Comments to the Author:

Although the authors have addressed the major scientific issues raised by the referees, the paper is technically not yet ready to be accepted for publication. The language of the papers requires major improvements, and should be finally checked out by a native English speaker. My specific comments in this regard are the following:

First, the use of tense, articles and prepositions needs to be checked out and corrected throughout the paper.

Response:

Thank you for pointing out the language problems in this paper and giving us the opportunity to correct them. We have asked professional native speaker “LucidPapers” to overall improve the English of the paper, and after that we proved their corrections in scientific meaning. Please see the edited and clean versions of this paper.

Second, there are a number of sentences that are either too long or complicated, or unclear parts, which makes them difficult for the readers. Especially, such sentences can be found on lines 92-93, 107-110, 127-131, 138-141, 164-166 (one cannot say was observed reduction 89%), 180-183 (check out how to write dates), 188-192, 205-209, 234-236, 245-251, 263-268, 285-288, 300-302, 307-308, 320-322, 332-334, 341-343, 348-349, 371-373, 383-384, 398-402, 418-420.

Response:

The English of the paper has been polished overall including all the sentences on these lines.

Third, the paper needs to list proper scientific aim(s). What is written on lines 79-82 does not motivate to read this paper in more detail.

Response:

The related context in rewritten in line 92-97 in the edited paper.

Other comments:

There should be a space between the number and unit when given values for quantities

Response:

This has been corrected in the revised paper.

Line 121: … Hong’s studies: papers cannot be cited like this

Response:

This has been revised as “The turbulent diffusion coefficient (DC) is calculated by the YonSei University PBL scheme (Hong et al., 2006)” on line 135 in the edited version.

I am not sure the authors use correctly the term “trend” on page 10 and later in the text.

Response:

All uses of “trend” (line 151,254,257,264,290,440 in the edited version of this paper) have been examined and corrected.

Line 231: should it be …overprediction of the temperature … rather than … temperature positive errors

Response:

This has been corrected as “overestimation of surface temperature (line 270 in the edited version of this paper)

Line 259: PM2.5 center of… does not sound a right way to express this

Response:

This phrase has been revised “The most polluted area with PM2.5 values of 500–700 μg/m3 …” on line “305-306” in the edited paper.

The Contributions to the Explosive Growth of $PM_{2.5}$ Mass due to Aerosols-Radiation Feedback and Further Decrease in Turbulent Diffusion during a Red-alert Heavy Haze in Jing-Jin-Ji in China

Hong Wang[1,2 *], Yue Peng[1,2], Xiaoye Zhang[1,3*], Hongli Liu[1], Meng Zhang[4], Huizheng Che[1], Yanli Cheng[1], Yu Zheng[1,2]

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The Contributions to the Explosive Growth of $PM_{2.5}$ Mass due to Aerosols-Radiation Feedback and Further Decrease in Turbulent Diffusion during a Red-alert Heavy Haze in Jing-Jin-Ji in China

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Abstract. The explosive growth~~ (EG)~~ of $PM_{2.5}$ mass usually ~~resulted ~~results in ~~$PM_{2.5}$ ~~extreme $PM_{2.5}$ levels and severe haze pollution in ~~e~~East China, and ~~they were~~is generally underestimated by current atmospheric ~~chemical ~~chemistry models. Based on ~~the atmospheric chemical~~one such model, GRPAES_CUACE, three ~~sensitive ~~sensitivity experiments – ~~of ~~a "background" experiment (EXP1), "online aerosol~~s~~ feedback" ~~online ~~experiment (EXP2), and an "~~decrease ~~80% decrease in turbulent diffusion coefficient" (DTD) of chemical tracers" experiment, based on EXP2 (EXP3) – ~~are ~~were designed to study the ~~contributions~~ contributions of ~~to the EG of $PM_{2.5}$ due to ~~aerosol~~s -~~–radiation feedback (AF) and DTD to the explosive growth of $PM_{2.5}$ ~~focusing on~~during a "red-alert" heavy haze event in China's Jing–~~-~~Jin–~~-~~Ji region~~ in China~~. The ~~study ~~results showed that the turbulent diffusion coefficient (DC) calculated by EXP1 ~~is ~~was about 60–~~-~~70 m^2/s on the clear day and 30–~~-~~35 m^2/s on the haze day. This difference ~~of ~~in DC was not enough to ~~discriminate ~~distinguish between the unstable atmosphere on the clear day and extreme~~ly~~ stable atmosphere during the ~~EG stage of ~~$PM_{2.5}$ explosive growth stage~~,~~. ~~and ~~Also, the inversion calculated by EXP1 was obviously weaker than the actual inversion from sounding observations on the haze day. This led to a 40%–~~-~~51% underestimation of $PM_{2.5}$ by EXP1; AF reduced by about 43%–~~-~~57% DC during ~~EG stage of~~the $PM_{2.5}$

批注 **[LP1]:** Acronyms and abbreviations should be kept to a minimum. There is no real advantage to the reader to introduce an acronym for 'explosive growth'.

explosive growth stage, which strengthened the local inversion obviously; ~~and~~ plus, the local inversion indicated by EXP2 was much closer to the sounding observations than that by EXP1. This resulted in a 20%–~~-~~25% reduction ~~of model negative errors of~~ $PM_{2.5}$ negative errors in the model, ~~and it was~~reaching as low as ~~-~~–16% to ~~-~~–11% in EXP2. However, the inversion produced by EXP2 was still weaker than the actual observation, and AF could not solve all the problems of $PM_{2.5}$ underestimation. Based on EXP2, the 80% DTD of chemical tracers in EXP3 resulted in ~~a~~ near-zero turbulent diffusion, ~~named~~ referred to as an “turbulent ~~intermittent~~ intermittence” ~~atmosphere~~ atmospheric state, which resulted in a further 14%–~~-~~20% reduction ~~of~~ in $PM_{2.5}$ underestimation, and the negative $PM_{2.5}$ errors ~~of was~~were reduced to ~~-~~–11% to 2%. The combined effects of AF and DTD solved over 79% of the underestimation of the explosive growth of $PM_{2.5}$ ~~EG~~ in this study. The results show that ~~the~~ online calculation of ~~aerosol-radiation feedback~~AF is essential for the prediction of $PM_{2.5}$ explosive growth~~EG~~ and peaks during severe haze in China’s Jing–~~-~~Jin–Ji ~~in China~~region. Besides~~ this~~, ~~an improvement in~~improving the ~~arithmetic~~ planetary boundary layer~~of PBL~~ scheme calculation ~~focusing on~~with respect to extremely stable ~~atmosphere~~ atmospheric stratification is also ~~indispensable~~ essential, for a reasonable description of local “turbulent ~~intermittent~~intermittence” and a more accurate prediction of $PM_{2.5}$ ~~EG~~ explosive growth during ~~the~~ severe haze in ~~Jing-Jin-Ji~~ in this region of China.

Keywords: a~~A~~erosol ~~-s R~~radiation ~~F~~feedback; ~~T~~turbulent ~~D~~diffusion; ~~PBL~~ planetary boundary layer ~~S~~scheme; ~~T~~temperature ~~I~~inversion; $PM_{2.5}$

批注 **[LP2]:** Please check that the changes made here reflect the intended meaning.

1 Introduction

Since 2013, East ~~e~~China has been ~~experienced~~ experiencing unprecedented intrusions of severe haze~~s~~ accompanied by high levels of particulate matter (PM) of less than 2.5 microns in aerodynamic diameter ($PM_{2.5}$), ~~caused~~ causing wide public concern ~~since 2013 until now~~ (Ding et al., 2013; Wang et al. 2013; Huang et al., 2014; Wang et al., 2014; Sun et al., 2014; Hua et al., 2016; Yang et al., 2015; Zhong et al., 2017, 2018a, 2018b). The ~~I~~instantaneous $PM_{2.5}$ concentration is usually ~~reached~~ in the hundreds of~~, or even one thousand~~ ug/m^3 during severe haze episodes, occasionally exceeding one thousand, in the metropolitan~~s~~ ~~in~~ region of Beijing–~~(JING),~~ Tianjin~~(JIN),~~ –Hebei ~~province (alias JI)~~, referred to here as Jing–Jin–Ji, and ~~their near~~its surroundings of East Shanxi, West Shandong, and North Henan in ~~e~~East China ~~(abbreviated this region as Jing-Jin-Ji in this study) during severe haze episodes~~ (Wang et al., 2014; Quan et al., 2014; Sun et al., 2014; Yang et al., 2015; Zheng et al., 2016). Studies have ~~showed~~ shown, however, that models generally underestimate~~d~~ the explosive growth ~~(EG)~~ and peak values of $PM_{2.5}$ during ~~the~~ severe hazes, especially in Jing–~~-~~Jin–~~-~~Ji ~~region~~ (Wang et al., 2013; Wang et al., 2014; Li et al., 2016).

The causes of $PM_{2.5}$ ~~EG~~ explosive growth and its underestimation by ~~atmosphere~~ atmospheric ~~chemical~~ chemistry models are complex and uncertain at present, ~~which may~~but possibly involves ~~in~~ local emissions, reginal transportation, aerosol physicochemical processes, gas–~~es~~ particle~~s~~ conversion, ~~meteorology~~ meteorological conditions, and so on. However, the actual atmospheric stability and how accurate it is described by atmospheric models is a fundamental problem that ~~can't~~ cannot be ignored among others. Local or regional ~~meteorology~~ meteorological conditions dictate~~s~~ whether ~~the~~ haze occurs and what the $PM_{2.5}$ level may be (Zhang et al., 2014; Zheng et al., 2015; Gao et al., 2016) when source emissions are unchanged for a short period of time. The ~~meteorology~~ meteorological conditions of the planetary boundary layer (PBL) ~~is~~ are ~~the~~ a key and direct trigger for ~~touching off~~the emergence of a haze event (Wang et al., 2014; Li et al., 2016; Zhong et al., 2017). Turbulent diffusion is an important factor to characterize PBL meteorology when the atmosphere is stable. Also, ~~I~~it is ~~also~~ a major ~~way~~ pathway of particle~~s~~ and gaseous pollutant~~s~~ ~~exchanging~~ exchange from the surface to upper atmosphere; and when haze occurs, ~~and further cleaned~~pollutant dispersal ~~by~~ via the upper-level winds can take place when haze ~~occurs~~ is accompanied by calm surface winds and weak vertical motion of air in surface layers and the PBL. The intensity of turbulent diffusion largely determines the severity of haze pollution. Thus, a ~~R~~reasonable

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description of turbulent diffusion by PBL schemes in atmospheric ~~chemical~~ chemistry models is ~~determinant~~ vital for the prediction of severe pollution ~~prediction~~ (Hong et al., 2006; Wang et al., 2015; Hu et al., 2012, 2013a, 2013b; Li et al., 2016). The latest studies in this field of research show~~ed~~ (Wang et al., 2015; Li et al., 2016) that current PBL schemes may be insufficient ~~enough~~ for describing the extremely weak turbulent diffusion conditions when extremely severe haze~~s~~ ~~occurred~~ occurs in Jing–~~-~~Jin–~~-~~Ji, which more broadly may be one important reason ~~for the underestimation of~~why $PM_{2.5}$ peaks are underestimated by atmospheric ~~chemical~~ chemistry models. ~~There~~ More specifically, there may be two independent reasons ~~resulting in this deficiency~~why the description of extremely weak turbulent diffusion in atmospheric models is deficient. One is that aerosol ~~-s~~ radiation feedback (AF) is not calculated online in the model run. AF may restrain turbulence by cooling the surface and PBL while heating the atmosphere above it when aerosols with certain absorption characteristics are concentrated in the PBL (Wang et al., 2010; Forkel et al., 2012; Gao et al., 2014, 2015; Wang et al., 2015; Ding et al., 2016; Li et al., 2016; Miao et al., 2016; Petaja et al., 2016; Gao et al., 2017; Qiu et al., 2017; Zhong et al., 2018). Ignoring AF is likely to lead to an obvious overestimation of turbulent diffusion when the $PM_{2.5}$ concentration exceeds a certain value, which is worthy of further study. ~~Another~~ The other possible reason is that the extremely weak turbulence resulting in extremely severe haze~~s~~ is not fully described by the atmospheric ~~chemical~~ chemistry model (Li et al., 2016).

In the present work, ~~A~~a "~~R~~red-alert" ~~H~~heavy ~~H~~haze event (issued by ~~China's~~ China's Ministry of Environmental Protection ~~issues air quality red alert~~ when the air pollution index is forecast~~ed~~ to exceed~~ing~~ 300 ~~in~~ over the next three days) that occurred ~~on~~ during 15–~~to~~ 23 December~~,~~ 2016 in China's Jing–~~-~~Jin–~~-~~Ji ~~in China~~region was selected to study the ~~contributions~~ contributing factors to $PM_{2.5}$ ~~EG~~ explosive growth and peaks ~~during severe haze due to AF~~, and the possible deficiency of atmospheric models in ~~description~~ describing ~~of the~~ extremely weak turbulent diffusion ~~of atmosphere models in this study~~.

2 Model, ~~D~~data and ~~Methodology~~methods

2.1 ~~GRAPES_CUACE~~ Model

Focusing on dust and haze pollution~~s~~ in China and East Asia, the Chinese Unified Atmospheric Chemistry Environment (CUACE) (Gong and Zhang, 2008) was online–~~-~~integrated into the mesoscale

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version of the Global/Regional Assimilation and PrEdiction System (GRAPES_meso), developed by the Chinese Academy of Meteorological Sciences (Chen et. al., 2008; Zhang and Shen, 2008), to build an online chemical weather forecasting model, GRAPES_CUACE (Wang et al., 2009, 2010; 2015a; Zhou et al., 2012). The main components of GRAPES_CAUCE include: a model dynamic core; a modularized physics package (Xu et al., 2008)~~,~~; an atmospheric chemistry module, CUCAE, with online coupling of ~~aerosols~~ direct and indirect aerosol feedback; and an emissions inventory. ~~The dynamic framework of GRAPES_CUACE is~~ The semi-implicit, semi-Lagrangian, fully compressible, and non~~-~~-hydrostatic~~al~~ dynamic framework is adopted in GRAPES_CUACE (Yang et al., 2007, 2008; Chen et al., 2008). A height-based~~-~~ terrain-~~-~~following coordinate system ~~was~~ is used, and there are 33 vertical layers form the surface to 30 ~~kilometers~~km. ~~The~~ A longitude-~~-~~latitude grid is adopted in the spatial discretization of ????, and ~~the~~ several horizontal resolution ~~is optional~~options are available. The ~~physical~~ physics package ~~is optional~~can also be tailored by the user (Xu et al., 2008), and ~~t~~Table 1 lists the specific physics and chemistry schemes used in this study. The ~~G~~gas-phase chemistry of RAD II (Stockwell et al., 1990), with 63 gaseous species through 21 photo~~-~~chemical reactions and 121 gas~~-~~-phase reactions, is used in this study. The aerosols include~~s~~ sea salt~~s~~ (SS), sand/dust (SD), black carbon (BC), organic carbon (OC), sulfates (SFs), nitrates (NIs) and ammonium salts (AMs), and aerosol~~s~~ processes involving ~~in~~ hygroscopic growth, coagulation, nucleation, condensation, dry and wet deposition~~s~~, scavenging, aerosol activation~~s~~, and ~~etc~~so on. The formation of ~~sulfate~~ SF aerosols and secondary organic aerosols~~ (SOA)~~ from gases, ~~nitrates~~ NIs and ammonium formed through gaseous oxidation, and ISORROPIA (Fountoukis et al., 2007) calculating the thermodynamic equilibrium between ~~nitrates~~ NIs and ammonium and their gas precursors, are considered in CAUCE, which ha~~d~~s been evaluated and introduced in previous studies (Gong and Zhang et al., 2008; Zhou et al., 2008, 2012).

Based on the modeled aerosol~~s~~ concentrations, vertical profiles of temperature ~~changing~~ change, including direct aerosol~~s~~ ~~direct~~ impacts~~ (DT/dt due to aerosols),~~ ~~is~~ are calculated by the radiation model and fed back online ~~feedback~~ to the model dynamic core ~~in~~ at each grid point ~~in~~ and every time step, which reforms the model temperature field, dynamic process, regional circulation and ~~meteorology~~ meteorological conditions, in turn ~~finally~~ ultimately ~~impacts~~ impacting the aerosol~~s~~ concentration~~ in turn~~. The external

批注 **[LP5]:** The spatial discretization of what?

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mixing of aerosols species (~~of~~ SS, SD, BC, OC, SF, NI, ~~and~~ AM) and particle size bins ~~is~~ are used in the calculation of ~~aerosols radiation feedback~~AF, ~~which was~~as introduced and evaluated in detail in previous studies (Wang et al., 2009, 2010, 2015a, 2015b). With this ~~double~~ two-way GRAPES_CUACE model, aerosol–~~s-~~radiation–~~-~~PBL–~~-~~meteorolog~~y~~ical interactions, as well as aerosol–~~s-~~cloud–~~-~~precipitation interactions~~,~~ and regional pollution and transportation of $PM_{2.5}$ etc., ~~had~~ have been successfully studied (Wang et al., 2010, 2015a, 2015b; Zhou et al., 2012, 2016; Jiang et al., 2015; Zhang et al., 2018).

The turbulent diffusion coefficient (DC) is calculated by the YonSei University ~~(YSU)~~ PBL scheme (Hong et al., 2006), which is a revised vertical diffusion package based on the nonlocal boundary layer vertical diffusion scheme in a ~~M~~medium-~~R~~range ~~F~~forecast ~~model~~ (MRF) model (Hong et al., 1996). The major ingredient of the revision is the inclusion of an explicit treatment of entrainment processes at the top of the PBL, ~~comparing~~ compared with the MRF PBL scheme. The specific DC calculation method ~~of DC~~ ~~was~~is shown in Hong~~'s studies~~ et al. (????)~~.~~, ~~This algorithm of DC~~and has been selected as a standard option ~~for the Medium Rang Forecast~~in ~~(~~MRF~~)~~ ~~Model~~ models (Caplan et al. 1997; Farfán and Zehnder, 2001; Basu, et al., 2002; Bright and Mullen, 2002; Mass et al., 2002) ~~and~~ as well as the Weather Research and Forecasting ~~(WRF)~~ model (Hong et al., 2006) in the National Centers for Environmental Prediction~~s~~ (NCEP) since its establishment.~~–~~

The ~~model~~ horizontal resolution of the model ~~is~~ adopted ~~as~~ here was 0.15° × 0.15°, to match the resolution of the emission source. Considering the impacts of the interregional transport of pollutants, ~~e~~East China (100°–~~-~~140°E, 20°–~~-~~60°N) (~~f~~Figure 1a) was set as the model domain, but our discussion ~~mainly~~ focuses mainly on the most polluted area, Jing–~~-~~Jin–~~-~~Ji ~~region~~ (~~the~~ red ~~box~~ frame in ~~f~~Figure 1a), ~~and~~ for which ~~f~~Figure 1b ~~shows~~illustrates the ~~features of~~ geographical ~~location~~ and ~~topography~~ topographical ~~of this region~~features. There are two balloon sounding stations, Xingtai and Beijing (yellow stars in ~~f~~Figure 1b) in our study area. Xingtai, located in southern Hebei province~~,~~ at the eastern foot of the Taihang Mountains, ~~and it~~ is influenced by ~~the sinking~~descending airflow from ~~Taihang~~ the ~~M~~mountains in winter, and in recent years has frequently been ranked ~~is~~ the most polluted city ~~and the $PM_{2.5}$ concentrations usually ranked the first~~ in China ~~in recently years~~. The topography of Xingtai and the serious haze pollution it experiences are closely related to its ~~is the typical representative of~~situation on the southern plain of Jing–~~-~~Jin–~~-~~Ji. Beijing,

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located next to Tianjin and surrounded by Hebei, lies in the transitional zone from the Yan Mountains to its southern plain, and ~~next to Tianjin and surrounded by Hebei,~~ represent~~ings~~ the most polluted areas in the central part of Jing–~~-~~Jin–~~-~~Ji.

2.2 Emissions ~~I~~inventory

Based on the Multi-resolution Emissions Inventory for China~~MEIC emission inventory~~ in 2012 (He et al., 2012), the changes ~~of~~ in East China of ~~5~~ five kinds of emission sources ~~–of~~ industrial, domestic, agricultural, natural, and traffic – ~~are~~ were obtained from ~~the~~ national ~~statistics~~ statistical data ~~of China national~~with respect to industry ~~factories~~, energy consumption, road networks, and motor vehicles, ~~are~~ and updated to 2015 ~~to~~ and 2016 ~~in east China~~. ~~5~~ Five reactive gases~~, i.e.~~ (SO_2, NO, NO_2, CO, NH_3), 20 volatile organic compounds [VOCs~~,~~ (~~i.e.~~ ALD, CH_4, CSL, ETH, HC_3, HC_5, HC_8, HCHO, ISOP, KET, NR, OL_2, OLE, OLI, OLT, ORA_2, PAR, TERPB, TOL, XYL), ~~(VOCs species~~ listed in ~~t~~Table 2~~)~~], and ~~5~~ five aerosol~~s~~ species~~, i.e.~~ (~~black carbon~~BC, ~~organic carbon~~OC, ~~sulfate~~SF, ~~nitrate~~ NI and fugitive dust), ~~are~~ were obtained ~~by~~ via the above emissions data according to the input requirement of the CUACE model. The horizontal grid resolution ~~is~~ was 0.15° × 0.15° and there ~~is~~ was one emissions data~~-~~set for each month ~~with~~ at hourly intervals.

2.3 Data ~~Used~~

Hourly observational PM2.5 concentration data for more than 1440 surface observational stations (blue dots in ~~f~~Figure 1) from the China National Environmental Monitoring Centre ~~(CNEMC)~~ (http://www.cnemc.cn) ~~from~~ during 15–~~to~~ 23 December 2016 were used to evaluate the model results~~;~~. The hourly observational ~~meteorology~~ meteorological data, including wind speed and temperature, from 500 surface automatic observation stations ~~in~~ of the China ~~Meteorology~~ Meteorological Administration (CMA) in the Jing–~~-~~Jin–~~-~~Ji region (red triangle in ~~f~~Figure 1b), were used ~~to~~ for model validation. ~~The m~~Meteorological balloon sounding data from the CMA at 0000 UTC (early morning) and 1200 UTC (~~and~~ dusk, ~~in~~ local time) in Beijing and Xingtai (yellow star in ~~f~~Figure 1b) ~~from CMA~~ during the same period were also used to compare with the modeled results~~;~~. There ~~are~~ is one AERONET station (Holben et al., 1998), Xianghe, and two CARSNET stations (Che et al., 2009; 2014; 2015), Beijing and Shijiazhuang, in the Jing–~~-~~Jin–~~-~~Ji region (black crosses in ~~f~~Figure 1b). Observed aerosol~~s~~ optical depth (AOD) and single

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scattering albedo (SSA) ~~date~~ data from these three stations ~~at~~ during the same ~~time~~ period were also used ~~to~~ for model evaluation~~;~~. NCEP 0.25° × 0.25° global analysis ~~grids~~ gridded data (https://rda.ucar.edu/datasets/ds083.3) were used as the model's initial and ~~every 6 hours~~six-hourly lateral boundary ~~meteorology~~ meteorological input fields. The initial values of chemical tracers were obtained according to their five-year mean climatic values. The results of the first 120 hours of the model ~~start are split out~~were discarded to eliminate the effects of the chemical initial fields.

2.4 ~~Experiments~~ Experimental ~~Design~~design

Both dynamic processes of the regional atmosphere and solar radiation have important impacts on ~~turbulence~~ turbulent diffusion and PBL processes. When severe haze ~~occurred~~occurs, it ~~was~~ has been ~~observed~~ showed from the observation study (Zhong et al., 2018) that ~~the~~ surface-level daily direct ~~radiant~~ radiative exposure ~~was observed reduction~~is reduced by around 89% ~~comparing~~ compared with ~~that on~~ clean days ~~(Zhong et al., 2018)~~, suggesting the ~~possible~~ possibility of a huge difference ~~of~~ in ~~turbulence~~ turbulent diffusion between severe haze and clean days. ~~It~~ However, it is difficult to distinguish between the two reasons ~~leading to the~~for extremely weak ~~turbulence~~ turbulent diffusion in the ~~truth~~ true atmosphere, because of the complicated relationship between ~~atmosphere~~ atmospheric dynamics and solar radiation. However, ~~some~~ meaningful ~~research~~ results ~~could~~ might be ~~expected~~ possible by conducting ~~sensitive~~ sensitivity experiments using an ~~atmosphere~~ atmospheric ~~chemical~~ chemistry model. ~~Three~~ Here, three ~~sensitive~~ such experiments ~~(of~~ EXP1, EXP2, and EXP3 – see Table 3 for descriptions) ~~are~~ were designed to discuss the ~~contributions~~ contributing factors to ~~the~~ extremely weak turbulence and corresponding $PM_{2.5}$ ~~EG~~ explosive growth~~due to AF~~, ~~and~~ along with the insufficient description ~~on the~~of extremely weak turbulent diffusion by PBL schemes in atmospheric ~~chemical~~ chemistry models. ~~(Descriptions of the three experiments listed in Table 3).~~ All other model dynamic processes, physical options, and initial input data of the meteorology and chemical tracers ~~are~~ were same for the three experiments, i.e., except ~~for~~ the differences shown in Table 3. In ~~the sensitive test in~~ EXP3~~, –~~, a further decrease in the ~~turbulence~~ turbulent diffusion coefficient (DTD~~-~~) based on EXP2 was only applied to the DC of chemical tracers in CUACE mode; ~~and~~the DC in other physical packages and the dynamic framework of GRAPES_MESO was the same ~~with that~~as in EXP1 and EXP2.

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批注 **[LP15]:** It is not clear to the editor what 'two reasons' are being referred to here. Return for further assistance/editing if necessary.

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3 Results and ~~D~~discussion~~s~~

~~This ~~The studied haze episode began on 15 December~~,~~ 2016. PM$_{2.5}$ began to gather and climb slowly at this time, but ~~it ~~was below 150 ug/m^3 in most of Jing–~~-~~Jin–~~-~~Ji ~~region ~~from 00:00 UTC ~~on ~~15 to 00:00 UTC ~~on ~~17 December~~,~~ – ~~and we name this~~a period we refer to as the “climbing stage”~~ (CS)~~ of PM$_{2.5}$.~~;~~ From 00:00 UTC ~~on ~~17 to 00:00 UTC 21 December, PM$_{2.5}$ increased rapidly, and ~~reached ~~reaching ~~the PM$_{2.5}$~~a peak~~s~~ of 400–~~-~~600 ug/m^3 in most of the study area. ~~This ~~We refer to this period ~~is named ~~as the “explosive growth ~~(EG) ~~stage” of PM$_{2.5}$. ~~This ~~In this section, we focus mainly ~~focuses ~~on the ~~contributions~~ contributions of ~~to the PM$_{2.5}$ EG due to ~~AF and ~~further ~~DTD to the PM$_{2.5}$ during this stage.

3.1 ~~The s~~Synoptic background~~ of the haze episode~~

The ~~upper atmosphere ~~circulation in the upper atmosphere and the surface-level synoptic system controlling Jing–~~-~~Jin–~~-~~Ji ~~region ~~remained relatively stable during the ~~haze ~~maintenance of this haze episode. Figure 2 displays the ~~G~~geopotential height~~ (GPH)~~, temperature~~ (Temp)~~, and ~~W~~winds~~ fields~~ ~~at ~~in the ~~high~~ upper (500 hPa), middle (700 hPa)~~,~~ and lower ~~atmosphere ~~(850 hPa) atmosphere, ~~and ~~as well as PBL levels (900, 950, 1000 hPa), ~~on ~~at 0000 UTC~~,~~ 19 December~~,~~ 2016, ~~as the typical representative~~to showing the ~~weather ~~meteorological background~~ of this haze event~~. It ~~is ~~can be seen that ~~GPH ~~the geopotential height in the upper atmosphere (500 hPa) showed zonal circulation in East Asia. There was a horizontal trough north ~~to ~~of Jing–~~-~~Jin–~~-~~Ji (black ~~box~~frame) in the upper and middle atmosphere (500 and 700 hPa), and ~~Jing-Jin-Ji~~the region was controlled by ~~the ~~moderate northwesterly or westerly air flow at the bottom of the trough. The ~~T~~temperature and wind fields at 500 and 700 hPa both showed that cold air in the upper and middle atmosphere was weak. ~~GPH ~~The 850-hPa geopotential height ~~in 850hPa ~~showed that the subtropical high ~~(SH in figure 2) ~~in the ~~e~~East ~~s~~Sea was strong; ~~and ~~also, Jing–~~-~~Jin–~~-~~Ji was in the pressure equalization field to the northwest periphery of the subtropical high and the wind was very weak ~~in ~~at this level due to the blocking of the subtropical high. ~~GPHs at~~The 900-, 950-~~,~~ and 100-hPa geopotential heights all showed that Jing–~~-~~Jin–~~-~~Ji was located in the pressure equalization field between the “northwest land high”~~ (LH in figure 2)~~ and southeast subtropical high within the whole PBL, and the land high was weaker than the subtropical high. This resulted in a small pressure gradient, weak and thin wind fields, and a stable ~~atmosphere ~~atmospheric situation within the PBL~~ in Jing-Jin-Ji region~~, which ~~is very helpful~~was conducive

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to the maintenance of the haze episode.

3.2 ~~The~~ Observation–model ~~C~~comparison~~ study of observation and model results~~

~~Not~~ Meteorological factors not only at the surface but also in the PBL ~~meteorology~~ are ~~the~~ key ~~factors~~ in affecting ~~the~~ haze processes ~~haze episode~~ and PM$_{2.5}$ ~~level~~ concentrations (Wang et al., 2014a, 2014b)~~,~~. Unfortunately, however, most numerical models struggle to simulate these aspects~~but it is well known that surface and PBL meteorology factors are more difficult to be predicted or simulated by most numerical models than those at middle and high atmosphere~~, which is also ~~the~~ a key point ~~affecting~~ determining the ~~prediction~~ performance of atmospheric ~~chemical~~ chemistry models (Hu et al., 2013a, 2013b; Li et al., 2016).

Using hourly ~~meteorology~~ meteorological data from surface automatic observation stations of the CMA, the surface wind speed and temperature ~~of~~ at Beijing~~,~~ and Xingtai, and the average ~~in~~ for Jing–~~-~~Jin–~~-~~Ji, ~~by~~ according to the results of EXP1, EXP2 and EXP3, ~~are~~ were evaluated ~~from~~ for the period 15–~~ to~~ 24 December~~,~~ 2016 (~~f~~Figure 3~~, up~~). It can be seen that, in Beijing, the modeled surface wind speed ~~by~~ in the three ~~model~~ experiments was in good agreement with ~~the~~ observation, ~~regardless~~ in terms of the ~~changing~~ overall trend~~,~~ as well as the maximum and ~~the~~ minimum values~~ of wind speed~~. The observed and modeled wind speed was basically below 2 m/s ~~from~~ during 17–~~ to~~ 21 December (i.e., the ~~EG~~ explosive growth stage of PM$_{2.5}$). The ~~M~~modeled wind speed ~~in~~ at Xingtai was slightly worse than ~~those in~~that at Beijing, but the ~~changing~~ overall trend of ~~wind speed~~change was basically consistent with ~~those of~~ observation, and the wind speed was also below 2 m/s during the ~~EG~~ explosive growth stage~~ of PM$_{2.5}$~~. The modeled wind speed was to an extent higher than ~~observation~~ observed ~~to a certain extent~~ at the beginning and end~~ing~~ ~~period~~ in Xingtai. The trend of ~~changing~~ change ~~trend of~~in the modeled average wind speed ~~in~~ for the Jing–~~-~~Jin–~~-~~Ji region showed reasonable agreement with ~~that of~~ observation and was ~~the~~ closest to the ~~observation~~ observed situation ~~at~~ in the ~~EG~~ explosive growth stage~~ of PM$_{2.5}$~~. ~~The~~ In general, the modeled regional wind ~~speed by model~~ was higher than ~~observation~~ observed~~in general~~. ~~The c~~Comparison of the wind speed ~~of~~ among the three ~~model~~ experiments showed that the wind speeds ~~by~~ in EXP2 and EXP3 ~~was~~ were basically same, but to a varying degree both were smaller than in EXP1 ~~in various degree in~~at Beijing~~,~~ and Xingtai, ~~and~~ as well as ~~average in~~for Jing–~~-~~Jin–~~-~~Ji as a whole, during ~~EG~~ the explosive growth stage, showing that

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AF decreased the surface wind speed. The trend of temperature ~~changing~~ change ~~trend by~~according to the three ~~model~~ experiments was also ~~consisted~~ consistent with ~~that of the~~ observation, ~~on the whole in~~at Beijing, Xingtai, and Jing~~-~~–Jin~~-~~–Ji as a whole. ~~But~~ However, it ~~also can be seen~~was found that the modeled temperature was obviously higher than ~~observation~~observed, especially during the ~~EG~~ explosive growth stage. The temperature ~~by~~ in EXP2 and EXP3 was basically same, but lower than ~~that by~~in EXP1, which ~~is~~ was much closer to ~~the~~ observation, indicating that AF reduced the ~~positive errors~~overestimation of surface temperature in Beijing, Xingtai, and ~~average in~~ Jing~~-~~–Jin~~-~~–Ji as a whole. However, ~~it can be seen that~~ the temperature ~~by~~ in EXP2 and EXP3 was also higher than ~~observation~~ observed during the ~~EG~~ explosive growth stage, suggesting a role played by ~~that some~~ other uncertainties in the PBL scheme ~~led to the temperature positive errors during EG stage~~ besides AF, which is ~~deserves~~ deserving of more detailed ~~further~~ study in ~~detail~~the future. Also shown in Figure 3 are the PBL~~-~~-mean winds of the three experiments ~~in~~ for Beijing, Xingtai, and ~~regional average in~~ Jing~~-~~–Jin~~-~~–Ji as a whole ~~were calculated and shown in figure 3 (down)~~. Unfortunately, ~~there are~~ no~~t~~ observational data were available to evaluate them. However, ~~C~~comparison of the PBL's wind and temperature ~~of~~according to the three ~~model~~ experiments showed that the PBL~~-~~-mean wind was basically below 4 m/s while the temperature ~~is~~ was high ~~at~~ in the ~~EG~~ explosive stage~~stage~~ ~~in~~ at Beijing, Xing~~-~~tai, and ~~average~~ in Jing~~-~~–Jin~~-~~–Ji as a whole. Similar to the ~~ground~~ surface-level results, the PBL~~-~~-mean wind speed and temperature ~~by~~ in EXP2 and EXP3 were basically the same, but the wind speed ~~by~~ in these two experiments was obviously lower than that ~~by~~ in EXP1. This indicated that the reduction ~~of~~ in wind speed by AF was more obvious in the PBL than ~~that in~~at ground level~~, —~~. Meanwhile, comparison of the surface-level and PBL temperature of the three experiments showed that the cooling effect ~~by~~ of AF ~~is~~ was much stronger at the surface than ~~that~~ in the PBL.

Aerosol~~s~~ optical properties, including AOD, SSA~~,~~ and asymmetry factor ~~(ASY)~~, largely determine~~s~~ the ~~aerosols~~ direct ~~radiation~~ radiative effects of aerosols. The observed AOD (Table 4) and SSA (Table 5) ~~in~~ at Shijiazhuang, Beijing and Xianghe ~~are~~ were used to evaluate the modeled results ~~from~~ for the period 15– ~~to~~ 22 December. Because the differences ~~of~~ in the modeled AOD and SSA ~~by~~ results of ~~the~~ EXP1, EXP2 and EXP3 ~~are~~ were small, ~~the results~~those of EXP1 only are ~~used~~ referred to here. ~~It can be seen that t~~The values of modeled AOD and SSA and their temporal ~~changing~~ trends of change ~~from~~ during 15– ~~to~~ 22

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December were basically consistent with ~~the~~ observation ~~in~~ at Beijing, Shijiazhuang and Xianghe, ~~proving the~~thus demonstrating good model performance in ~~the~~ terms of its description of aerosol~~s~~ optical properties. Both the observed and modeled SSA ~~in~~ at Shijiazhuang, Beijing~~,~~ and Xianghe (~~t~~Table 5) ~~shows~~ showed that the SSA was obviously higher during the ~~EG~~ explosive growth stage ~~of $PM_{2.5}$ than~~compared with that at the beginning or end~~ing~~ ~~stage~~ of the haze on 15–~~to~~16 and 22 December, illustrating that the scattering characteristics of composite aerosols increase~~d~~ obviously when high AOD and $PM_{2.5}$ occur~~red~~ on severe haze days in the Jing–~~-~~Jin–~~-~~Ji region. The accurate description ~~in~~ of AOD and SSA, especially ~~the~~ with respect to the change in SSA ~~changing~~ from clean to haze days, is the ~~basic~~ basis ~~in~~ of the following discussion ~~of~~on the effects of aerosols ~~effects~~ on $PM_{2.5}$.

Figure 4 displays the averaged observed $PM_{2.5}$ ($PM_{2.5}$_OBS) and simulated $PM_{2.5}$ of EXP1 ($PM_{2.5}$_EXP1), EXP2 ($PM_{2.5}$_EXP2) and EXP3 ($PM_{2.5}$_EXP3) ~~experiments~~ during the ~~EG~~ explosive growth stage. It can be seen from the $PM_{2.5}$_OBS results that the averaged $PM_{2.5}$ values ~~were~~ generally ~~over~~ exceeded 100 $\mu g/m^3$ in east China, and Jing–~~-~~Jin–~~-~~Ji ~~covered~~ comprised the most polluted areas ~~and~~ with $PM_{2.5}$ ~~reached~~ reaching ~~up to~~ 300–~~to~~ 400 $\mu g/m^3$ in parts of Beijing, Tianjin, ~~Middle~~central-south Hebei ~~province~~, western ~~frontier region of~~ Shandong ~~province~~, and northern Henan ~~province~~. The most polluted area with $PM_{2.5}$ values of 500–700 $\mu g/m^3$ appeared in southern Hebei and northern Henan provinces and the maximum value of $PM_{2.5}$ even exceeded 700 $\mu g/m^3$ in part area in southern Hebei.~~The $PM_{2.5}$ center of 500–700 $\mu g/m^3$ appeared in southern Hebei and North northern Henan province, and with the $PM_{2.5}$ maximum of 700 $\mu g/m^3$ was found in southern Hebei.~~ ~~The c~~Comparison ~~study~~ of $PM_{2.5}$_EXP1 and $PM_{2.5}$_OBS shows that $PM_{2.5}$_EXP1 ~~is~~ was obviously lower than $PM_{2.5}$_OBS on the whole. ~~It is noteworthy that~~Notably, EXP1 failed to simulate the $PM_{2.5}$ over 300 $\mu g/m^3$. $PM_{2.5}$_OBS ~~is~~ was about approximately 200–~~to~~ 300 $\mu g/m^3$ over most of Shandong ~~province~~, while ~~the~~ $PM_{2.5}$_bk ~~is~~ was only 100–~~to~~ 200 $\mu g/m^3$ in this region. Compared with $PM_{2.5}$_EXP1, the $PM_{2.5}$_EXP2 values ~~are~~ were significantly improved by AF, and ~~they are~~were much closer to ~~the~~ $PM_{2.5}$_OBS. The ~~H~~high $PM_{2.5}$_OBS centers of 300–~~to~~ 400, 400–~~to~~ 500~~,~~ and 500–~~to~~ 600 $\mu g/m^3$ ~~are~~ were almost simulated by EXP2, indicating the important effects of AF ~~on~~ in ~~the model simulations~~simulating such high values of $PM_{2.5}$ ~~high values~~. However, the simulated areas ~~of~~ of these centers ~~simulated $PM_{2.5}$ values of 300 to 400, 400 to 500, and 500 to 600μg/m^3~~

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~~are~~were ~~still~~ smaller than ~~that~~ those of ~~the~~ PM$_{2.5}$_OBS. EXP2 also ~~fails~~ failed to simulate the maximum PM$_{2.5}$ values over 600 μg/m^3 observed in southern Hebei ~~province~~. PM$_{2.5}$_EXP3 just about ~~makes~~ made up for this ~~shortage~~shortcoming~~,~~; ~~comparing~~ compared with PM$_{2.5}$_EXP1 and PM$_{2.5}$_EXP2, PM$_{2.5}$_EXP3 ~~is~~ was undoubtedly the closest to PM$_{2.5}$_OBS both in terms of PM$_{2.5}$ extremes and ~~its~~ the area of influence ~~area~~. ~~This study result~~These findings illustrate~~s~~ that both AF and DTD in atmospheric ~~chemical~~ chemistry models are required for the effective prediction of PM$_{2.5}$ ~~EG~~ explosive growth during ~~the~~ severe haze in China's Jing–~~-~~Jin–~~-~~Ji ~~in China~~region.

3.3 ~~The~~ Change in downward solar radiation flux ~~change~~ by aerosols and DTD

PM in the atmosphere will inevitably lead to ~~the~~ changes ~~of~~ in surface and ~~atmosphere~~ atmospheric solar radiation flux. When severe haze occurs, most PM is concentrated in the atmosphere near the surface and within the PBL~~,~~; solar radiative flux reaching the ground is reduced greatly, which is ~~the~~ a direct trigger ~~factor~~ for the subsequent changes in thermodynamics, dynamics, and then atmospheric stratification. Any factor leading to ~~the~~ a change ~~of~~ in the ~~atmosphere~~ atmospheric PM loading might result in a change ~~of~~ in the surface downward solar radiation flux (SDSRF). We calculated the percentage changes ~~of~~ in SDSRF (W/m^2) between EXP2 and EXP1 [~~(~~(SDSRF$_{\_EXP2}$ ~~-~~– SDSRF$_{\_EXP1}$) / SDSRF$_{\_EXP1}$~~)~~], and EXP3 and EXP1 [~~(~~(SDSRF$_{\_EXP2}$ ~~-~~– SDSRF$_{\_EXP1}$) / SDSRF$_{\_EXP1}$)~~)~~], to study the impacts on SDSRF ~~by~~ of aerosols and DTD. Figure 5 shows the mean percentage change ~~of~~ in SDSRF (W/m^2) ~~by~~ owing to aerosols (a) and aerosols plus DTD, ~~(b) of~~during ~~EG~~ the explosive growth stage. It can be seen that SDSRF was reduced by more than 50% by aerosols ~~in~~ over most of the study region~~,~~ (60%~~-~~–65% in Jing, Jin, most of Ji, and ~~N~~northern Shandong, and even 65%~~-~~–70% in Jing, Jin, and part of Ji), indicating the important influence of aerosols on SDSRF. Comparison of ~~f~~Figures 5b and 5a ~~showed~~ shows that this reduction ~~of~~ in SDSRF ~~by~~ owing to aerosols (~~f~~Figure 5a) in EXP2 was further strengthened by the DTD of chemical tracers in EXP3 (~~f~~Figure 5b) in certain regions, because DTD ~~made~~ led to the accumulation of more PM$_{2.5}$ ~~gather~~ near the surface (~~f~~Figure 3), less transport ~~less~~ and, subsequently, ~~this led to the~~an ~~increasing~~ increase ~~of~~ in total PM$_{2.5}$ loading. It can also ~~can~~ be seen that the difference ~~of~~ between ~~f~~Figures 5a and ~~figure~~ 5b ~~was~~ is ~~not too much~~negligible. This is because ~~that~~ the major impact~~s~~ of DTD ~~is~~ was to reform the vertical distribution of the ~~atmosphere~~ atmospheric loading of PM$_{2.5}$, and its impact~~s~~ on the total~~-~~ column ~~of~~ PM$_{2.5}$ ~~is not so~~

~~much~~was minor. On the other hand, the reduction ~~of~~ in SDSRF ~~due~~ owing to aerosol~~s~~ radiation was already ~~very great~~considerable, and so the change ~~of~~ in SDSRF ~~due~~ owing to the increased total-column $PM_{2.5}$ by DTD~~,~~ would ~~not~~ be ~~so great on a~~ secondary~~ basis~~. This value of ~~the~~ SDSRF reduction ~~due~~ owing to aerosols and DTD is basically consistent with the 56%–~~-~~89% difference of observational ~~radiant~~ radiative exposure between clear and haze days ~~at~~ during the same period (Zhong et al., 2018).

3.4 ~~The~~ Influence of aerosols~~’~~ ~~reform~~ on the reforming of the local ~~atmosphere~~ atmospheric temperature profile

Offline and online studies indicate~~d~~ ~~the~~ a reforming of the ~~atmosphere~~ atmospheric temperature profile ~~by~~ owing to ~~aerosols~~ the direct effect of aerosol radiation (Wang et al., 2010, 2015b; Forkel et al., 2012; Gao et al., 2014, 2015; Wang et al., 2014; Gao et al., 2017; Ding et al., 2016). In our previous work~~s~~ (Wang et al., 2015a, 2015b), ~~C~~composite aerosol~~s~~ mixing of ~~black carbon~~BC, ~~organic carbon~~OC, ~~sulfate~~SF, ~~nitrate~~NI, dust, ammonium, and sea salt aerosols ~~had been~~was online coupled~~ online coupled~~ into the ~~in~~ GRAPES_CAUCE model. On this basis, in the present study, the changes ~~of~~ in the mean temperature profile of Jing–~~-~~Jin–~~-~~Ji ~~region of~~during daytime ~~due~~ owing to aerosol~~s~~ radiation were calculated ~~from~~ for 15–~~ to~~ 20 December~~,~~ 2016~~ in this work~~. It can be seen from Figure 6 that aerosols cooled the atmosphere below 750–~~ to~~ 800 hPa, ~~while~~ but warmed ~~the atmosphere~~it above this height. Considering the PBL height may be as low as several hundreds to one thousand meters when severe haze~~s~~ occurs in Jing–~~-~~Jin–~~-~~Ji (Wang et al., 2015a; Zhong et al., 2017), it may be concluded that the whole PBL and its near upper atmosphere ~~was~~ were cooled by aerosols to a ~~different~~ varying extent during the different stages of this haze process. The ~~aerosols’~~ warming effects of aerosols above 750–~~-~~850 hPa ~~height~~ were very weak, and the temperature ~~changes~~ differences among different days were also small. However, the ~~aerosols’~~ cooling effects of aerosols ~~shows~~ varied the most between different days ~~differences~~ from the surface to 975 hPa ~~height on different day~~. ~~The~~ For instance, surface daytime cooling ~~is~~ was about 2.2 K on 19 December, 1.5 K on 18 and 20 December, 1 K on 17 December, and 0.5–~~-~~0.6 K on 15–~~ to~~ 16 December. This ~~aerosols’~~ cooling effect of aerosols decreased rapidly with ~~the~~ height. The difference ~~of~~ in the cooling rate~~s~~ between the surface and 850 hPa ~~is~~ was 1.8 K on 19 December, 1.3 K on 18 and 20 December, 1 K on 17 December, and 0.3–~~-~~0.4 K on 15 and 16 December. The difference ~~of~~ in the cooling rate~~s~~ ~~by~~ owing to aerosols between

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the surface and the upper PBL ~~are~~ was much bigger during the ~~EG~~ explosive growth stage than ~~that of~~the ~~CS~~climbing stage. This may have resulted in ~~the~~ further intensification of the temperature inversion layer that ~~pre-~~already existed during the haze event, which will be discussed ~~in figure 7~~ in the following section.

The ~~vertical sounding~~ meteorolog~~y~~ical data from the vertical soundings ~~in~~ taken at Beijing and Xingtai ~~can be~~were used to ~~prove~~ verify ~~if~~ this change ~~of~~ in the temperature profile ~~by~~ owing to aerosols ~~is correct or not~~. Figure 7 shows the vertical temperature profiles of the sounding observations and the modeled temperature profiles ~~by~~ of EXP1 and EXP2 during the climbing stage~~CS~~ (Figure 7a) and ~~EG~~ explosive growth stage (Figure 7b) at the two stations. The temperature profiles (Figure 7a) show~~s~~ that ~~both~~ the model~~ed~~ results ~~by~~ of EXP1 and EXP2 both ~~partly~~ simulated in part the observed temperature inversion ~~in~~ at Beijing and Xingtai on 15~~ to ~~16 December. The ~~very little~~negligible difference between the temperature profiles ~~by~~ of EXP1 and EXP2 ~~indicated~~ indicates that aerosol~~s~~ radiation had very little impact~~s~~ on the temperature profiles and local inversion during the climbing stage~~CS of PM$_{2.5}$~~. Nevertheless, Figure 7b shows that the observed temperature inversions were obviously stronger and thicker on 18~~ to ~~19 December (~~EG~~ explosive growth stage) than those on 15~~ to ~~16 (climbing stage~~CS of PM$_{2.5}$~~), both in Xingtai and Beijing. The temperate profiles ~~by~~ of EXP2 were much closer to the observational results than ~~that by~~those of EXP1~~,~~; and especially, the temperature inversions were much stronger and also closer to ~~the~~ observation than ~~that by~~those of EXP1. This result ~~proved~~ proves that the ~~effective~~ correction of local inversions by aerosols during the ~~EG stage of~~ PM$_{2.5}$ explosive growth stage was effective.

However, it ~~also~~ can also be seen~~,~~ that the inversions ~~by~~ of EXP2, which included online AF, ~~are~~ were still weaker than ~~the truth observed inversion~~observed ~~in~~ at the two stations. This suggests ~~that~~ there must be other ~~causes~~ reasons, besides the online calculation of AF, for the underestimation of the observed extremely strong inversion by the model~~ besides the online calculation of AF~~, which is worthy of ~~studying~~further study.

3.5 ~~The contributions~~Contributions of ~~to PM$_{2.5}$ EG due to~~ AF and DTD to PM$_{2.5}$ explosive growth

Turbulent diffusion ~~process~~ is the main ~~way~~ process of gas and particle~~s~~ ~~exchanging~~ exchange from ~~ground~~ the surface to ~~the~~ upper atmosphere, and ~~then removed~~removal by ~~the~~ high-altitude transport,

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~~which~~ and one of the key tasks of atmospheric chemistry models is to capture this process~~usually achieved by turbulent diffusion process in the chemical atmospheric models~~. Firstly, the inversion and weak turbulent diffusion, which generates from ~~atmosphere~~ atmospheric dynamic processes, leads to ~~atmosphere~~ atmospheric stabilization and determines the occurrence of haze and its strength (Zheng et al., 2016). Once the haze occurs, ~~the~~ aerosol~~s~~ radiation may in turn reinforce the inversion ~~in turn~~ when aerosols exceed~~s~~ a certain critical value, ~~and~~ leading to more $PM_{2.5}$ gathering near the ground. The relative importance of these two aspects on $PM_{2.5}$ ~~EG~~ explosive growth may vary with ~~the~~ $PM_{2.5}$ ~~values~~ concentrations and ~~meteorology~~ meteorological conditions, but they are irreplaceable for ~~the~~ a reasonable prediction and simulation of $PM_{2.5}$ ~~EG~~ explosive growth and peaks ~~by~~ in atmospheric models.

Figure 8 displays the hourly ~~changing~~ change ~~of~~ in observed $PM_{2.5}$ ($PM_{2.5}$_OBS) and the modeled $PM_{2.5}$ ~~by~~ of EXP1, EXP2~~,~~ and EXP3 ~~experiments~~, together with the modeled turbulent DC of the three experiments, in Beijing (Figure 8a) and Xingtai (Figure 8b), ~~from~~ for the period 15–~~to~~23 December. Comparison of the $PM_{2.5}$ modeled by EXP1, EXP2~~,~~ and EXP3 with observation in Beijing (Figure 8a) shows that the ~~modeled~~ $PM_{2.5}$ modeled by EXP3 was the closest to observation during the whole haze episode, which agreed with the results of the regional distribution of the ~~EG~~ explosive growth stage illustrated in Figure 4. EXP1 underestimated the $PM_{2.5}$ obviously ~~from~~ during 17–~~to~~22 December, and this underestimation was even more obvious with ~~the~~ increasing ~~of~~ $PM_{2.5}$. This difference between the modeled and observed $PM_{2.5}$ was ~~the~~ largest during the ~~EG~~ explosive growth stage ~~of $PM_{2.5}$~~. AF ~~shortened~~ reduced this difference to a ~~great~~ considerable extent, and the $PM_{2.5}$ ~~by~~ of EXP2 was much closer to ~~the~~ observation than that ~~by~~ of EXP1 during the ~~EG~~ explosive growth stage ~~of $PM_{2.5}$~~. However, ~~it can be seen that~~ there ~~was~~ were certain differences between the observed and ~~modeled~~ $PM_{2.5}$ and that modeled by EXP2, illustrating that AF ~~can't~~ cannot completely fill the ~~big~~ sizeable gap between observed and modeled $PM_{2.5}$. The $PM_{2.5}$ ~~by~~ of EXP3 ~~shortened~~ reduced this gap further, ~~and shows~~showing the best agreement with observation, especially during the $PM_{2.5}$ ~~EG~~ explosive growth stage.

It can also ~~can~~ be seen from ~~f~~Figure 8a that the DC ~~by~~ of EXP1 was about 30–~~-~~40 m^2/s during the ~~EG~~ explosive growth stage ~~of $PM_{2.5}$~~, which was about 50% of the 60–~~-~~70 m^2/s on ~~the~~ clear days (15 or 22 December). Obviously, ~~the~~ this 50% DC difference~~s~~ between ~~the~~ clear and severe haze days may ~~not~~ be

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~~enough~~ insufficient to ~~discriminate~~ separate the difference ~~of~~ in turbulent diffusion intensity between the extremely stable atmosphere on haze days and the unstable atmosphere on clear days, which is ~~the~~ an important reason for the ~~underestimation~~ underestimated ~~of~~ $PM_{2.5}$ ~~EG~~ explosive growth ~~by~~ in EXP1. Compared with EXP1, the AF in EXP2 led to a notable enhancement of the temperature inversion (Figure 7b), a significant decrease in the turbulent diffusion ~~on~~ of $PM_{2.5}$ during the ~~EG~~ explosive growth stage, and a low maximum DC at noon ~~by EXP2 (was~~ as low as 14 m^2/s on 20 December~~,~~ ~~which decreased about~~ a reduction of 50% ~~comparing~~ compared with ~~that by~~ EXP1). The ~~M~~maximum DC at noon ~~by EXP2~~ on haze days in EXP2 was only about 20% of that on clear days. The maximum DC at noon ~~by~~ in EXP3 was lower than 5 m^2/s on 20 December and, at the same time, the $PM_{2.5}$ modeled by EXP3 was further increased and ~~it~~ was also much ~~further~~ closer to the observed $PM_{2.5}$ ~~observation~~ than the $PM_{2.5}$ ~~by~~ of EXP2.

~~It can be seen from the comparative study~~Through comparison of the temporal ~~changing~~ change ~~between~~ of DC and $PM_{2.5}$ ~~by~~ in EXP1, EXP2~~,~~ and EXP3 in Beijing, ~~that~~ it is clear that ~~the~~ an overestimation of turbulent DC ow~~n~~ing to ~~lack~~ the absence of online~~-~~ ~~calculation~~ calculated ~~of~~ AF, ~~and~~ as well as a deficient description of ~~the~~ extremely stable stratification ~~by~~ in the PBL schemes ~~in~~ of the atmospheric model, can lead to a distinct underestimation of $PM_{2.5}$ ~~EG~~ explosive growth and peaks when severe haze ~~occurred~~ occurs in China's Jing–Jin–Ji ~~in China~~region.

The trends of ~~changing~~ change ~~trends~~ ~~of~~in DC and $PM_{2.5}$ at Xingtai ~~by~~ in the three ~~sensitive~~ experiments ~~in Xingtai~~ (Figure 8b) ~~shows the~~are similar ~~results with~~to those ~~in~~ at Beijing. The $PM_{2.5}$ ~~by~~ of EXP3 was also ~~the~~ closest to observation, followed by EXP2, and then EXP1 was the worst, during the whole haze episode. However, during the ~~EG~~ explosive growth stage ~~of $PM_{2.5}$~~, the relative contributions ~~on the $PM_{2.5}$ peak values due to~~ of AF and DTD to the $PM_{2.5}$ peak values showed some differences ~~with~~ to those ~~in~~ at Beijing. The contributions ~~to $PM_{2.5}$ peaks due to~~ of DTD to $PM_{2.5}$ peaks were more important than ~~that~~ those ~~by~~ of AF ~~in~~ at Xingtai. Located ~~at~~ in the eastern foothills of the Taihang Mountains, Xingtai is usually affected by ~~the~~ downhill airflow. ~~and t~~Temperature inversions in this area ~~is~~ form and strengthen ~~easy~~ easily~~to form and strengthened~~, leading to stronger inversion, weaker turbulent diffusion, and more stable atmospheric stratification~~,~~. ~~but~~ However, this kind of inversion and weak turbulent diffusion, derived from the local terrain, is ~~more difficult~~harder ~~to describe by~~for PBL schemes in atmospheric ~~chemical~~

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chemistry models to describe, and likely underestimated~~.~~.

Figure 9 ~~shows the~~is a diagrammatic sketch of the contributions ~~to the PM$_{2.5}$ of EG stage due to~~ of AF and DTD to the PM$_{2.5}$ of the explosive growth stage according to~~summarized by~~ the results ~~of~~ at Beijing and Xingtai. It can be seen that the DC ~~by~~ of EXP1 was 30–~~-~~35 m^2/s, ~~DC by~~while that of EXP2 was 15–~~-~~17 m^2/s, ~~means~~ meaning ~~that~~ AF ~~reduces~~ reduced the DC by about 43%~~ -~~–57%~~ DC of EXP1~~, which led to the rise in simulated PM$_{2.5}$ from 144 ug/m^3 ~~by~~ in EXP1 to 205 ug/m^3 ~~by~~ in EXP2 ~~in~~ at Beijing, and from 280 ug/m^3 ~~by~~ in EXP1 to 360 ug/m^3 in EXP2 ~~in~~ at Xingtai. This means that AF reduced the underestimation of PM$_{2.5}$ at Beijing and Xingtai by 20% ~~in Beijing~~ and 25%~~ in Xingtai of simulated PM$_{2.5}$ negative errors,~~, respectively. The DC ~~by~~ of EXP3 was as low as 4–~~-~~6 m^2/s during the ~~EG~~ explosive growth stage~~ of PM$_{2.5}$~~, ~~showing~~ demonstrating the joint effects of AF and DTD reduced the DC to less than 4–~~-~~6 m^2/s, near-zero, which we ~~name~~ refer to ~~it~~ as "turbulent ~~intermittent~~intermittence". ~~-~~The direct result~~s~~ of this "turbulent ~~intermittent~~intermittence" ~~is~~ was ~~the~~ a further ~~increasing~~ increase ~~of~~ in the simulated surface PM$_{2.5}$, based on EXP2. DTD ~~decreases~~ reduced ~~14% to 20%~~ the underestimation of simulated PM$_{2.5}$ by 14% to 20%, and the ~~errors of~~ PM$_{2.5}$ errors in~~by~~ EXP3 were reduced to as low as ~~-~~–11% to 2%.

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4. Conclusions

Using an atmospheric ~~chemical~~ chemistry model, GRAPES_CUACE, three experiments (EXP1, EXP2 and EXP3) were designed to study the reason for the explosive growth of PM$_{2.5}$ mass during a "red-alert" heavy haze event that occurred ~~on~~ during 15–~~to~~ 23 December~~,~~ 2016 in China's Jing–~~-~~Jin–~~-~~Ji ~~in China~~region. The contributions ~~to the PM$_{2.5}$ by~~ of AF and DTD to the PM$_{2.5}$~~aerosols feedback and a further decrease in turbulent diffusion coefficient of chemical tracers~~, representing ~~a~~ compensation for the deficient description of extremely weak turbulent diffusion ~~by~~ in the PBL scheme ~~in~~ of the atmospheric models, ~~are~~ were studied by ~~analysing~~ analyzing the changes ~~of~~ in PM$_{2.5}$, ~~surface downward solar radiation flux~~SDSRF, wind speed and temperature, ~~diffusion coefficient~~DC, and the relationships ~~between~~ among them, ~~of~~ in the three experiments.

~~The study~~Results show~~s~~ that the ~~diffusion coefficient~~DC ~~by~~ in EXP1 ~~is~~ was about 60–~~-~~70 m^2/s on clear days and 30–~~-~~35 m^2/s on haze days. The 50% difference ~~of~~ between the two was ~~not~~ considered ~~enough~~ insufficient to ~~discriminate~~ separate the unstable atmosphere on clear days and the extreme stable atmosphere on severe haze days, ~~comparing~~ compared with the differences ~~of~~ in direct downward solar radiation between clear and haze days, which ~~is~~ was also ~~proved~~ proven indirectly by the weaker inversion ~~calculated by~~of EXP1 than that ~~of~~ from ~~the actual~~ sounding observations. This led to a 40%~~-~~–51% underestimation of the PM$_{2.5}$ peaks ~~by~~ in EXP1 during the ~~explosive growth stage of~~ PM$_{2.5}$ explosive growth stage. Online calculation of ~~aerosols radiation feedback~~AF reduced the surface and PBL wind speed and cooled the surface and PBL atmosphere. The surface daytime cooling due to aerosol~~s~~ radiation was 1.5–~~-~~2.2 K during the explosive growth stage ~~of PM$_{2.5}$~~ and 0.5–~~-~~0.6 K during the climbing stage ~~of PM$_{2.5}$~~. The ~~aerosols'~~ cooling effect of aerosols decreased rapidly with ~~the~~ height, and this ~~is~~ was ~~the~~ a major reason for the strengthening of the temperature inversion during the explosive growth stage ~~of PM2.5~~. The reduced DC ~~by~~ owing to AF ~~was up to~~reached 43%~~-~~–57% during the PM$_{2.5}$ ~~EG~~ explosive growth stage ~~of PM2.5~~. ~~The impacts on PM$_{2.5}$ due to AF was distinct during the explosive growth stage of PM$_{2.5}$ while very little during climbing stage of PM$_{2.5}$ in the model run, indicating a critical value of 150 ug/m^3 of PM$_{2.5}$ leading to an effective AF in online atmospheric chemical model.~~ The local inversion simulated ~~by~~ in EXP2 was strengthened and closer to the actual sounding observation than that ~~by~~ of EXP1. This resulted in a 20%–~~-~~25% reduction ~~of~~ in the ~~PM$_{2.5}$~~ underestimation of PM$_{2.5}$, ~~and~~ with PM$_{2.5}$ errors ~~by~~ in EXP2 ~~was~~ being as low as ~~-~~−16 to ~~-~~−11% during the explosive growth stage ~~of PM$_{2.5}$~~. The impact on PM$_{2.5}$ owing to AF in the model run was distinct during the explosive growth stage, but minor during the climbing stage, indicating a critical value of 150 ug/m^3 of PM$_{2.5}$ leading to an effective AF in online atmospheric chemistry models.~~The impacts on PM$_{2.5}$ due to AF was distinct during the explosive growth stage of PM$_{2.5}$ while very little during climbing stage of PM$_{2.5}$ in the model run, indicating a critical value of 150 ug/m^3 of PM$_{2.5}$ leading to an effective AF in online atmospheric chemical model.~~ However, the local inversion simulated by EXP2 was still weaker than ~~the actual observation~~observed, and the PM$_{2.5}$ ~~by~~ of EXP2 was still smaller than ~~observation~~observed, illustrating ~~that~~ AF could not solve all the PM$_{2.5}$ underestimation problems. In EXP3, the ~~DC Further~~ DTD of particles and gas based on EXP2 resulted in a 14%~~-~~–20% lessening of the PM$_{2.5}$ underestimation based on EXP2, and the PM$_{2.5}$ errors of EXP3 ~~was~~ were reduced to ~~-~~−11% to 2%.

~~This~~ The present study ~~result illustrated~~illustrates that the PBL schemes in current atmospheric ~~chemical~~ chemistry models ~~is~~ are probably insufficient for describing the extremely stable atmosphere

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resulting in explosive growth of $PM_{2.5}$ and severe haze in China’s Jing–~~-~~Jin–~~-~~Ji ~~in China~~region~~,~~. ~~which~~ This may involve ~~in~~ two important reasons: ~~One is~~ the absence of an online calculation of AF, ~~another is the~~and/or a deficient description of ~~the~~ extremely weak turbulent diffusion by the PBL scheme in the atmospheric ~~chemical~~ chemistry model. Our study suggests that an online calculation of AF and an improvement in the ~~arithmetic~~ representation of turbulent diffusion in PBL schemes, with a focus~~ing~~ on extremely stable ~~atmosphere~~ atmospheric stratification, in atmospheric ~~chemical~~ chemistry models, are indispensable for a reasonable description of local “turbulent ~~intermittent~~intermittence” and an accurate prediction of the explosive growth and peaks of $PM_{2.5}$ of severe haze in China’s Jing–~~-~~Jin–~~-~~Ji ~~in China~~region.

Author Contributions:

Hong Wang and Xiaoye Zhang designed the idea and experiments~~,~~; Hong Wang and Yue Peng carried them out; Hongli Liu prepared the emissions data and introduction; Meng Zhang ~~did certain~~performed some of the model runs~~.~~; Huizheng Che and Yu Zheng processed the AOD and SSA observational data~~.~~; Yanli Cheng completed ~~t~~Table 3 and the related introduction.

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Table 1. ~~Physics~~ Physical and ~~C~~chemi~~stry~~cal processes in GRAPES_CUACE.

~~Physics and Chemistry~~Process	~~o~~Option~~s~~	Reference~~s~~
Explicit precipitation	WDM6	Lim and Hong~~,~~ (2010)
Cumulus cloud~~s~~	KFETA ~~S~~scheme	Kain~~,~~ (2004)
Longwave radiation	Goddard	Chou et al.~~,~~ (2001)
Shortwave radiation	Goddard	Chou et al.~~,~~ (1998)
Surface layer	SFCLAY ~~S~~scheme	Pleim~~,~~ (2007)
~~Planatory Boundary layer~~PBL	MRF ~~S~~scheme	Hong et al.~~,,~~ (1996, 2006)
Land surface	SLAB ~~S~~scheme	Kusaka et al.~~,~~ (2001)
Gas-phase chemistry	RADM II	Stockwell et al.~~,~~ (1990)
Aerosol~~ Scheme~~	CUACE	Zhou et al.~~,~~ (2012)
Aerosol ~~D~~direct effect	External ~~M~~mixing	Wang et al.~~,~~ (2015)
Aerosol ~~I~~indirect effect	CAUCE+WDM6	Zhou et al.~~,~~ (2016)

Table 2. ~~Sensitive Experiments~~ Design of sensitivity experiments.

Experiment~~s~~	Description ~~of model Experiments~~
EXP1	Background experiment: ignoring aerosol~~s~~ radiation and ~~-~~conventional DC of chemical tracers by PBL scheme in GRAPES_CUACE
EXP2	~~Sensitive experiment with~~Online ~~aerosols radiation feedback~~AF online and conventional DC of chemical tracers by PBL scheme in GRAPES_CUACE
EXP3	~~Sensitive experiment with~~Online ~~aerosols radiation feedback~~AF ~~online, only~~ and DC of chemical tracers ~~is~~ set ~~as~~ to 20% of ~~the~~ conventional DC~~-~~ calculated by PBL scheme, representing ~~a supposed~~ compensation for the deficient description of extremely weak turbulent diffusion by the PBL scheme~~,~~; DC in physical and dynamic processes ~~was~~ the same ~~with~~ as EXP1

Table 3. VOCs in the emissions data.

VOC~~s~~	Full name
ALD	Acetaldehyde and higher aldehydes
CH4	Methane
CSL	Cresol and other hydroxy substituted aromatics
ETH	Ethane
HC3	Alkanes w/ 2.~~7x10~~7 × 10^{-13} > kOH < 3.~~4x10~~4 × 10^{-12}
HC5	Alkanes w/ 3.~~4x10~~4 × 10^{-12} > kOH < 6.~~8x10~~8 × 10^{-12}
HC7	w/kOH > 6.~~8x10~~8 × 10^{-12}
HCHO	Formaldehyde
ISOP	Isoprene
KET	Ketones
OL2	Ethene
OLI	Internal olefins
OLT	Terminal olefins
ORA2	Acetic and higher acids
PAR	Paraffin carbon bond
TERPB	Monoterpenes
TOL	Toluene and less reactive aromatics
XYL	Xylene and more reactive aromatics

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Table 4. Observed and ~~M~~modeled daily AOD (* stands for shortage of observation).

Date	Shijiazhuang		Beijing		Xianghe	
	OBS	MODEL	OBS	MODEL	OBS	MODEL
15	0.46	0.55	0.07	0.12	0.10	0.15
16	0.62	0.60	0.14	0.18	0.60	0.40
17	1.30	1.10	0.50	0.56	1.33	1.05
18	1.42	1.20	0.69	0.75	0.87	0.97
19	1.26	1.30	0.50	0.86	0.96	0.90
20	*	1.20	1.90	1.70	*	1.50
21	*	0.65	1.76	1.50	1.78	1.60
22	0.18	0.30	0.10	0.20	0.18	0.22

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Table 5. Observed and ~~M~~modeled daily SSA (* stands for shortage of observation).

Date	Shijiazhuang		Beijing		Xianghe	
	OBS	MODEL	OBS	MODEL	OBS	MODEL
15	0.83	0.85	0.81	0.83	0.86	0.84
16	0.83	0.85	0.88	0.86	0.92	0.86
17	0.88	0.89	0.88	0.90	0.93	0.90
18	0.87	0.89	0.91	0.92	0.90	0.90
19	0.86	0.91	0.90	0.93	0.92	0.91
20	*	0.90	*	0.93	*	0.92
21	*	0.88	0.93	0.93	*	0.90
22	0.82	0.83	0.84	0.86	0.88	0.84

带格式表格

Figure captions

批注 **[LP32]:** See captions below figures for individual edits.

Fig. 1. (a) Model domain and location of Jing–Jin–Ji. (b) Geographic location and topography of Jing–Jin–Ji. Blue dots are the locations of $PM_{2.5}$ observations; red triangles are the locations of automatic weather stations; yellow stars are the two sounding stations; black crosses are the CARSNET and AEROSNET stations.~~**Fig.1** Model domain and location of Jing-Jin-Ji (a), Features of geographical location and topography of Jing-Jin-Ji (b) (blue dots are the locations of $PM_{2.5}$ observation, red triangles stands for the locations of automatic weather stations, and yellow stars are the two sounding station, black crosses are the CARSNET and AEROSNET stations)~~

Fig. 2. Geopotential height (color-shaded; gp10m), temperature (dashed black contours; K) and wind (wind bars; m/s) in the (a) upper (500 hPa) and (b) middle (700 hPa) atmosphere, and geopotential height and wind in the (c) lower atmosphere (850 hPa) and (d–f) PBL (900, 950, 1000 hPa), at 0000 UTC 19 December 2016.~~Fig. 2 GPH (shaded, gp10m), Temp (broken black line, K) and Wind (wind bar, m/s) at high (500hPa) and middle (700hPa), and GPH and Wind at low atmosphere (850hPa) and PBL levels (900, 950, 1000hPa) on 00 UTC, 19 December, 2016~~

Fig. 3. Observed and modeled wind speed and temperature at the surface (upper panels), and the PBL-mean wind speed and temperature (lower panels), from the results of EXP1, EXP2 and EXP3 for Beijing, Xingtai, and the average for Jing–Jin–Ji as a whole, during 15–24 December 2016.~~Fig. 3 Observed and modeled wind speed and temperature at surface (up) and PBL mean wind speed and temperature (down) by EXP1, EXP2, and EXP3 in Beijing, Xingtai, and average in Jing-Jin-Ji from 15 to 24 December~~

Fig. 4. Mean observed (OBS_$PM_{2.5}$) and modeled $PM_{2.5}$ concentration (μg/m^3) of the $PM_{2.5}$ explosive growth stage, from the results of EXP1, EXP2 and EXP3 ($PM_{2.5}$_EXP1, $PM_{2.5}$_EXP2 and $PM_{2.5}$_ EXP3, respectively).~~Fig.4 Mean Observed (OBS_$PM_{2.5}$) and Modeled PM2.5 concentration (μg/m3) of EG stage of $PM_{2.5}$ by EXP1, EXP2, EXP3 ($PM_{2.5}$_EXP1, $PM_{2.5}$_EXP2, and $PM_{2.5}$_ EXP3)~~

Fig. 5. Mean percentage change in SDSRF (W/m^2) owing to (a) aerosols and (b) aerosols+DTD during the explosive growth stage.~~Fig. 5 The mean percentage change of SDSRF (W/m^2) due to aerosol (a) and aerosol and DTD (b) of EG stage~~

Fig. 6. Profiles of average temperature changes in Jing–Jin–Ji owing to AF (K) during 15–20 December

2016.~~Fig.6 Profiles of the average temperature changes in Jing-Jin-Ji due to AF (K) from 15 to 20 December, 2016.~~

Fig. 7. Sounding-observed and modeled temperature profiles in EXP1 and EXP2 during the (a) climbing stage and (b) explosive growth stage in Beijing and Xingtai.~~Fig.7 The Sounding-observed and modeled temperature profiles by EXP1 and EXP2 during CS (a) and EG stage (b) in Beijing and Xingtai.~~

Fig. 8. Hourly change of $PM_{2.5}$_OBS, $PM_{2.5}$_EXP1, $PM_{2.5}$_EXP2, and $PM_{2.5}$_EXP3 (μg/m^3), together with the DC at 950 hPa of the three experiments (DC_EXP1, DC_EXP2, DC_EXP3) during 15–22 December 2016 in (a) Beijing and (b) Xingtai.~~**Fig.8** Hourly changing of $PM_{2.5}$-OBS, $PM_{2.5}$-EXP1, $PM_{2.5}$-EXP2, and $PM_{2.5}$-EXP3 (μg/m^3), together with the turbulent diffusion coefficient at 950hPa of the three experiments (DC_EXP1, DC_EXP2, DC_EXP3) from 15 to 22 December, 2016 in Beijing (a) and Xingtai (b)~~

Fig. 9. Diagrammatic sketch of the contributions of AF and DTD to the $PM_{2.5}$ explosive growth.~~**Fig.9** The diagrammatic sketch of the contributions to the $PM_{2.5}$ EG due to AF and DTD~~

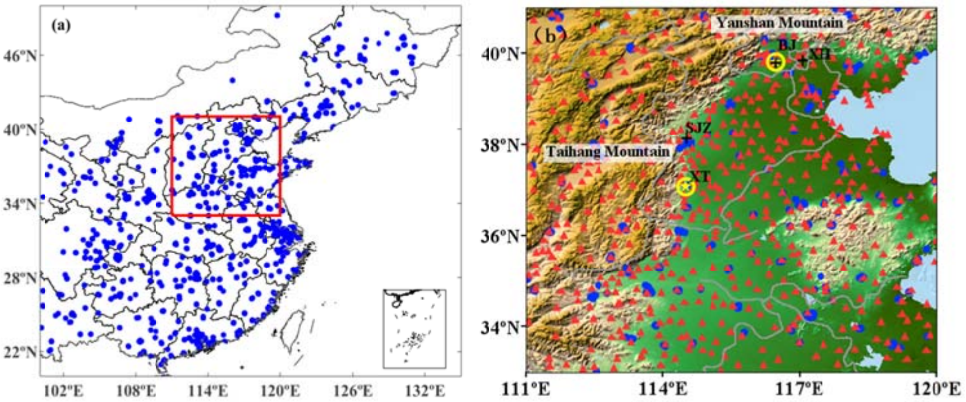

Fig. 1, (a) ~~-~~Model domain and location of Jing–~~-~~Jin–~~-~~Ji ~~(a),~~. (b) ~~Features of g~~Geographic~~al~~ location and topography of Jing–~~-~~Jin–~~-~~Ji ~~(b)~~. ~~(b~~Blue dots are the locations of $PM_{2.5}$ observations~~,~~; red triangles ~~stands~~

批注 [LP33]: In (b), change the labelling to Taihang Mountain**s** and Yanshan Mountain**s** (i.e., plural).

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~~for~~are the locations of automatic weather stations~~,~~; ~~and~~ yellow stars are the two sounding stations~~,~~; black crosses are the CARSNET and AEROSNET stations.~~)~~

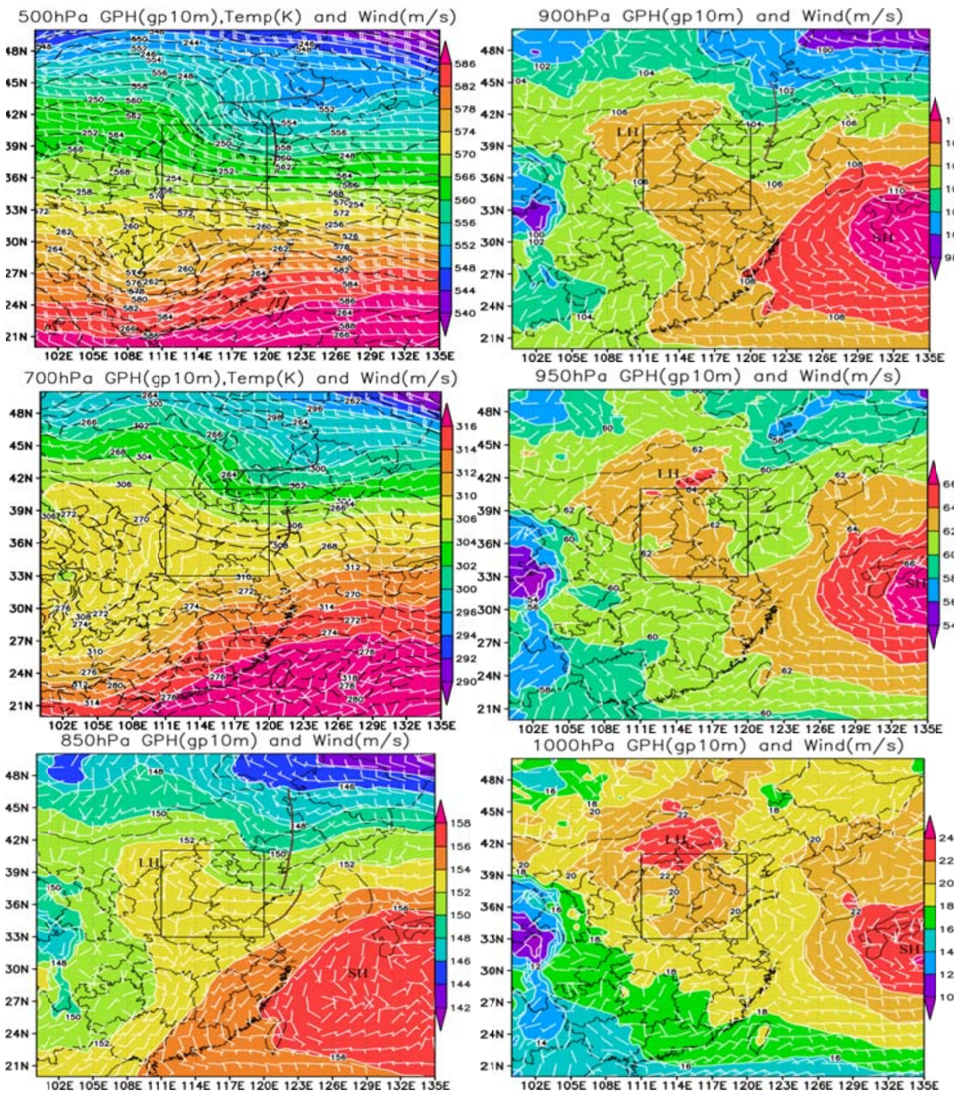

Fig. 2. ~~GPH~~ Geopotential height (color-shaded~~,~~; gp10m), ~~Temp~~ temperature (~~broken~~ dashed black ~~line~~contours~~,~~; K) and ~~W~~wind (wind bars~~,~~; m/s) ~~at~~ in the (a) ~~high~~ upper (500 hPa) and (b) middle (700 hPa) atmosphere, and ~~GPH~~ geopotential height and ~~W~~wind ~~at~~ in the (c) lower atmosphere (850 hPa) and (d–f) PBL ~~levels~~ (900, 950, 1000 hPa), ~~on~~ at 0000 UTC~~,~~ 19 December~~,~~ 2016.

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批注 [LP34]: Please label the panels (a) to (f).

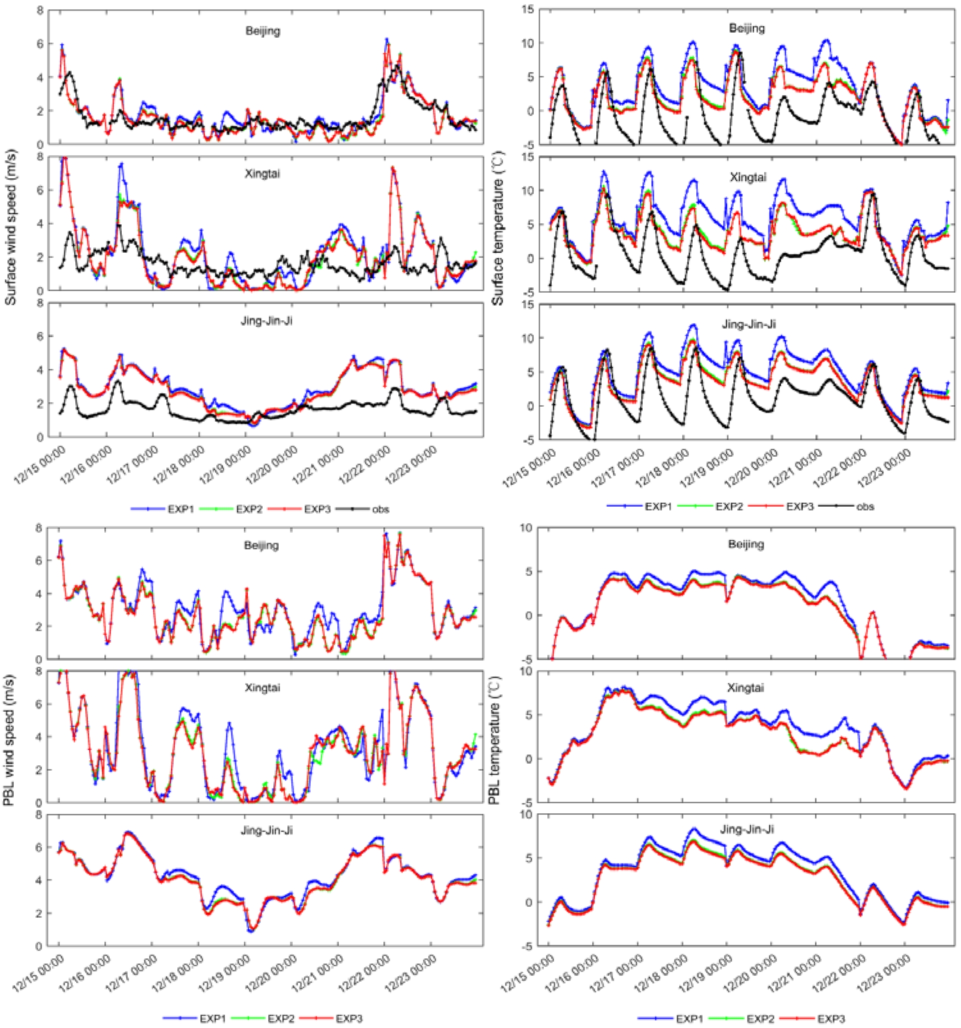

Fig. 3. Observed and modeled wind speed and temperature at the surface (upper panels), and the PBL-mean wind speed and temperature (~~down~~lower panels), ~~by~~ from the results of EXP1, EXP2~~,~~ and EXP3 ~~in~~ for Beijing, Xingtai, and the average ~~in~~ for Jing-~~-~~Jin-~~-~~Ji as a whole, ~~from~~ during 15– ~~to~~ 24 December 2016.

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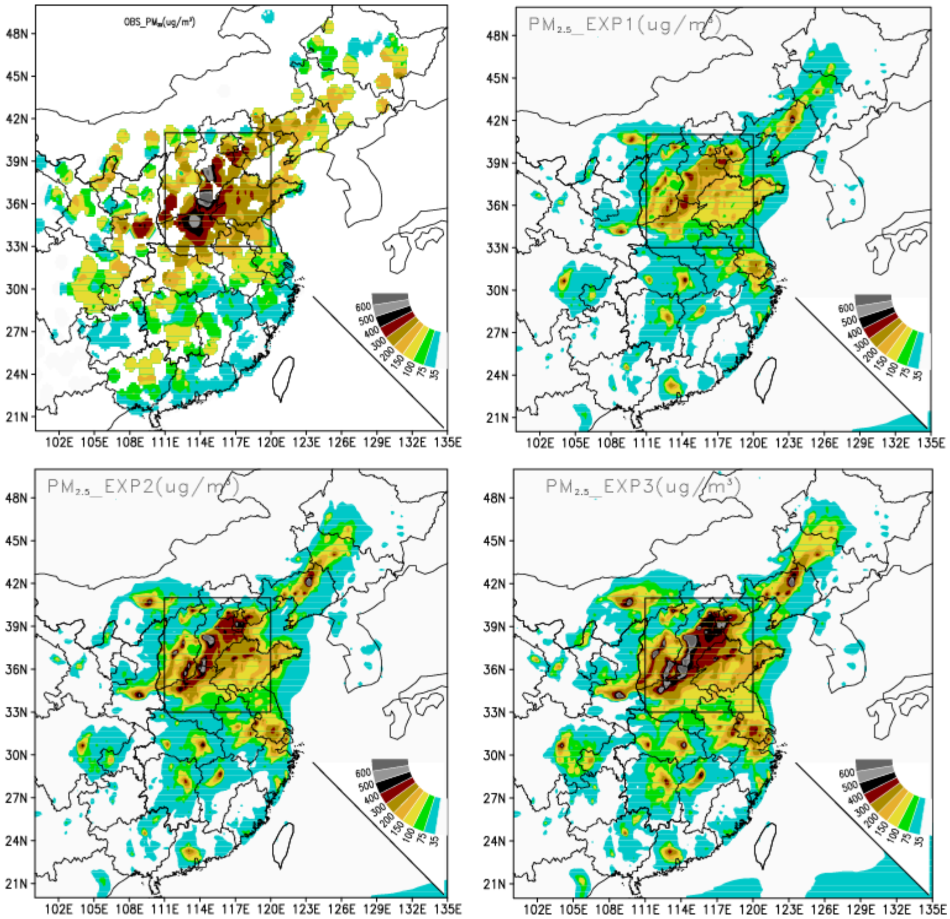

Fig. **4.** Mean ~~O~~observed (OBS_PM$_{2.5}$) and ~~M~~modeled PM$_{2.5}$ concentration (μg/m^3) of ~~EG stage of~~ the PM$_{2.5}$ explosive growth stage, from the results of~~by~~ EXP1, EXP2~~,~~ and EXP3 (PM$_{2.5}$_EXP1, PM$_{2.5}$_EXP2~~,~~ and PM$_{2.5}$_ EXP3, respectively).

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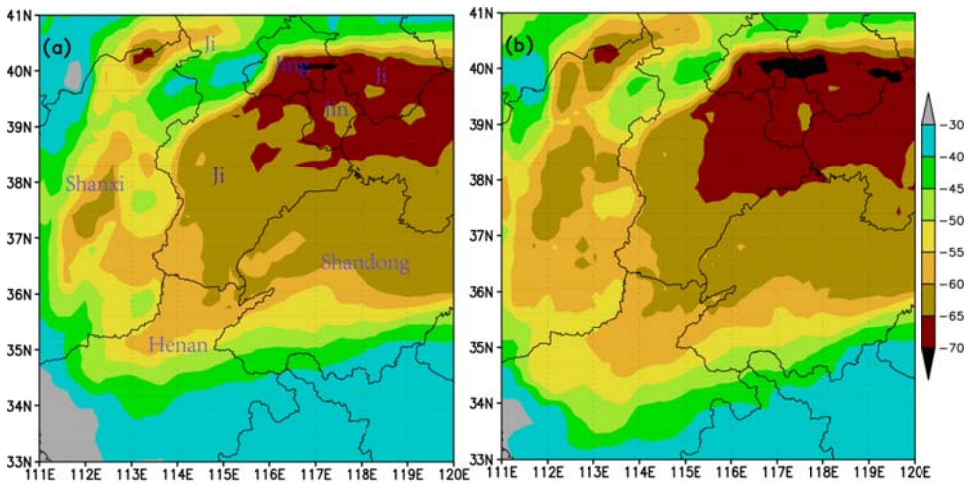

Fig. 5. ~~The m~~Mean percentage change ~~of~~ in SDSRF (W/m^2) ~~due~~ owing to (a) aerosols ~~(a)~~ and (b) aerosols ~~and~~ +DTD ~~(b)~~ ~~of~~ during the ~~EG~~ explosive growth stage.

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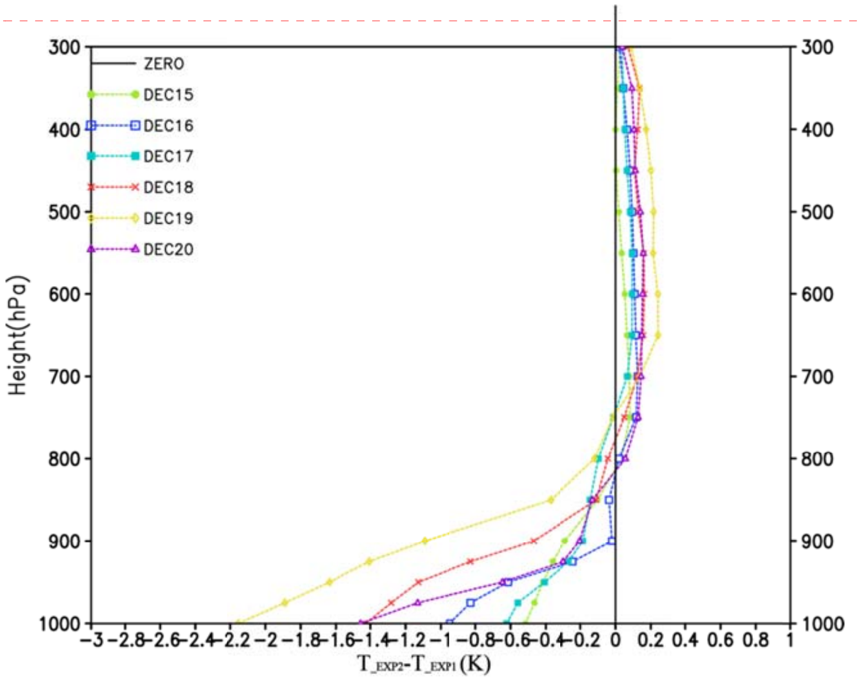


批注 **[LP35]:** Insert a space before the bracketed units in the *y*-axis label.

Fig. **6.** Profiles of ~~the~~ average temperature change~~s~~ in Jing~~-~~–Jin~~-~~–Ji ~~due~~ owing to AF (K) ~~from~~ during 15–~~to~~ 20 December~~,~~ 2016.

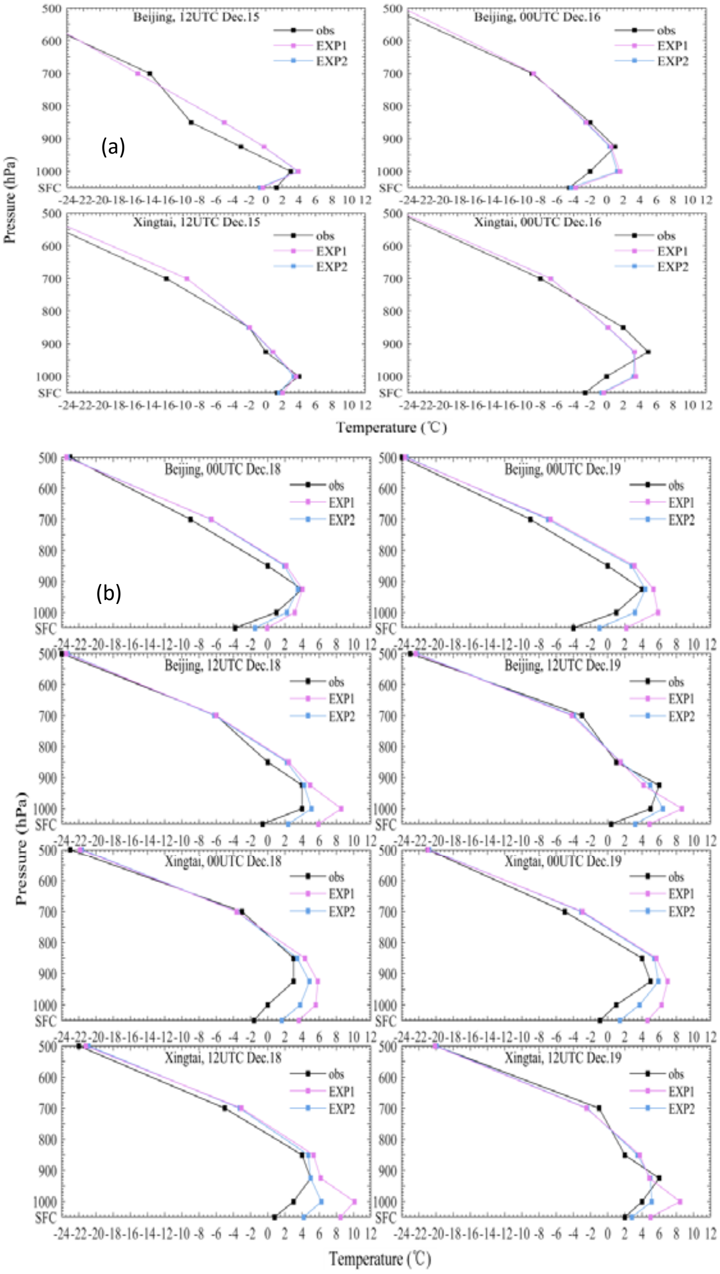
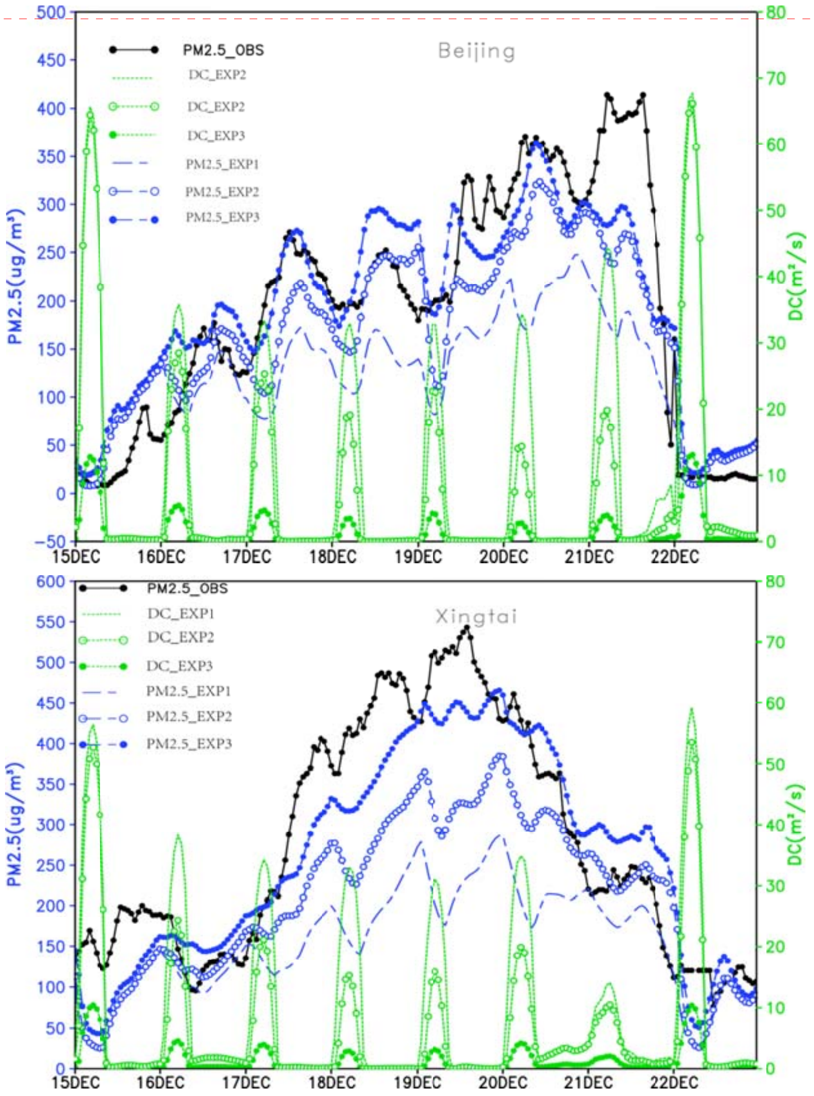


Fig. 7. Sounding-~~-~~observed and modeled temperature profiles ~~by~~ in EXP1 and EXP2 during the (a) climbing stage~~CS~~ ~~(a)~~ and (b) ~~EG~~ explosive growth stage ~~(b)~~ in Beijing and Xingtai.



批注 [LP36]: Insert a space before the bracketed units in the vertical-axis labels.

Fig. 8. Hourly ~~changing~~ change of PM$_{2.5}$_OBS, PM$_{2.5}$_EXP1, PM$_{2.5}$_EXP2, and PM$_{2.5}$_EXP3 (μg/m^3), together with the ~~turbulent diffusion coefficient~~DC at 950 hPa of the three experiments (DC_EXP1, DC_EXP2, DC_EXP3) ~~from~~ during 15–~~to~~ 22 December 2016, ~~2016~~ in (a) Beijing ~~(a)~~ and (b) Xingtai ~~(b)~~.

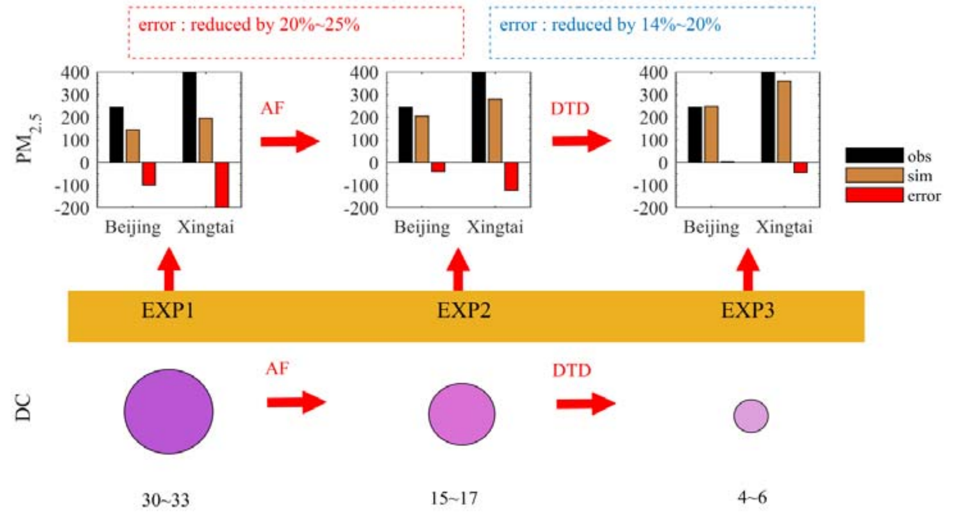


Fig. 9. ~~The d~~Diagrammatic sketch of the contributions ~~to the $PM_{2.5}$ EG due to~~ of AF and DTD to the $PM_{2.5}$ explosive growth.

批注 **[LP37]:** Replace the tildes (~) with en dashes (–) in the annotation to indicate a range.