WRF-Chem v3.9 simulations of the East Asian dust storm in May 2017: modeling sensitivities to dust emission and dry deposition schemes

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Abstract

Dust aerosol plays an important role in the radiative budget and hydrological cycle, but large uncertainties remain for simulating dust emission and dry deposition processes in models. In this study, we investigated dust simulation sensitivity to two dust emission schemes and three dry deposition schemes using Weather Research and Forecasting model coupled with chemistry (WRF-Chem). Results showed that simulated dust loading is very sensitive to different dry deposition schemes, with the relative difference of dust loading using different dry deposition schemes range from 20%-116%. Two dust emission schemes are found to produce significantly different spatial distribution of dust loading. The difference of dry deposition velocity in different dry deposition schemes comes from the parameterization of collection efficiency from impaction and rebound effect. An optimal combination of dry deposition scheme and dust emission scheme has been identified to best simulate the dust storm in comparison with observation and to include better physical treatment of dust

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25　emission and surface collection processes. The optimal dry deposition scheme accounts for the rebound effect and the

collection efficiency from impaction changes with the land use categories and therefore has a better physical treatment of dry

deposition velocity. Our results highlight the importance of dry deposition schemes for dust simulation.

1　Introduction

Dust aerosol is an important component in the atmosphere and it can impact many processes of the Earth system. Through

30　absorbing and scattering shortwave and longwave radiative fluxes, dust can alter the radiative budgets, which is called the

direct effect (Chen et al., 2013; Kok et al., 2017; Zhao et al., 2010, 2011, 2012). Acting as cloud condensation nuclei (CCN)

and ice nuclei (IN), dust can change cloud properties and precipitation, which is called the indirect effects (Creamean et al.,

2013; Demott et al., 2010). Besides, dust aerosol can absorb solar radiation and change the atmospheric stability and

therefore cloud formation, which is known as the semi-direct effect (Hansen et al., 1997). Furthermore, natural dust is

35　important for air quality assessments and has significant impacts on human health (Abuduwaili et al., 2010; Chen et al., 2019;

Hofer et al., 2017; Jiménez-Guerrero et al., 2008; Ozer et al., 2007). Although great progress has been made in dust models and

dust simulations in recent decades, large uncertainties remain in dust simulations (Huneeus et al., 2011; Prospero et al., 2010;

Todd et al., 2008; Uno et al., 2006; Zender et al., 2004; Zhao et al., 2013).

A complete description of dust events includes dust emission, deposition and transport processes. The differences of dust

40　simulation mainly result from the uncertainties of dust emission, deposition and transport processes in models. One

uncertainty is from dry deposition processes. Dry deposition refers to the transport of particles from the atmosphere to the

Earth's surface in the absence of precipitation (Seinfeld and Pandis, 2006). In most aerosol modeling, dry deposition velocity

V_d is used to calculate the dry deposition flux and V_d is usually modelled using the resistance-based approach (Pryor et al.,

2008). In the resistance-based approach, V_d is determined by gravitational settling, aerodynamic resistance and surface

45　resistance. Surface resistance is determined by collection efficiency from Brownian diffusion, impaction and interception

and is corrected for particle rebound. Slinn (1982) proposed a semi-analytical description of particle collection efficiencies

based on the wind tunnel studies, and many dry deposition schemes since then are variants of this model (Binkowski and

Shankar, 1995; Giorgi, 1986; Peters and Eiden, 1992; Zhang et al., 2001). As the formulations for collection efficiencies

from different dry deposition schemes are derived from measurements that have been obtained under different

50   meteorological conditions and land surface types, there remains a large discrepancy of these formulations between different

dry deposition models (Petroff et al., 2008).

At present, the comparisons of different dry deposition schemes with reliable field measurements are mainly focused on

one-dimensional dry deposition models (Hicks et al., 2016; Khan and Perlinger, 2017; Petroff et al., 2008; Ruijrok et al.,

1995). For example, Hicks et al. (2016) compared five deposition models with observations and found that V_d predicted for

55   particles less than 0.2 μm is consistent with the measurements, but predicted V_d can vary greatly in the size range of 0.3 to

about 5 μm. However, few studies have been conducted to study how different dry deposition schemes affect aerosol

concentrations and their spatial distribution in the 3D numerical models. Wu et al. (2018) compared the effects of different

dry deposition schemes on black carbon simulation in a global climate model (CESM-CAM5), but did not examine how

different dry deposition schemes affect aerosol concentrations for large-size aerosol particles, such as dust.

60   Another uncertainty of dust simulation is the treatment of dust emission process in models. Natural dust is typically emitted

from dry, erodible surfaces when the wind speed is high. Dust emission process is closely related to soil texture, soil

moisture content, surface conditions, atmospheric stability and the wind velocity (Marticorena and Bergametti, 1995). Dust

emission schemes are used to predict the dust emission flux and to describe the dust size distribution. Many studies have

compared and evaluated the performance of different dust emission schemes (Kang et al., 2011; LeGrand et al., 2019; Su and

65   Fung, 2015; Wu and Lin, 2013, 2014; Yuan et al., 2019; Zhao et al., 2010, 2006). These studies show large diversity of

simulated dust emission flux among different dust emission schemes. Zhao et al. (2006) implemented two dust emission

schemes in the NARCM (Northern Aerosol Regional Climate Model) regional model, and found that both schemes captured

the dust mobilization episodes and produced the similar spatial distributions of dust loading over East Asia, but the dust

emission fluxes and surface concentrations differ a lot. Kang et al. (2011) compared three dust emission schemes in

70   WRF-Chem and found that the difference between the vertical dust fluxes derived from the three emission schemes can

reach to several orders of magnitude. Yuan et al. (2019) found that one scheme strongly underestimated the dust emission

while another two schemes can better show the spatial and temporal variation of dust AOD based on a storm outbreak in

Central Asia. These differences mainly come from the dust emission flux parameterizations and differences in soil and

surface input parameters in different dust emission schemes (Chen et al., 2017).

75   While dust emission schemes have been studied quite extensively, few studies have examined dust emission and dry deposition schemes simultaneously. As both dust emission schemes and dry deposition schemes contribute significantly to the uncertainties in dust simulations, evaluating dust schemes based on a single dry deposition scheme may be problematic, especially if the dry deposition schemes employed have deficiency. For example, as a widely used regional model that has been coupled with a variety of dust emission schemes, the WRF-Chem model has been used in many studies to evaluate the

80   performance of dust emission schemes (LeGrand et al., 2019; Su and Fung, 2015; Wu and Lin, 2013, 2014; Yuan et al., 2019). But most of these studies use the GOCART aerosol scheme and only one dry deposition scheme (Wesely, 1989) is coupled within the GOCART aerosol scheme. Zhang et al. (2019) compared the modelled dust deposition using the GOCART aerosol scheme in WRF-Chem with observed dust deposition, and found that modelled dust deposition is highly underestimated by more than one order of magnitude compared to the observed deposition. This indicates that the dry

85   deposition scheme (Wesely, 1989) in GOCART aerosol scheme may not be suitable for dust simulation and needs to be further improved.

In this study, we adopted the MOSAIC aerosol scheme coupled within the WRF-Chem model to study how dry deposition schemes and dust emission schemes affect dust simulations by evaluating model results against observations. As the MOSAIC aerosol scheme includes several different dry deposition schemes, this allows us to choose more advanced dry

90   deposition schemes. As the default MOSAIC aerosol scheme only includes the GOCART dust emission scheme, we further implemented the dust emission scheme Shao2011 (Shao et al., 2011) in the MOSAIC aerosol scheme, which allows us to compare these two widely used dust schemes along with multiple dry deposition schemes. The goals of this study are: (1) to study dust simulation sensitivity to different dust emission schemes and dry deposition schemes, (2) to explore which combination of dust emission scheme and dry deposition scheme can better simulate dust storms in East Asia. The paper is

95   organized as follows. Sect. 2 introduces the WRF-Chem model, dust emission schemes and dry deposition schemes used, experiments design and measurements. Sect. 3 analyzes the dust simulation sensitivity to dust emission schemes and dry deposition schemes and the comparisons with observations. Sect. 4 is the summary and discussion.

2   Methodology and measurements

2.1   Model description

100   In this study, WRF-Chem version 3.9 is used. WRF-Chem is built based on the regional mesoscale model WRF, and fully coupled with gas and aerosol chemistry module (Grell et al., 2005). The model setups are listed in Table 1. The Noah land surface model (Chen and Dudhia, 2001) and the Yonsei University (YSU) planetary boundary scheme (Hong et al., 2006) are used in this study. The Rapid Radiative Transfer Model for General Circulation (RRTMG) radiation scheme (Iacono et al., 2008) is used to calculate the longwave and shortwave radiation. The Grell-Freitas convective scheme (Grell and Freitas, 2014)

105   and the Morrison two-moment microphysics scheme (Morrison et al., 2008) are used. The gas-phase chemistry module used is the Carbon-Bond Mechanism version Z (CBMZ, Zaveri and Peters, 1999). The aerosol module used here is the Model for Simulating Aerosol Interactions and Chemistry with 4 bins (MOSAIC 4-bin) (Zaveri et al., 2008). The MOSAIC aerosol scheme uses sectional approach to represent aerosol size distribution. The MOSAIC 4-bin aerosol scheme divides aerosol particles into four size bins by aerosol diameter: 0.039-0.156, 0.156-0.625, 0.625-2.5, 2.5-10.0 μm. The MOSAIC aerosol

110   scheme includes sulfate, methane sulfonate, nitrate, chloride, carbonate, ammonium, sodium, calcium, black carbon (BC), primary organic mass (OC), liquid water and other inorganic mass (OIN). The OIN species include silica, other inert minerals and trace metals. The emitted dust from dust emission schemes is assigned to the OIN class of MOSAIC to simulate the major aerosol processes. To study the sensitivity of dust simulation to different dust emission schemes and dry deposition schemes, we test two different dust emission schemes (see Sect. 2.2) and three dry deposition schemes (see Sect. 2.3) within

115   MOSAIC.

2.2   Dust emission schemes

Dust emission schemes include empirical schemes and schemes based on dust physical processes. Because of differences in input parameters and formulas to calculate dust flux, dust emission varies among different dust emission schemes. The Goddard Chemistry Aerosol Radiation and Transport (GOCART) dust emission scheme (Ginoux et al., 2001) is an empirical

120   scheme and was implemented in MOSAIC by Zhao et al. (2010). The University of Cologne (UoC) dust emission schemes

(Shao, 2001, 2004; Shao et al., 2011) (Shao schemes) are size-resolved dust emission scheme based on the wind erosion physical theory. Shao2011 (Shao et al., 2011) is a simplified version of Shao2004 (Shao, 2004), but the performances of the full scheme (Shao2004) and the simplified scheme are equally effective (Shao et al., 2011). The Shao dust emission schemes are widely used for dust simulations in East Asia, and have been found to perform well in simulating dust emission fluxes

125   (Shao et al., 2011; Su and Fung, 2015; Wu and Lin, 2014). Therefore, to test the sensitivity of dust simulation to different dust emission schemes, we implemented the Shao2011 dust emission scheme in MOSAIC. Each dust emission scheme is described in detail below.

2.2.1 GOCART

The formula of vertical dust flux in GOCART is approximated as:

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$$F_p = \begin{cases} CSs_p u_{10}^2 (u_{10} - u_t) & \text{if } u_{10} > u_t \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where C is an empirical proportionality constant and S is the source function. s_p is the fraction of each size class of the emitted dust. u_{10} is the horizontal wind speed at 10 meters. u_t is the threshold wind speed below which the dust emission does not occur. The emitted dust emission flux from GOCART scheme is re-distributed into different bins for MOSAIC as Zhao et al. (2010).

135   **2.2.2 Shao2011**

The Shao2011 dust emission scheme is a size-resolved dust emission scheme based on the wind erosion physical theory. The dust flux is determined by:

$$F(d_i, d_s) = c_y \eta_{mi} (1 + \sigma_m) g \frac{Q(d_s)}{u_*^2} \tag{2}$$

where $F(d_i, d_s)$ is the dust emission rate of particle size d_i generated by the saltation of particles of sizes d_s; c_y is the

140   dimensionless coefficient; η_{mi} is the mass fraction of free dust for a unit soil mass; σ_m is bombardment efficiency; $Q(d_s)$ is the saltation flux averaged over the range of sand particle sizes. As the Shao2011 scheme is a size-resolved dust emission scheme, we cut the size bins for MOSAIC aerosol scheme from Shao2011 directly. The details of the Shao2011 dust emission

scheme are described in Appendix A. There is a bug in calculating dust emission flux in Shao2011 scheme reported after

WRF-Chem v3.9, we have already corrected it in our simulation (See Appendix A). We should mention that the Shao2011 dust

145 emission scheme used in this study is not the original version in WRF-Chem v3.9 and the details will be discussed in Sect. 3.1

and Appendix B.

2.3 Dry deposition schemes

For dry deposition schemes, dry deposition velocity (V_d) is used to calculate dry deposition flux. V_d is determined by

gravitational settling velocity (V_g), aerodynamic resistance (R_a) and surface resistance (R_S). There are three dry deposition

150 schemes available in WRF-Chem coupled with the MOSAIC module and used in this study as referred to BS95 (Binkowski

and Shankar, 1995), PE92 (Peters and Eiden, 1992) and Z01 (Zhang et al., 2001). Each dry deposition scheme will be

described in detail below.

2.3.1 BS95

In the BS95 scheme (Binkowski and Shankar, 1995), V_d is expressed as:

155 $$V_d = V_g + \frac{1}{R_a + R_s + R_a R_S V_g} \tag{3}$$

where R_a and R_s are aerodynamic and surface resistance; V_g is the gravitational settling velocity and is given as:

$$V_g = \frac{\rho_p d_p^2 g C_c}{18\mu} \tag{4}$$

where ρ_p is the density of particles, d_p is particle diameter, C_c is the Cunningham correction factor as a function of d_p and

mean free path of air (λ), and μ is the viscosity dynamic of air. The surface resistance is calculated as:

160 $$R_s = \frac{1}{u_*(E_B + E_{IM})} \tag{5}$$

where E_B and E_{IM} are collection efficiencies from Brownian diffusion and impaction, respectively. E_B and E_{IM} are

calculated as follows:

$$E_B = Sc^{-\frac{2}{3}} \tag{6}$$

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$$E_{IM} = 10^{-\frac{3}{St}} \tag{7}$$

165 where Sc is the Schmidt number, given by $Sc = \nu/D$. ν is the kinematic viscosity of air and D is the particle Brownian

diffusivity. St is the Stokes number, given by:

$$St = \frac{u_*^2 v_g}{g\nu} \tag{8}$$

2.3.2 PE92

In PE92 scheme (Peters and Eiden, 1992), the dry deposition velocity (V_d) is expressed as:

170 $$V_d = V_g + \frac{1}{R_a + R_S} \tag{9}$$

The formula of V_g and R_a is the same as in BS95, but the way to calculate R_S is quite different. In PE 92, R_S is

parametrized as:

$$R_S = \frac{1}{u_*(E_B + E_{IM} + E_{IN})R} \tag{10}$$

where E_{IN} is collection efficiency from impaction and R is the factor for particle rebound. E_{IM}, E_{IN} and R are expressed

175 as follows:

$$E_{IM} = \left(\frac{St}{0.8 + St}\right)^2 \tag{11}$$

$$E_{IN} = \frac{(0.0016 + 0.0061 z_0) d_p}{1.414 \times 10^{-7}} \tag{12}$$

$$R = e^{-2\sqrt{St}} \tag{13}$$

z_0 is the roughness length and d_p is particle diameter. Stokes number is given by:

180 $$St = \frac{\rho_p d_p^2}{9\mu d_c} u \tag{14}$$

u is the horizontal wind velocity, d_c is the diameter of the obstacle.

2.3.3 Z01

In Z01 scheme (Zhang et al., 2001), the formula of V_d is the same as in BS95 scheme (Eq. (3)). Surface resistance R_S is

calculated as:

$$R_S = \frac{1}{\epsilon_0 u_*(E_B+E_{IM}+E_{IN})R} \qquad (15)$$

$$E_B = Sc^{-\gamma} \qquad (16)$$

where γ depends on land use categories (LUC) and lies between 1/2 and 2/3.

E_{IM} is expressed as:

$$E_{IM} = \left(\frac{St}{\alpha+St}\right)^\beta \qquad (17)$$

where β equals to 2 and α depends on LUC. The Stokes number is given by:

$$St = V_g u_*/gA \qquad (18)$$

over vegetated surfaces (Slinn, 1982) and

$$St = V_g u_*^2/g\nu \qquad (19)$$

over smooth surfaces or surfaces with bluff roughness elements (Giorgi, 1988). E_{IN} is expressed as:

$$E_{IN} = \frac{1}{2}\left(\frac{d_p}{A}\right)^2 \qquad (20)$$

over vegetated surfaces and $E_{IN} = 0$ for non-vegetated surfaces, where A is the characteristic radius of collectors and depends on LUC. R is expressed as:

$$R = e^{-1.0\sqrt{St}} \qquad (21)$$

The main difference of formulas used to calculate dry deposition velocity for three different dry deposition schemes are listed in Table 2. For surface resistance parameterization, PE92 and Z01 include the rebound effect and collection efficiency from interception, while BS95 neglects the rebound effect and collection efficiency from interception. For the collection efficiency from impaction parameterization, all three schemes use Stokes number to parameterize E_{IM}, but the formulas are quite different. BS95 has a different formula from PE92 and Z01, while the PE92 and Z01 have the same formula but with different coefficients. For PE92, the coefficient for E_{IM} is constant for all the surface types. For Z01, the coefficients α and β for E_{IM} change with different surface types. For the collection efficiency from interception parameterization, BS95 ignores this effect; PE92 and Z01 use different formulas and variables to calculate E_{IN}. For rebound effect, BS95 does not

consider the rebound effect; PE92 and Z01 use the same e-exponential form $e^{-b\sqrt{St}}$ to calculate the rebound effect with different coefficient b. For PE92, b is 2.0; for Z01, b is 1.0. In addition, the parameterization of Stokes number is quite different for different dry deposition schemes. For BS95, the formulation of St tends to emphasize the nature of the flow

210   field (Binkowski and Shankar, 1995; Pryor et al., 2008). For Z01, the formulation of St is from Slinn (1982) over vegetated surfaces and from Binkowski and Shankar (1995) over smooth surfaces. The formulation of St from Slinn (1982) and Peters and Eiden (1992) are focus on the individual obstacles (Pryor et al., 2008).

2.4   Experiments Design

We use WRF-Chem v3.9 with 20 km × 20 km horizontal resolution to simulate the dust storm in May 2017. The domain

215   covers most of the East Asia (14-60°N, 74-130°E). The simulation period is from 26 April to 7 May 2017. During this period, a severe dust storm event originated from northwestern China and Outer Mongolia, and air quality deteriorated dramatically in a very short time in downwind areas (Guo et al., 2019; Zhang et al., 2018). Meteorological conditions are initialized and forced at the lateral boundaries using the 6-hourly National Center for Environmental Prediction Final (NECP FNL) Operational Global Analysis data at a resolution of 1°×1°. The meteorological conditions are reinitialized every 24 hours.

220   This method has already been used in other simulations (Su and Fung, 2015; Zhang et al., 2016), which has been verified that a better meteorological field can be obtained. The output of the aerosol field from the previous 1-day run was used as the initial chemical conditions for the next 1-day run. The MOSAIC aerosol scheme was used for all the simulations. Simulation results prior to 28 April are treated as model spin up for chemical initial condition and are not included in results presented in Sect. 3. The model results from 1 May to 7 May are used for the dust loading and concentration analysis. And the model

225   results from 28 April to 7 May are used for the dust emission analysis as the dust emission before 1 May also have influence on the dust concentration during 1 May to 7 May. To study the dust simulation sensitivity to dust emission and dry deposition schemes, we run 6 experiments with two different dust emission schemes and three dry deposition schemes (See Table 3). The corresponding model configuration for dust emission and dry deposition processes of the six experiments also listed in Table 3.

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2.5   Measurements

Hourly surface observed PM10 is used to compare with the simulated PM10 from WRF-Chem. In China, hourly surface PM10 concentrations were collected from more than 1000 environmental monitoring stations maintained by the Ministry of Environmental Protection (MEP). The hourly PM10 data from 1 May to 7 May, 2017 were downloaded from http://beijingair.sinaapp.com/. We collocated the PM10 data to WRF-Chem simulation grids to evaluate model performance with different configurations.

Daily aerosol optical depth (AOD) from Moderate Resolution Imaging Spectroradiometer (MODIS) is used to compare with our simulated AOD from WRF-Chem. The MODIS onboard Aqua satellite was launched by the NASA in 2002 and Aqua is a part of A-Train satellite constellation. To compare modelled AOD with observations, we use AOD retrievals at 550 nm from MODIS AOD products on Aqua with daily gridded data at a resolution of 1°×1° (MYD08_D3, Collection 6, combined dark target and deep blue AOD). The MODIS Aqua collection daily MYD08_D3 files were obtained from https://ladsweb.nascom.nasa.gov. As Aqua passes through every region of Earth at 13:30 p.m. local time, we extract the model simulation results at 13:00 p.m. to compare with the daily MODIS AOD.

3   Results

3.1   Dust simulation sensitivity to dust emission schemes

In this section, we examine the changes of the simulated dust loading using different dust emission schemes. Figure 1 shows simulated mean dust loading for six experiments over the 7-day simulation period 1-7 May, 2017. When using the same dry deposition scheme (BS95, PE92 or Z01), different dust emission schemes give very different dust spatial distribution. Compared with the Shao2011 scheme, GOCART has higher dust loading over the Taklimakan desert but has relatively lower dust loading over the Gobi Desert, the south of Outer Mongolia and most parts of northern China. The difference of the spatial distribution of dust loading is mainly caused by the different spatial distribution of dust emission flux from dust emission schemes, as shown in Fig. 2. As the dust emission before 1 May also have influence on the dust loading during 1

May to 7 May, the total dust emission from 28 April to 7 May are analyzed. The total dust emission from 00:00 UTC 28 April to 23:00 UTC 7 May over GD from GOCART and Shao2011 are 5.42 Tg and 13.62 Tg, respectively. The total dust emission from 00:00 UTC 28 April to 23:00 UTC 7 May over TD from GOCART and Shao2011 are 7.12 Tg and 2.73 Tg respectively (Fig. 2c). Over Gobi Desert, Shao2011 scheme has higher dust emission than GOCART; while over Taklimakan Desert, GOCART scheme has higher dust emission than Shao2011 (Fig. 2c).

The first column of Fig. 3 shows the spatial distribution of friction velocity, threshold friction velocity, the difference between friction velocity and threshold friction velocity and the dust emission flux from Shao2011 at 06:00 UTC on 3 May. The areas where the friction velocity is greater than the threshold friction velocity is mainly located in the west inner Mongolia and the south of Outer Mongolia (Fig. 3e). This is consistent with Fig. 3g. When the friction velocity is larger than threshold friction velocity, dust can be emitted from the surface. The second column of Fig. 3 shows the spatial distribution of wind speed at 10 meters, threshold velocity, the difference between wind speed at 10 meters and threshold velocity and the dust emission flux from the GOCART dust emission scheme. Different from Shao2011, the dust emission regions from GOCART are not only determined by wind speed, but also constrained by erodibility factor (Eq. (1)). From Fig. 3f, the threshold velocity is much smaller than the wind speed at 10 meters in most areas. In these areas, GOCART use Eq. (1) to calculate the dust emission flux, and the source function S depends on the erodibility factor. The dust emission flux in GOCART is directly scaled by erodibility factor. Figure 4 shows the erodibility factor which describes the fraction of erodible surface in each grid cell. As shown in Fig. 3h, dust emission occurs where the wind speed is high and the erodibility factor is larger than 0. So the difference of dust emission between GOCART and Shao2011 is mainly due to the difference of threshold conditions for dust emission and the difference of formulas and parameters for calculating dust emission flux.

Over Taklimakan desert (TD), Shao2011 produces lower dust emission flux than GOCART. As mentioned by Wu and Lin (2014), there are two possible reasons for this. One is that dust generated by the intermittent turbulence is not considered in Shao2011 scheme. Dust can be generated by the intermittent turbulence rather than by the mean wind shear when the wind speed is low (Klose and Shao, 2012). While GOCART uses the erodibility factor and the empirical formula to calculate the dust emission flux, dust can be emitted where the wind speed is relatively low. Another reason may be the incorrect soil particle size distribution over TD. The incorrect soil particle size distribution can lead to the unreasonable dust emission flux

in Shao2011 over TD. Over Gobi Desert (GD), the GOCART scheme has lower dust emission than the Shao2011 scheme. As mentioned by Su and Fung (2015), the erodibility factor over Gobi Desert is highly underestimated and need to be improved for the GOCART dust emission scheme.

280   We note that, the Shao2011 dust emission scheme we used in this study is based on WRF-Chem v3.9 with some modifications from WRF-Chem v3.7.1 as documented in Appendix B. The modified Shao2011 simulates better dust loading than the original Shao2011 scheme in WRF-Chem v3.9 (not shown). Simulated dust emission fluxes can differ a lot between two versions of the Shao2011 scheme in WRF-Chem v3.9 and WRF-Chem v3.7.1, which is mainly caused by different soil particle size distributions in two versions. The differences of Shao2011 among different WRF-Chem versions are documented

285   in Appendix B.

3.2   Dust simulation sensitivity to dry deposition schemes

In this section, we analyze dust simulation sensitivity to different dry deposition schemes using the six experiments. For simulated dust loading using the GOCART dust emission scheme (the first row in Fig. 1), compared to the BS95 dry deposition scheme, PE92 and Z01 produce higher dust loading over the dust source regions and remote regions. The relative

290   difference of mean dust loading from PE92 and Z01 relative to BS95 is 20% and 59% respectively. As for the simulated dust loading using the Shao2011 dust emission scheme (the second row in Fig. 1), PE92 and Z01 schemes also produce higher dust loading than BS95 scheme, and the relative difference to BS95 is 72% and 116% respectively. This indicates that dust simulation is very sensitive to dry deposition schemes.

Figure 5a shows the modeled dry deposition velocity over desert surface. As desert dust mass is mainly concentrated in the

295   large particle size range, our dry deposition analysis focuses on the coarse mode (near the reference diameter marked as colored dots in Fig. 5). BS95 produces larger V_d than PE92 and Z01 in the coarse aerosol mode. Larger V_d leads to larger dry deposition and thus lower dust loading, consistent with the lower simulated dust loading from the BS95 scheme discussed above (Fig. 1). In Eq. (3), the dry deposition velocity is comprised of gravitational velocity, aerodynamic resistance and surface resistance. The diversity of different dry deposition schemes mainly comes from the way to

300   parameterize surface resistance, and differences from gravitational settling and aerodynamics resistance are small (not

shown), consistent with previous studies (e.g., Bergametti et al., 2018). Figure 5b shows the surface resistance from different

schemes as a function of particle diameter (Dp). In the coarse aerosol mode, Z01 produces the largest surface resistance,

followed by PE92 and BS95. Larger surface resistance causes smaller dry deposition velocity in Z01, thus larger dust

concentration as shown in Fig. 1.

305   The surface collection efficiency is comprised of Brownian diffusion, impaction, and interception and is corrected for

particle rebound (see Eq. (10)). Collection from Brownian diffusion is most important for the smaller particles while

collection from impaction and interception play a more important role for large particles in surface collection processes.

Figure 5c shows the surface collection efficiency from impaction (E_{IM}) from different schemes as a function of particle

diameter. Impaction occurs when there are changes in the direction of airflow, and their inertia carries them across the

310   sublayer to the surface (Seinfeld and Pandis, 2006). BS95 gives the largest E_{IM} and Z01 gives the smallest. Based on field

observation data, Slinn (1982) used a semi-empirical fit for smooth surface (Eq. (7)), and Binkowski and Shankar (1995)

adopted this formula for E_{IM} and used it for all land surface types. Peters and Eiden (1992) uses Eq. (17) to describe E_{IM},

with α equals to 0.8 and β equals to 2 to get the best fit for the data collected over a spruce forest. In Zhang et al. (2001)

scheme, α varies with LUC and β is chosen as 2. For BS95 and PE92, the formula of E_{IM} is derived from a specific land

315   surface type, but they have been applied to all land surface types in WRF-Chem. This may lead to large uncertainties for dry

deposition over the whole domain with different surface types. As E_{IM} of Z01 varies with LUC, Z01 may have a better

physical treatment of E_{IM} than the other two dry deposition schemes.

Figure 5d shows the surface collection efficiency from interception (E_{IN}). Collection from interception occurs when particles

moving with the mean flow and the distance between an obstacle and particle center is less than half of the diameter, and

320   E_{IN} therefore depends on the particle diameter and the characteristic radius of the collectors (Seinfeld and Pandis, 2006).

E_{IN} is important for large particles on hairs at the leaf surface, and is negligible over non-vegetated surface such as the

desert surface we analyzed here (Chamberlain, 1967; Slinn, 1982; Zhang et al., 2001). In BS95, the effect of interception is

not considered. In the original PE92 scheme as described in Peters and Eiden (1992), E_{IN} is also not considered. But in the

PE92 scheme used in WRF-Chem, E_{IN} increases with particle diameter as in Eq. (12). In Z01, the effect of interception is

325   considered as Eq. (20) over vegetated surface and is not considered for non-vegetated surface (as shown in Fig. 5d over

desert surface type). The parameterization of E_{IN} partially results in the difference of surface resistance between PE92 and the other two dry deposition schemes.

Figure 5e shows the rebound factor from different dry deposition schemes. Rebound and resuspension have long been recognized as a mechanism by which the surface can act as sources of particles (Pryor et al., 2008). Due to limited

330   knowledge on particle rebound and resuspension processes, most dry deposition models adopted the form of the rebound effect as $R = e^{-b\sqrt{St}}$ suggested by Slinn (1982) (Zhang and Shao, 2014; Zhang et al., 2001), while some dry deposition schemes do not include the rebound effect with R=1.0 (Binkowski and Shankar, 1995; Petroff and Zhang, 2010; Zhang and He, 2014). BS95 does not consider the rebound effect. b is equal to 2.0 for PE92 scheme and 1.0 for Z01 scheme. Another difference between PE92 and Z01 is the threshold particle diameter for including the rebound effect. Rebound effect is

335   included for PE92 when particles are larger than 0.625 μm and for Z01 when particles are larger than 2.5 μm. In summary, the smaller E_{IM} and rebound factor lead to larger R_S in Z01, while the larger E_{IM} leads to smaller R_S in BS95, and the moderate E_{IM} and rebound effect give a moderate R_S for PE92.

Stokes number is the ratio of the particle stop distance to the characteristic length of the flow, and it describes the ability of particles to adopt the fluid velocity (Pryor et al., 2008; Seinfeld and Pandis, 2006). Over smooth surfaces, the formula of St

340   for BS95 and Z01 is the same, as shown in Eq. (19). In PE92, St is calculated using Eq. (14), which is similar to the formula used in Slinn (1982). Figure 5f shows the Stokes number from different dry deposition schemes. BS95 and Z01 schemes give a larger St than PE92. Stokes number is used to calculate both R and E_{IM}. The difference of Stokes number and the different formulas of R and E_{IM} lead to the different R and E_{IM} among different dry deposition schemes (Fig. 5c and 5e).

Our discussion indicates that Z01 has a better physical treatment of dry deposition velocity, as Z01 considers the rebound

345   effect and E_{IM} changes with LUC. The Z01 scheme has also been documented to agree better with measured dry deposition fluxes and dry deposition velocity (e.g., Zhang et al., 2012; Connan et al., 2018). Zhang et al. (2012) compared the dry deposition fluxes measured at five sites in Taiwan with the modeled dry deposition fluxes and found that the measured dry deposition fluxes can be reproduced reasonably well using the Z01 scheme. Connan et al. (2018) conducted experimental campaigns on-site to determine dry deposition velocity of aerosols and found that the Z01 scheme is most suitable for

350   operational use in the size range 0.2-10 μm. All these indicate that the Z01 dry deposition scheme is better than other two dry

deposition schemes.

3.3 Comparisons with observations

To better evaluate the performance of different experiments, we compared the model results with observations. Figure 6

shows hourly observed PM_{10} concentrations over observational sites at 02:00 UTC on 4 May, 2017 (10:00 Beijing Time (BJT)

355 on 4 May, 2017). Very high PM_{10} values (> 1000 μg m^{-3}) are observed in northern China. Figure 7 compares simulated

PM_{10} in six experiments with observed PM_{10}. During the comparison, the observational sites closest to the model grids are

paired up. The correlation coefficients (R), root mean square errors (RMSE) between model and observations, and the mean

simulated and observed PM_{10} for all the sites over the five regions during the 7-day period 1-7 May are marked in Fig. 7. The

simulated PM_{10} of all the six experiments have obviously underestimated the observations. Among all these experiments,

360 GOBS95 has the lowest average PM_{10} concentration, with a value of 26.45 μg m^{-3}, and S11Z01 has the largest one, with a

value of 105.17 μg m^{-3}, the closest one to the observed mean value of 172.70 μg m^{-3}. S11Z01 gives a large R of 0.77 and

the smallest RMSE of 96.14 compared to other experiments. Table 4 shows the R and RMSE between the model and

observations for PM_{10} for six experiments over five sub regions and over whole China. Over TD, GOBS95 gives the largest

R and smallest RMSE. Over GD, GOZ01 and S11Z01 gives a better performance compared with other experiments. For

365 other regions (NCP, NEP and YR), S11Z01 gives a relatively larger R and smallest RMSE. For all the stations in total,

S11Z01 gives a larger R of 0.83 and the smallest RMSE of 82.98. Overall, the S11Z01 experiment has the best performance

for simulating this dust storm.

Figure 8 shows the MODIS observed daily mean AOD and WRF-Chem simulated AOD on 4 May for six experiments. For

strong dust storms like the one we examined here, dust particles contribute the most to AOD, and AOD therefore can

370 represent the dust loading in the atmosphere. To match the MODIS AOD observation time, simulated AOD at 13:00 p.m.

local time is used for comparison. For each 1 °×1° grid with observed AOD from MODIS, the average value of simulated

AOD from WRF-Chem in this grid is calculated. The simulated AOD already collocated with MODIS AOD in Fig. 8.

Extremely high AOD values were observed in the northern China from MODIS (Fig. 8a). When using GOCART dust

emission scheme, AOD is highly underestimated over most regions except over Taklimakan Desert (Fig. 8b, 8c, 8d). When

375   using Shao2011 dust emission scheme coupled with BS95 or PE92 dry deposition scheme (Fig. 8e, 8f), AOD is also

underestimated over most regions, but with relatively larger AOD than using GOCART dust emission scheme. AOD from

the S11Z01 experiment is the closest one to the MODIS observed AOD (Fig. 8g). For a more quantitative comparison, we

collocated the simulated AOD with observed MODIS AOD over the 7-day simulation period 1-7 May, 2017. Table 5 shows

the correlation coefficient (R) and root mean square error (RMSE) between the model and observed AOD for six

380   experiments during 1-7 May. Overall, S11Z01 experiment gives a larger correlation coefficient and the RMSE is almost the

same among different experiments, the correlation coefficient is still lower than 0.5. The low correlation may partly come

from the spatial and temporal limitation of satellites and the difficulties to retrieve aerosol in the vicinity of clouds for

satellites.

In summary, both ground and satellite observations indicate that the S11Z01 experiment yields the best performance in

385   simulating this dust storm. As we discussed in Sect. 3.2, the Z01 dry deposition scheme indeed has a better physical

treatment and performs better than some other dry deposition schemes.

4   Summary and discussion

In this study, we analyzed the dust simulation sensitivity to different dust emission schemes and dry deposition schemes. In

order to compare different dust emission schemes, the Shao2011 dust emission scheme has been implemented into the

390   MOSAIC aerosol scheme in WRF-Chem v3.9. Six model experiments were conducted to simulate the dust storm in May 2017

over East Asia, with two dust emission schemes (GOCART and Shao2011) and three dry deposition schemes (BS95, PE92 and

Z01). The simulation results of different experiments were evaluated against surface and satellite observations.

Our results show that dust loading is very sensitive to different dry deposition schemes. The relative difference of dust loading

in different experiments range from 20%-116% when using different dry deposition schemes. The difference of dry deposition

395   velocity in different dry deposition schemes comes from the parameterization of surface resistance, and difference in surface

resistance mainly comes from the parameterization of collection efficiency from impaction and rebound effect. In addition,

different dust emission schemes result in different spatial distribution of dust loading, as dust emission fluxes in dust source

regions differ a lot among different dust emission schemes, which is mainly attributed to differences in the threshold conditions

for dust emission and in formulas and parameters for calculating dust emission flux. We noted that, the Shao2011 dust

400   emission scheme is different among different WRF-Chem versions, and simulated dust emission fluxes in WRF-Chem v3.9

and WRF-Chem v3.7.1 can differ a lot, which is mainly caused by differences in soil particle size distributions used in two

versions (see Appendix B).

Compared with both surface PM_{10} station observations and MODIS AOD, the Shao2011 dust emission scheme coupled with

the Z01 dry deposition scheme produces the best simulation for the dust storm in East Asia. Our analysis indicates Z01

405   accounts for the rebound effect and E_{IM} changes with LUC and therefore has a better physical treatment of dry deposition

velocity than the two other dry deposition schemes. Previous studies have also shown that the Z01 scheme agrees better with

measured dry deposition fluxes and dry deposition velocity (e.g., Zhang et al., 2012; Connan et al, 2018). The Shao2011 dust

emission scheme has larger dust emission fluxes than GOCART dust emission scheme over Gobi Desert, and the transport of

dust emitted from Gobi Desert is the most important source of dust weather in northern China. The Shao2011 scheme has also

410   been documented to give better performance in dust simulation over East Asia (Su and Fung, 2015).

This study highlights the importance of dry deposition process in dust simulation. Future studies on dust simulation should

pay attention to improve dry deposition schemes as well as the dust emission schemes. Additional field measurements of dry

deposition process and comparisons with model results are required to reduce the uncertainties on dust simulation.

Appendix A: Description of the Shao2011 dust emission scheme

415   Here we describe the Shao2011 dust emission scheme in more detail as a supplement to the Sect. 2.2.2 of this article. The

saltation flux $Q(d_s)$ in Eq. (2) is calculated as:

$$Q(d_s) = (1 - c_f)c_0 \frac{\rho}{g} u_*^3 \left(1 - \frac{u_{*t}}{u_*}\right)\left(1 + \frac{u_{*t}}{u_*}\right)^2 \tag{A1}$$

where c_f is the fraction of vegetation cover, $(1-c_f)$ means the fraction of erodible surface area, c_0 is a coefficient. u_{*t} is

the threshold friction velocity, u_* is the friction velocity. When u_* is larger than u_{*t}, it calculates the dust emission flux.

420   Before WRF-Chem v4.0, there is a bug in calculating the saltation flux $Q(d_s)$ in Shao2011. They miscalculate the last term as

$(1+\left(\frac{u_{*t}}{u_*}\right)^2$) in WRF-Chem codes (LeGrand et al., 2019). In WRF-Chem v4.0 and later versions, they fixed this bug and we

also fixed this bug in our simulations.

The threshold friction velocity u_{*t} is calculated as:

$$u_{*t} = u_{*t0} f_\lambda f_\theta \ldots \tag{A2}$$

425 where u_{*t0} is the ideal threshold friction velocity when soil is dry, bare and free of crust and salt, f_λ is the correction

functions for surface roughness, f_θ is the correction functions for soil moisture. The ideal threshold friction u_{*t0} is

calculated as:

$$u_{*t0} = \sqrt{a_1 \frac{\rho_p}{\rho_a} gd + \frac{a_2}{\rho_a d}} \tag{A3}$$

where a_1 and a_2 are constant. ρ_p and ρ_a are particle and air density. d is the particle diameter.

430 The correction functions for surface roughness f_λ is calculated as:

$$f_\lambda = [(1 - m\sigma\lambda)(1 + m\beta\lambda)]^{\frac{1}{2}} \tag{A4}$$

where m is a constant, σ is the ratio of roughness-element basal area to frontal area, λ is the frontal area index, β is the

ratio of the drag coefficient of an isolated roughness element on the surface to the drag coefficient of the substrate surface

itself.

435 The mass fraction of free dust η_{mi} is calculated as:

$$\eta_{mi} = \int_{d - \frac{\Delta d_i}{2}}^{d + \frac{\Delta d_i}{2}} p_m(d)\delta d \tag{A5}$$

where $p_m(d)$ is the minimally disturbed particle-size distribution, which is regarded as a composite of several log-normal

distribution, $p_m(d)$ is expressed as:

$$p_m(d) = \frac{1}{d} \sum_{i=1}^{J} \frac{w_j}{\sqrt{2\pi}\sigma_j} exp(-\frac{(lnd - lnD_j)^2}{2\sigma_j^2}) \tag{A6}$$

440 soil samples collected from experiment sites are used to determine the particle size distribution.

Appendix B: The Shao2011 dust emission scheme in different versions of WRF-Chem

As we noted in Sect. 3.1, the Shao2011 scheme in different versions of WRF-Chem can produce significantly different dust

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emission fluxes. Here we document differences in Shao2011 among different WRF-Chem versions:

1. The first difference is c_0. c_0 is a coefficient used to calculate the saltation flux as in Eq. (A1). In versions before
445   WRF-Chem v3.8, c_0 is equal to 0.5; in WRF-Chem v3.8 and later versions, c_0 is equal to 2.3 (Table B1).

2. The second difference is β. β is a coefficient used to calculate the correction function for surface roughness f_λ in Eq.
    (A4). In versions before WRF-Chem v3.8, β is 90; in WRF-Chem v3.8 and later versions, β is 200 (Table B1).

3. The third difference is caused by the minimally disturbed particle-size distribution $p_m(d)$ (see Eq. (A6)). $p_m(d)$ is
    used to calculate the free dust fraction η_{mi} (see Eq. (A5)). Free dust fraction is the fraction of dust that has lower
450   enough binding energy so that it can be easily lifted from the surface by either aerodynamic forces or mechanical
    abrasion (Shao, 2001). The η_{mi} is used to calculate the dust emission rate in Eq. (2). 12 soil types are included in all
    WRF-Chem versions. In WRF-Chem v3.8 and later versions, each soil type has a corresponding $p_m(d)$ as listed in
    Table B1 from Shao et al. (2010); in versions before WRF-Chem v3.8, there are only four $p_m(d)$ as listed in Table 1
    from Shao (2004) for 12 soil types (Fig. B1). For example, (f) sand and (g) loamy sand soil types use the same free dust
455   fraction distribution in versions before WRF-Chem v3.8. As shown in Table B2, the loam and clay loam are the two soil
    types with the largest percentage, while the other soil types account for a very small percentage. From Fig. B1c and Fig.
    B1e, for loam and clay loam soil types, the free dust fraction is so small in the particle size range 0-10 um in
    WRF-Chem v3.8 and later versions, almost all close to 0; while in the versions before WRF-Chem v3.8, the free dust
    fraction is relatively high. In different WRF-Chem versions, the total saltation flux Q is the same, but dust emission flux
460    $F(d_i)$ is different due to different free dust fraction (see Eq. (2)). With smaller free dust fraction, the dust emission flux
    is smaller in WRF-Chem v3.8 and later versions.

To examine the importance of these changes, we run four experiments to quantify the contribution of each factor (Table B3).
For control run, c_0 is 2.3, β is 200 and $p_m(d)$ has 12 distributions based on WRF-Chem v3.8 or later versions. For case1
experiment, β is changed to 90, the one used in WRF-Chem v3.7.1 and all other parameters are kept the same as in control
465   run. The dust emission of case1 is 1.35 times higher than the control run. For case2 experiment, c_0 is changed to 0.5, the
one used in WRF-Chem v3.7.1, and all other parameters remain the same as in control run. The dust emission of case2 is
twenty-one percent of the dust emission of the control run. For case3 experiment, $p_m(d)$ is adopted from WRF-Chem

v3.7.1 and has four distributions, and all other parameters remain the same as in control run. The dust emission of case3 is 13

times higher than the control run. This indicates that the difference of dust emission between different versions of Shao2011

470   scheme is mainly caused by the change of $p_m(d)$. As $p_m(d)$ is determined by soil particle size distribution, this also

highlights the need to improve the accuracy of soil texture.

We should mention that the Shao2011 dust emission scheme we used in this study is based on WRF-Chem v3.9 with the soil

particle size distribution from WRF-Chem v3.7.1, which simulates better dust loading compared with observations.

Compared with the original Shao2011 scheme in WRF-Chem v3.9, the total dust emission simulated in our experiments

475   during 1-7 May is 13 times higher.

Code availability

The source code of WRF-Chem is available at http://www2.mmm.ucar.edu/wrf/users/download/get_sources.html (last access:

31 October 2019). The modified WRf-Chem v3.9 with Shao2011 dust emission scheme implemented in MOSAIC aerosol

scheme is available upon request to the corresponding author.

480   **Data availability**

The 6-hourly National Center for Environmental Prediction Final (NECP FNL) Operational Global Analysis data at a

resolution of $1°\times1°$ can be obtained from: https://rda.ucar.edu/ (last access: 31 October 2019). The observed PM10 data is

collected from the National air quality real time release platform at: http://106.37.208.233:20035/ (last access: 31 October

2019). The historical data of air quality used in this study can be downloaded from: http://beijingair.sinaapp.com/ (last access:

485   31 October 2019). Daily MYD08_D3 files from the MODIS onboard Aqua satellite can be obtained from

https://ladsweb.nascom.nasa.gov (last access: 31 October 2019).

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Author contributions

MW and YZ conceived the idea and designed the model experiments. YZ performed the simulations, conducted the analysis and wrote the manuscript. CZ and SC provided guideline for the dust simulations in WRF-Chem and helped in the
490 interpretation of the results. XH and ZL provided guideline for the WRF-Chem simulations and contributed to the model experiments design. YG helped in the PM10 data processing and usage. Everyone edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1. WRF-Chem configuration

Atmospheric Process	WRF-Chem option	Namelist Variable	Option
Surface Layer physics	Noah land-surface model	sf_surface_physics	2
Boundary Layer Physics	YSU scheme	bl_pbl_physics	1
Longwave/Shortwave Radiation	RRTMG	ra_lw(sw)_physics	4
Cumulus Clouds	Grell-Freitas	cu_physics	3
Cloud microphysics	Morrison double-moment	mp_physics	10
Gas-phase/aerosol chemistry	CBMZ/ MOSAIC 4-bin	chem_opt	9

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685 **Table 2.** Three dry deposition schemes

Scheme	BS95	PE92	Z01
V_d	$V_d = V_g + \dfrac{1}{R_a + R_s + R_a R_S V_g}$	$V_d = V_g + \dfrac{1}{R_a + R_S}$	$V_d = V_g + \dfrac{1}{R_a + R_s + R_a R_S V_g}$
R_S	$R_s = \dfrac{1}{u_*(E_B + E_{IM})}$	$R_s = \dfrac{1}{u_*(E_B + E_{IM} + E_{IN})R}$	$R_s = \dfrac{1}{\varepsilon_0 u_*(E_B + E_{IM} + E_{IN})R}$
E_{IM}	$E_{IM} = 10^{-St}$	$E_{IM} = \left(\dfrac{St}{0.8 + St}\right)^2$	$E_{IM} = \left(\dfrac{St}{\alpha + St}\right)^\beta$
E_{IN}	0	$E_{IN} = \dfrac{(0.0016 + 0.0061 z_0)d_p}{1.414 \times 10^{-7}}$	$E_{IN} = \dfrac{1}{2}\left(\dfrac{d_p}{A}\right)^2$
R	1.0	$R_1 = e^{-2\sqrt{St}}$	$e^{-1.0\sqrt{St}}$
St	$St = \dfrac{u_*^2 v_g}{gv}$	$St = \dfrac{\rho_p d_p^2}{9\mu d_c}u$	$St = \dfrac{v_g u_*}{gA}$ (vegetated surfaces) $St = \dfrac{v_g u_*^2}{gv}$ (smooth surfaces)

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Table 3. Model experiments and the corresponding model configuration in WRF-Chem. Note that the dust_opt =15 option for

Shao2011 is added to WRF-Chem by ourselves.

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Experiment name	Dust emission scheme	Dry deposition scheme	dust_opt	dust_schme	aer_drydep_opt
GOBS95	GOCART	BS95	13	/	1
GOPE92	GOCART	PE92	13	/	101
GOZ01	GOCART	Z01	13	/	301
S11BS95	Shao2011	BS95	15	3	1
S11PE92	Shao2011	PE92	15	3	101
S11Z01	Shao2011	PE92	15	3	301

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Table 4. Correlation coefficient (R) and root mean square error (RMSE) between the model and observations for PM_{10} over

five sub regions and over whole China in Fig. 6 for six experiments listed in Table 3.

Region	R/RMSE	GOBS95	GOPE92	GOZ01	S11BS95	S11PE92	S11Z01
TD	R	0.64	0.53	0.59	0.34	0.37	0.37
TD	RMSE	79.61	91.91	106.61	124.25	119.54	115.68
GD	R	0.75	0.78	0.82	0.76	0.75	0.74
GD	RMSE	174.81	137.14	77.81	193.23	128.21	82.58
NCP	R	0.75	0.73	0.73	0.78	0.76	0.77
NCP	RMSE	231.2	221.05	197.43	189.08	164.25	107.20
NEP	R	0.62	0.63	0.58	0.70	0.68	0.68
NEP	RMSE	177.17	174.52	171.96	159.47	144.77	126.91
YR	R	0.45	0.42	0.43	0.67	0.61	0.61
YR	RMSE	105.96	105.97	93.97	94.07	93.79	69.94
Total	R	0.50	0.60	0.63	0.85	0.83	0.83
Total	RMSE	146.58	137.96	120.57	133.71	113.88	82.98

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725 **Table 5.** Correlation coefficient (R) and root mean square error (RMSE) between the model and MODIS observation for

AOD for six experiments over the 7-day simulation period 1-7 May, 2017.

	GOBS95	GOPE92	GOZ01	S11BS95	S11PE92	S11Z01
R	0.32	0.37	0.27	0.40	0.39	0.42
RMSE	0.46	0.46	0.46	0.46	0.47	0.47

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745   **Table B1.** Differences in Shao2011 dust emission scheme between different WRF-Chem versions

	Before WRF-Chem v3.8	WRF-Chem v3.8 and later
c_0	0.5	2.3
β	90	200
η_{mi}	/	/

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Table B2. Percentage of each soil type in the whole East Asia domain

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Soil type	Sand	Loamy sand	Sandy loam	Silt loam	silt	loam
percentage	2.6%	0.2%	4.0%	9.3%	0	47.6%
Soil type	Sandy clay loam	Silty clay loam	Clay loam	Sandy clay	Silty clay	clay
percentage	8.6%	0	21.7%	0	0.05%	6.0%

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Table B3. Sensitivity of the simulated total dust emission from the Shao2011 to model parameters over the 7-day simulation period 1-7 May, 2017. The multiple of the dust emission of different cases is calculated with respect to the control run.

	C_0	β	η_{mi}	Dust emission (Tg)	Multiple
control run	2.3	200	12 types	1.35	1.00
case1	2.3	90	12 types	1.83	1.35
case2	0.5	200	12 types	0.29	0.21
case3	2.3	200	4 types	17.5	13.00

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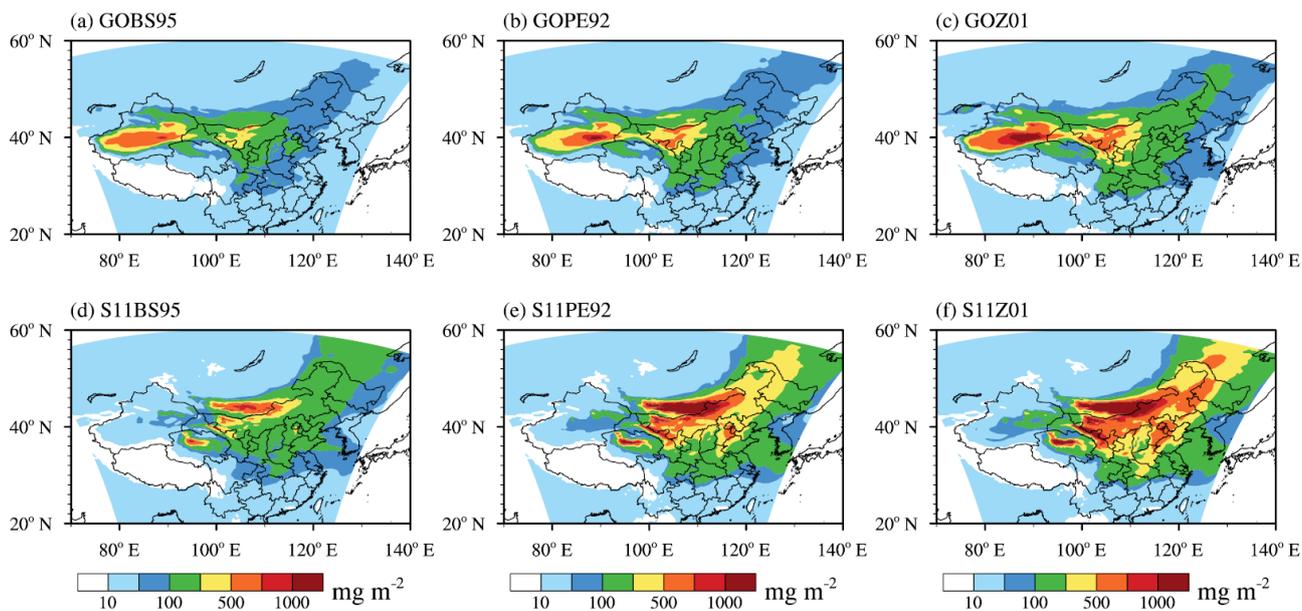
Figure 1. Spatial distribution of simulated mean dust loading for six experiments (a)GOBS95, (b)GOPE92, (c)GOZ01, (d)S11BS95, (e)S11PE92, (f)S11Z01 over the 7-day simulation period from 00:00 UTC on 1 May to 23:00 UTC on 7 May, 2017 (unit: mg m^{-2}).
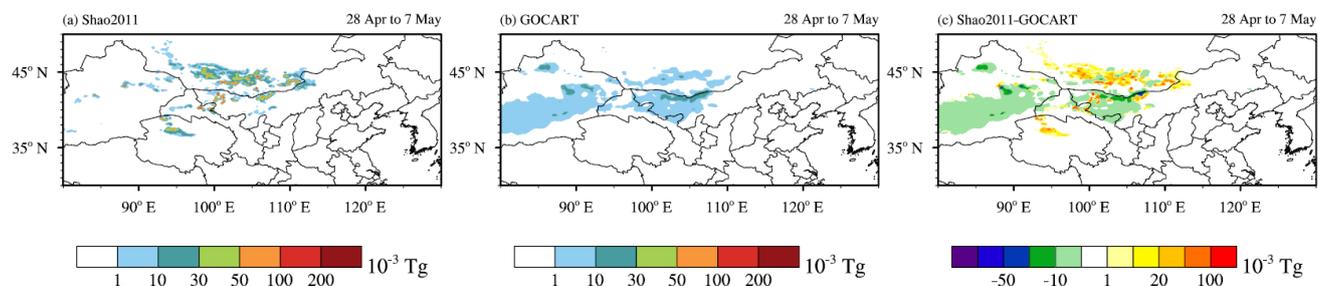
Figure 2. The simulated total dust emission (10^{-3} Tg) from two dust emission schemes: (a) Shao2011 and (b) GOCART from 00:00 UTC on 28 April to 23:00 UTC on 7 May, 2017. (c) The total dust emission flux difference between Shao2011 and GOCART. The diameter of the emitted dust is less than 10 μm in both GOCART and Shao2011 dust emission schemes.
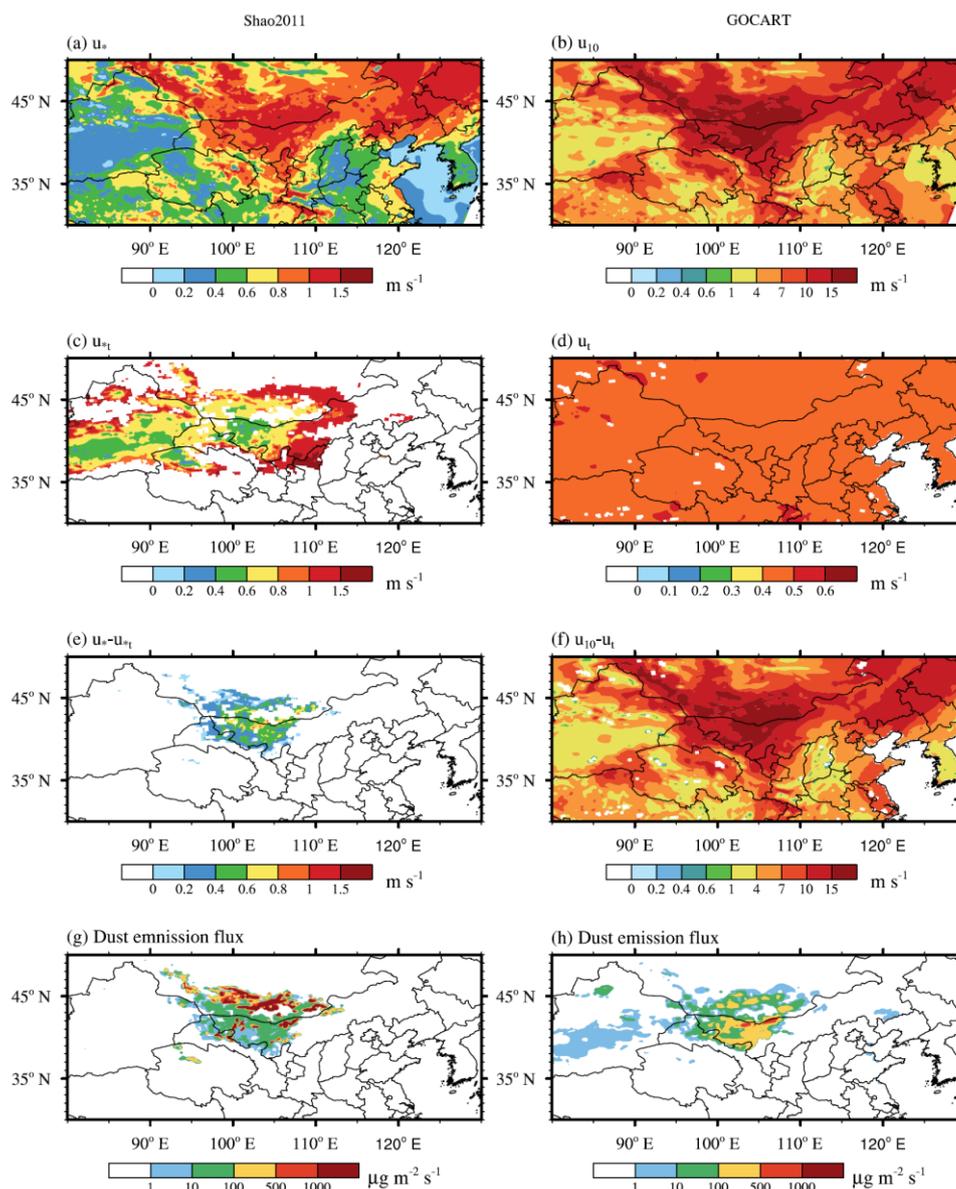
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Figure 3. Spatial distribution of (a) friction velocity (u_*), (c) threshold friction velocity (u_{*t}) and (e) the difference between

u_* and u_{*t} ($u_* - u_{*t}$) from Shao2011 dust emission scheme at 06:00 UTC on 3 May, 2017; (b) wind speed at 10 meters

(u_{10}), (d) threshold velocity (u_t) and the difference between u_{10} and u_t ($u_{10} - u_t$) from GOCART dust emission scheme

at 06:00 UTC on 3 May, 2017. Spatial distribution of (g) dust emission flux from Shao2011, (h) dust emission flux from

825   GOCART at 06:00 UTC on 3 May, 2017.
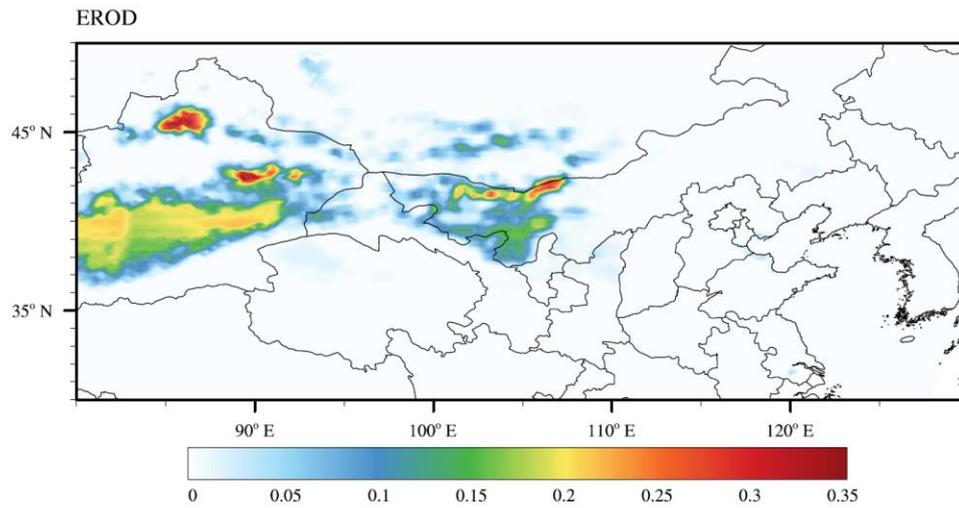
Figure 4. The fraction of erodible surface in each grid cell used in GOCART dust emission scheme.

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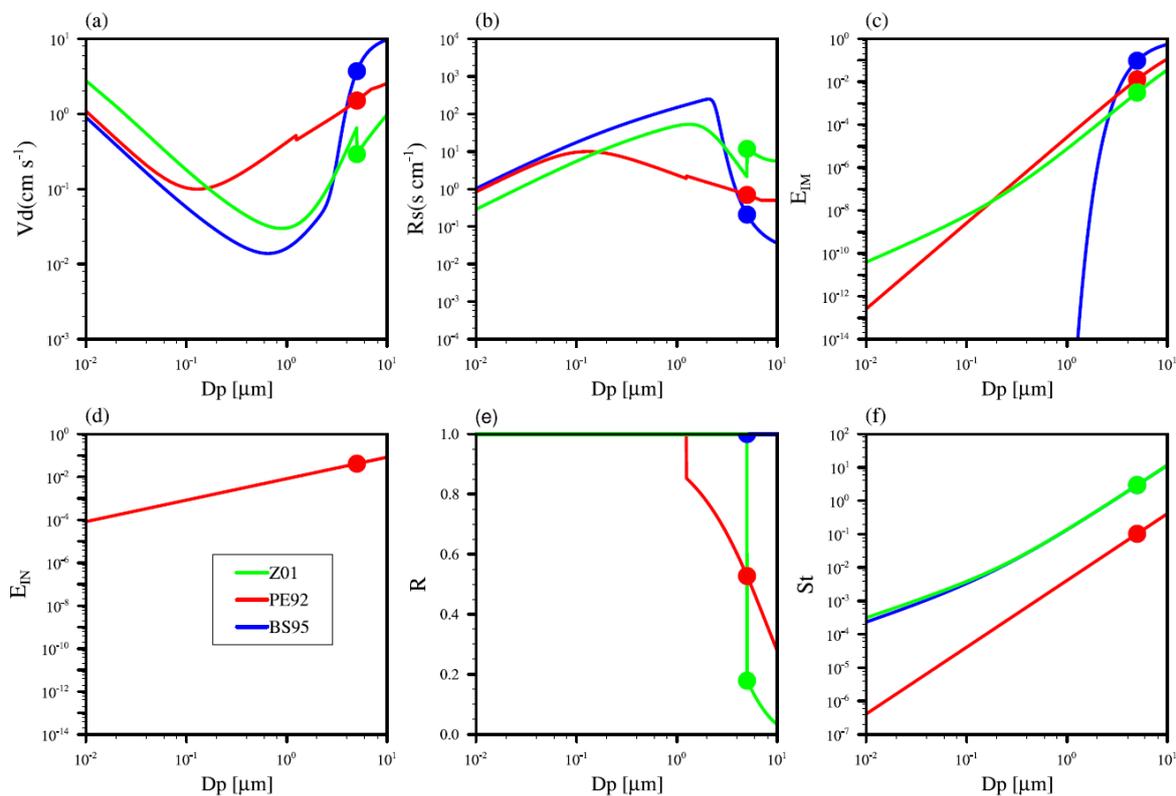
Figure 5. (a) Dry deposition velocity (V_d), (b) surface resistance (R_S), (c) surface collection efficiency from impaction (E_{IM}), (d) surface collection efficiency from interception (E_{IN}), (e) rebound (R) and (f) stokes number (St) as a function of particle diameter (Dp) over desert surface computed using different dry deposition schemes (BS95, PE92 and Z01). The colored dots indicate at the reference diameter of 5μm.
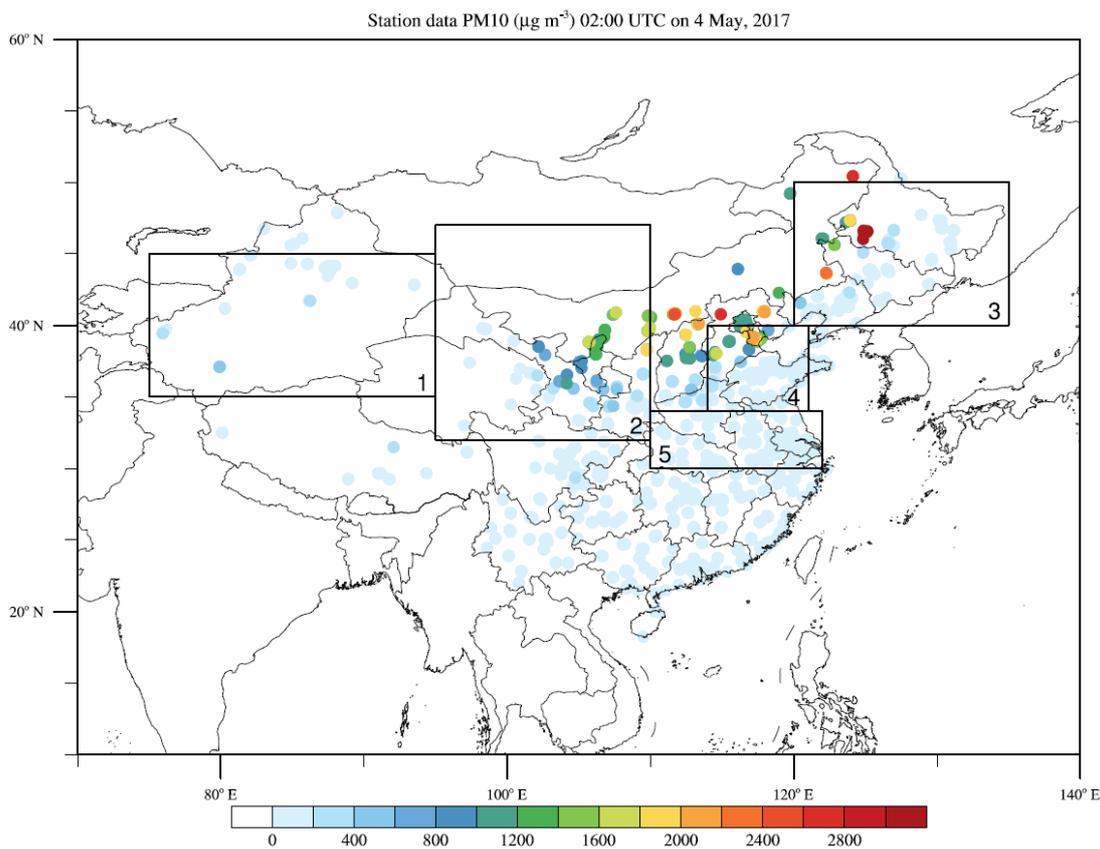
Figure 6. Five sub regions and observed PM_{10} concentrations. "1" represents Taklimakan Desert (TD), "2" represents Gobi Desert (GD), "3" represents Northeastern plain (NEP), "4" represents North China Plain (NCP), "5" represents Middle and lower reaches of Yangtze River Plain (YR). The colored dots represent observed PM_{10} concentrations over observational sites at 02:00 UTC on 4 May, 2017 (10:00 Beijing Time (BJT) on 4 May, 2017).
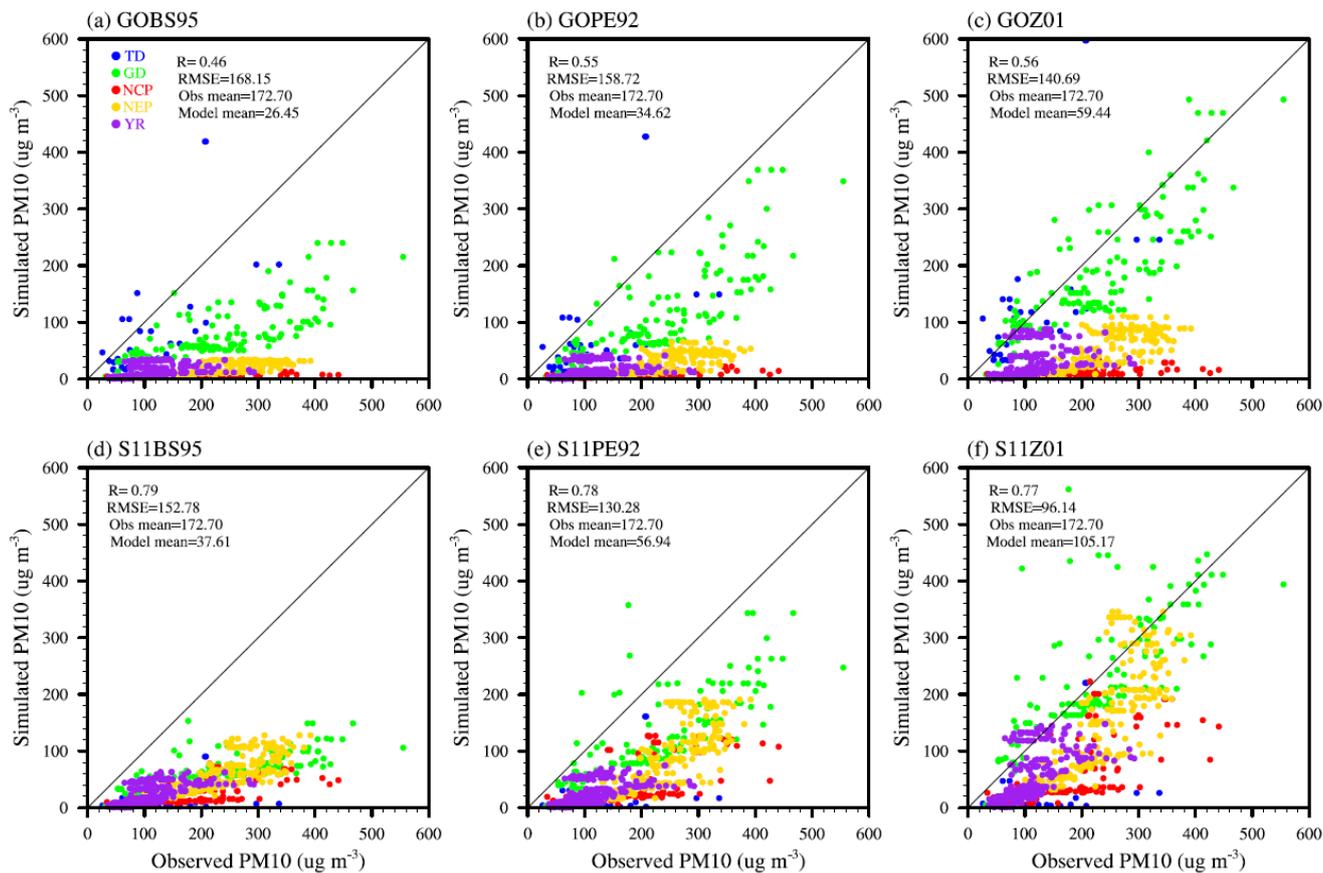
Figure 7. Simulated PM$_{10}$ versus observed PM$_{10}$ for six experiments (a)GOBS95, (b)GOPE92, (c)GOZ01, (d)S11BS95, (e)S11PE92, (f)S11Z01 over the 7-day simulation period 1-7 May, 2017. "Obs mean" is mean PM$_{10}$ from observation, "Model mean" is mean PM$_{10}$ from simulation, "R" is the correlation coefficient between model and observations, "RMSE" is the root mean square error. Different color dots represent different regions as shown in Fig. 6.
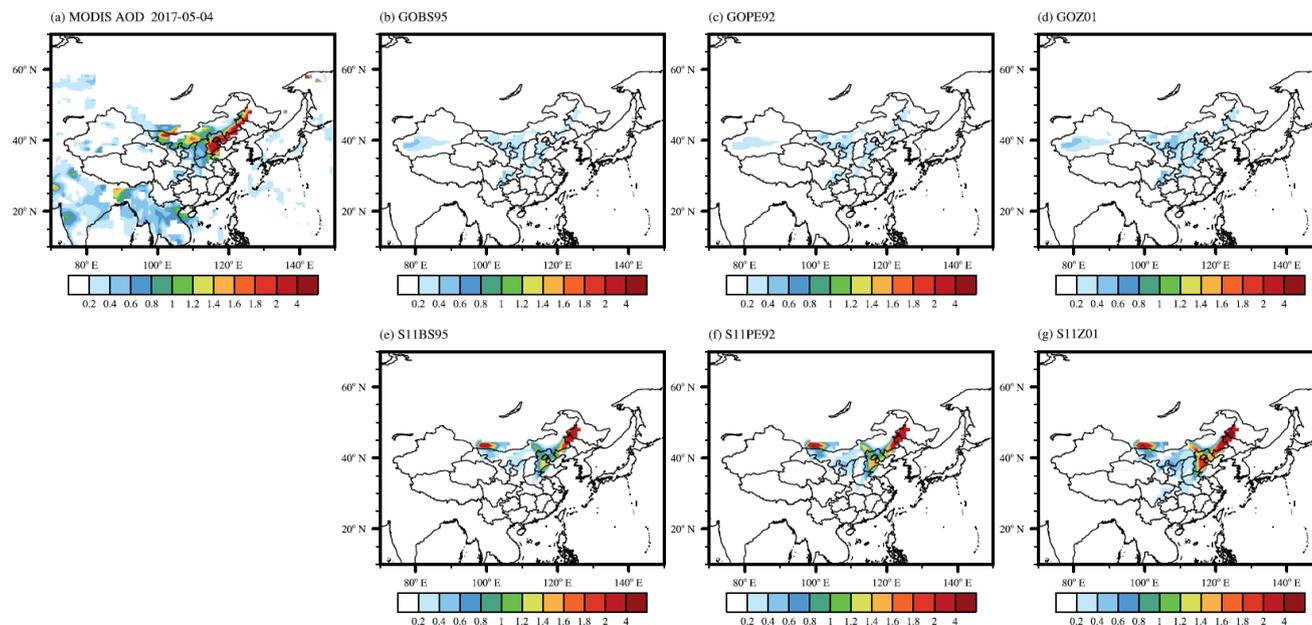
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Figure 8. Simulated and observed AOD on 4 May, 2017: (a) Distribution of daily mean aerosol optical depth (AOD) at 550

nm derived from MODIS-Aqua; WRF-Chem simulated AOD at 13:00 p.m. local time for six experiments (b) GOBS95, (c)

GOPE92, (d)GOZ01, (e)S11BS95, (f)S11PE92, (g) S11Z01. The simulated AOD already collocated with MODIS AOD.
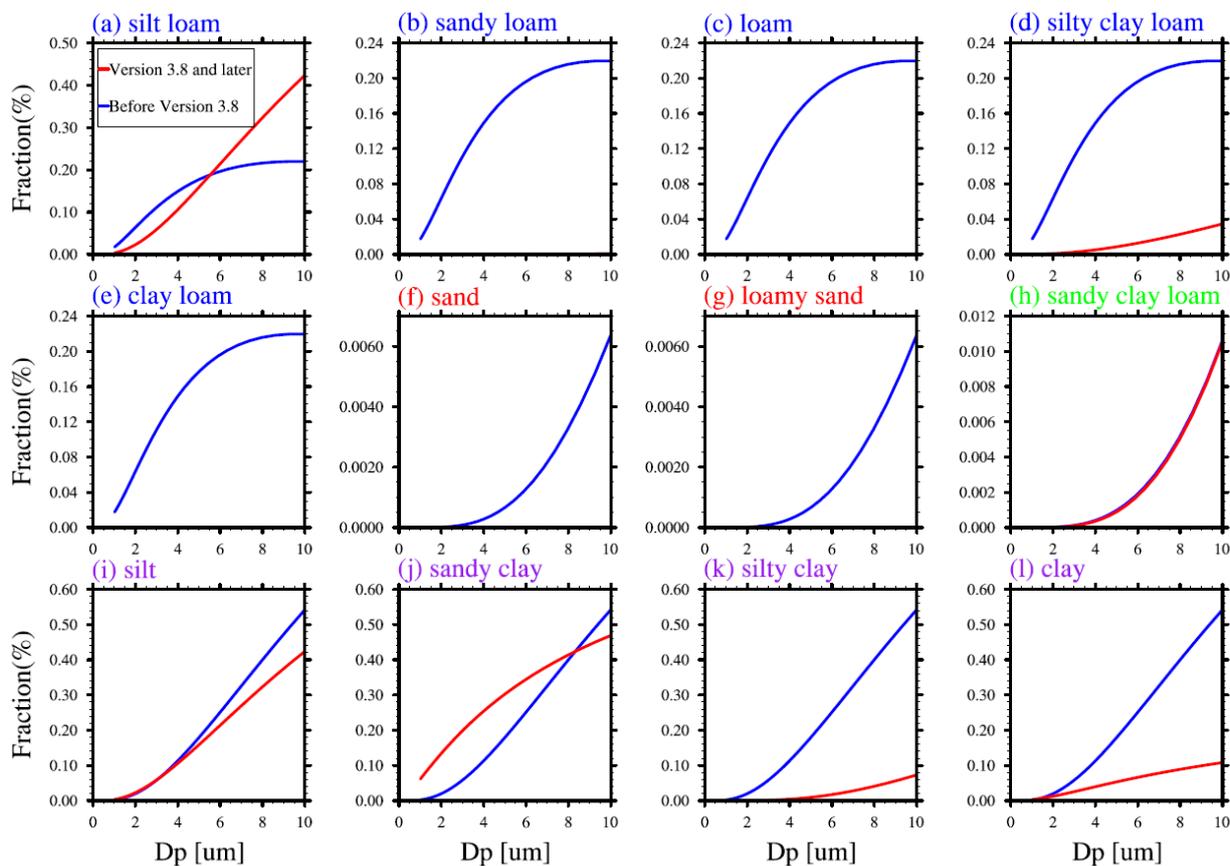
Figure B1. Free dust fraction for 12 soil types as a function of particle diameter (Dp). The red lines represent the free dust fraction in WRF-Chem v3.8 and later versions. The blue lines represent the free dust fraction before WRF-Chem v3.8. The colors of the soil type font in the upper left corner of the plot are different. In WRF-Chem v3.8 and later versions, each soil type has a corresponding free dust fraction distribution. In versions before WRF-Chem v3.8, several soil types share a free dust fraction distribution. The same soil type font color indicates that a free dust fraction is shared among these soil types in versions before WRF-Chem v3.8.