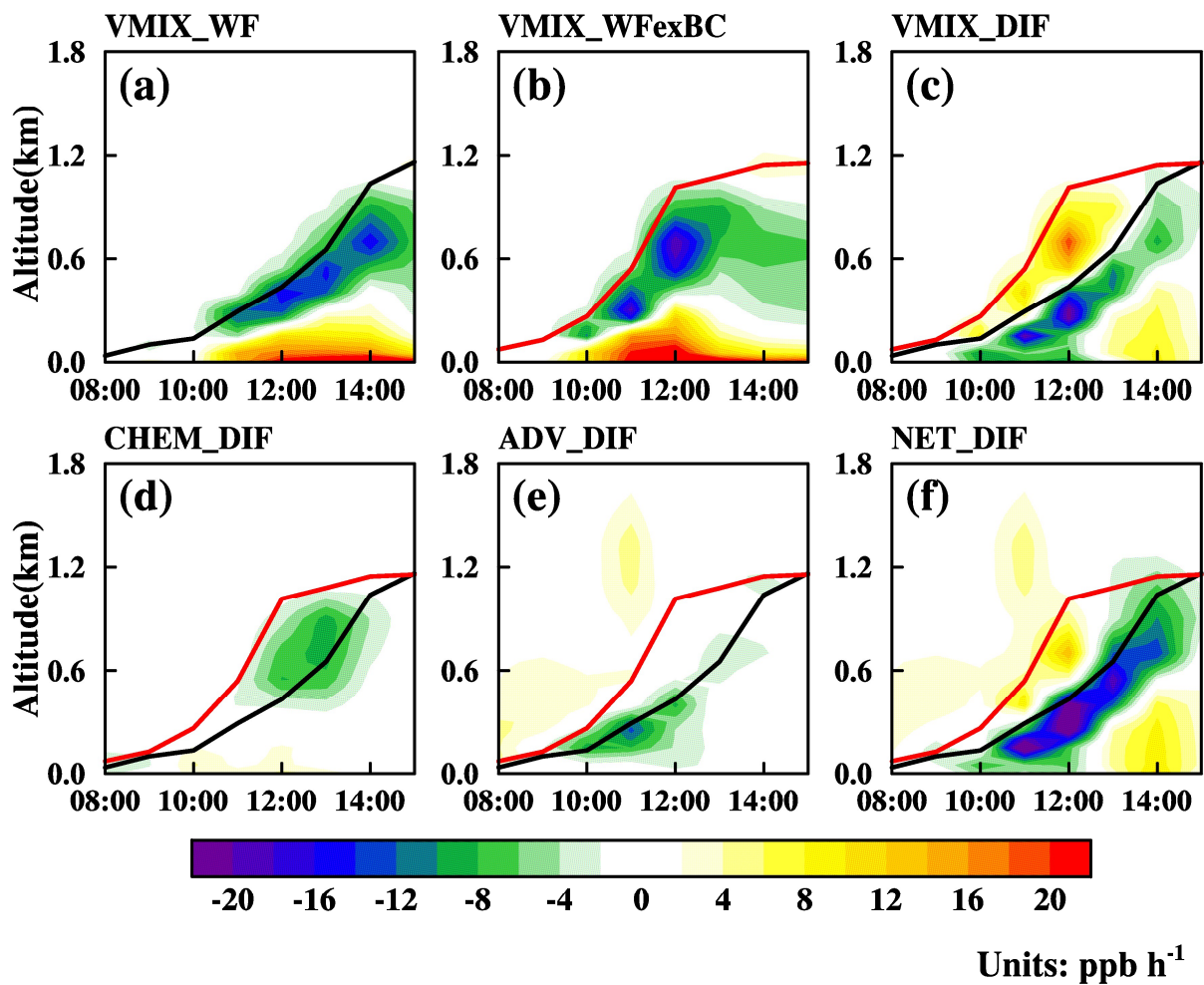
Figure 6: Vertical distribution of ozone contribution from the vertical mixing process in Exp_WF (a) and Exp_WFexBC (b). Changes of VMIX (VMIX_DIF; c), CHEM (CHEM_DIF; d), and ADV (ADV_DIF; e) between the two experiments, and the net value of the changes from all processes (NET_DIF; f) from 08:00 to 15:00. Units are ppb h^{-1}. The black and red lines denote the BLH in Exp_WF and Exp_WFexBC.
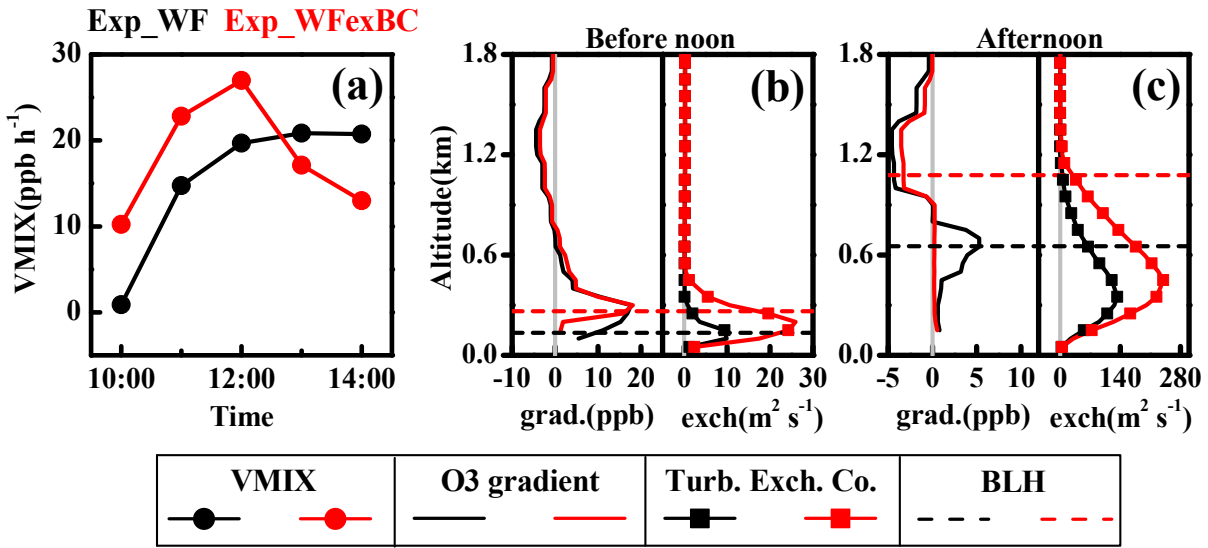
Figure 7: (a) Time series of vertical mixing contribution (line with circle; unit: ppb h^{-1}) from 10:00 to 14:00 and profiles of ozone vertical gradients (solid line; unit: ppb) and turbulence exchange coefficient (line with square; unit: m^2 s^{-1}) in Exp_WF (black) and Exp_WFexBC (red) before noon **(b)** and afternoon **(c)**. BL heights (BLH; dashed line; unit: km) of Exp_WF and Exp_WFexBC are denoted in **(b)** and **(c)**