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Investigation of the influence of mineral dust on airborne particulate matter during the COVID-19 epidemic in spring 2020 over China

Lin Liang a,b, Zhiwei Han a,b,*, Jiawei Li a, Mingjie Liang a,b

a Key Laboratory of Regional Climate-Environment for Temperate East Asia (RCE-TEA), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (CAS), Beijing, 100029, China
b University of Chinese Academy of Sciences, Beijing, 100049, China

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ABSTRACT

A regional air quality model system (RAQMS) driven by the Weather Research and Forecasting model (WRF) is applied to investigate the distribution and evolution of mineral dust and anthropogenic aerosols over China in April 2020, when air quality was improved due to reduced human activity during the COVID-19 epidemic, whereas dust storms began to attack China and deteriorated air quality. A dust deflation model was developed and improved mineral dust prediction. Model validation demonstrated that RAQMS was able to reproduce PM\textsubscript{10}, PM\textsubscript{2.5} and aerosol components reasonably well. China suffered from three dust events in April 2020, with the maximum hourly PM\textsubscript{10} concentrations exceeding 700 μg m\textsuperscript{-3} in downwind cities over the North China Plain (NCP). Mineral dust dominated PM\textsubscript{10} mass (>80%) over the Gobi deserts in north and west China, while it comprised approximately 30-50% of PM\textsubscript{10} over wide areas of east China. The domain and monthly mean dust mass fractions in PM\textsubscript{10} were estimated to be 47% and 43% over the North China Plain and east China, respectively. On average, mineral dust contributed up to 22% and 21% of PM\textsubscript{2.5} mass over the North China Plain and east China in April 2020, respectively. Sulfate and nitrate produced by heterogeneous chemical reactions on dust surface accounted for approximately 9% and 13% of secondary inorganic aerosols (SIA) concentration over the North China Plain and east China, respectively. The results from this study demonstrated that mineral dust made an important contribution to particulate matter mass during the COVID-19 epidemic in spring 2020 over China.

1. Introduction

Mineral dust is one of the major components of global aerosols. It is estimated that approximately 100–460 Mt of dust emitted into the atmosphere annually over east Asia (Laurent et al., 2006). Dust can be lifted to high altitude and transported to downwind regions thousands of kilometers away, deteriorating air quality and damaging human health. Dust aerosol can be a platform where heterogeneous chemical reactions take place, which perturbs chemical compositions in the atmosphere. Dust aerosols scatter and absorb solar and longwave radiations. Mineral dust covered by secondary inorganic aerosols is able to act as cloud condensation nuclei (CCN) and dust aerosol is also a good ice nucleus (IN), likely exerting significant impact on radiation balance, cloud and precipitation. East Asia is characterized by large amounts of gas precursors and it is one of the major desert regions in the world. Frequent dust storms originated from Gobi deserts from southern Mongolia and Inner Mongolia of China often moved southeastward, encountering anthropogenic emissions over east China, which provides a good opportunity to explore dust evolution and interaction between anthropogenic and natural aerosols.

Dust deflation process plays a key role in dust cycle, which determines dust particle loadings in the atmosphere. Dust emission flux is controlled by a series of factors, such as land use, surface properties, soil texture, as well as meteorological factors. A number of field observation experiments have been carried out to investigate dust mobilization processes and dust properties over Chinese deserts (Zhang et al., 2003; Huang et al., 2008). Recently, Yang et al. (2019) observed that when soil moisture was above 3.0%, the threshold wind speed for dust deflation...
increased with soil moisture increasing in the Taklimakan Desert during 2008–2018. Munkhsetseg et al. (2016) reported that the threshold friction velocity increased from 0.44 m s$^{-1}$ for dry soil to 0.67 m s$^{-1}$ for wet soil in a typical Mongolian grassland in May 2009. Li and Zhang, 2014 found that dust particle appeared to have larger size and smaller dust emission flux under wet soil conditions in the Horqin Sandy Land of China based on observations of dust events in 2010.

Some dust models have been developed in recent two decades to explore the processes of dust deflation, transport and diffusion, dry and wet deposition. In general, two types of dust model were often applied, one is physically based model, which represents complicated mechanisms of dust generation (Marticorena and Bergametti, 1995; Shao, 2001; Alfaro et al., 2001; Gong et al., 2003), another is empirical model (Zender et al., 2003; Liu et al., 2003; Han et al., 2004) based on analysis of laboratory and field observations for key parameters determining dust mobilization. Numerous modeling studies on mineral dust processes and effects were conducted over major deserts of the world, e.g., the Sahara Desert, Arabian Desert, Central Asian Desert, North American Desert, Australian Desert etc. O’Loingsigh et al., 2017 analyzed dust transport dynamics over the eastern half of Australia for the 2000–2009 Millennium Drought decade (2000–2009) based on trajectory model and observations and revealed different wind systems responsible for dust transport from central Australia to Australian east coast. Anisimov et al. (2018) reproduced strong dust storms in April 2007 in the central Arabian Peninsula by WRF-Chem, and reported that about 25 Tg dust was emitted in Arabian Peninsula during a 10-day dust storm period and 40% of the locally deposited dust was subject to wet removal processes. Lamancusa and Wagstrom, 2019 revealed by GEOS-Chem simulation that dust emitted from the northern regions of the Sahara underwent 25% more latitudinal and 2% more longitudinal transport than dust emitted from the more southern regions. Kim et al. (2021) investigated the sources and interannual variations of the springtime fine-mode dust over western North America by the NASA Unified WRF model. The model results indicated that although permanent deserts and semi-arid regions in western North America were the major source, long-range transpacific transported dust was a dominant dust source in springtime. Francis et al. (2022) simulated by WRF-Chem the effects of a major dust event in the Sahara Desert in June 2020 and found that the dust event lasted for more than five days and dust loading over the eastern tropical Atlantic was 7.9 Tg. A number of numerical studies have also been carried out to develop dust model and to characterize east Asian dust evolution processes and impacts (Gong and Zhang, 2008; Li et al., 2011; Chen et al., 2013, 2016; Han et al., 2012; Liu et al., 2015; Fu et al., 2016; Tian et al., 2021a). Fu et al (2016) reduced the low bias in PM$_{10}$ concentrations by CMAQ in eastern China from 2006 to 2010 by improving calculation of threshold friction velocity based on field experiment. Tian et al. (2021a) updated key parameters of dust deflation in the dust scheme of GEOS-Chem and reduced the normalized mean bias by about 30% during a dust storm from 27 March to April 2, 2015. Dai et al. (2020) proposed a new method for estimating dust emission with threshold wind speed as a function of soil moisture based on observational data in the Gobi deserts of Mongolia from 2000 to 2018. Although dust models have been developed, uncertainties still exist due to limitations in our understanding of mobilization processes and in identification of surface properties and key parameters, thus prediction of mineral dust aerosols remains one of the challenging issues in air quality and climate modeling.

Since January 2020, the novel coronavirus (COVID-19) began to attack China. In order to control the spread of the COVID-19 epidemic, Chinese government implemented strict measures on January 23, 2020 to control transportation, social and industrial activities, which resulted in evident changes in anthropogenic emissions, with SO$_2$, NO$_x$, CO, non-methane volatile organic compounds (NMVOCs) and primary PM$_{2.5}$ emissions decreased by 27%, 36%, 28%, 31% and 24%, respectively, in February 2020 compared with the same month in 2019 (Zheng et al., 2021). While human activity and anthropogenic emissions were reduced by the control measures, which led to a series of responses in air pollutants of anthropogenic origins (Huang et al., 2020; Sun et al., 2020), mineral dust events began to happen, complicating air pollution in east China. There were three dust events passed through north China and affected parts of east China in April 2020. The most severe one occurred on 24–25 April, when the maximum hourly PM$_{10}$ concentration in Beijing exceeded 470 µg m$^{-3}$, with AQI (Air Quality Index) reaching 350 and level 6 (the highest class indicating severe pollution). On 24 April, Beijing municipality launched the first air pollution alert in 2020, with primary pollutant being PM$_{10}$, which suggested the arrival of a dust storm. Therefore, it is meaningful to explore the evolution of mineral dust aerosols and the dust impact on air quality in China.

In this study, firstly, a dust deflation model is developed to better represent dust emission and airborne dust concentration, and then it was applied with RAQMS to investigate the evolution processes of dust aerosols and dust impact on downwind particulate matter (PM) and chemical components. The relative contribution of mineral dust and anthropogenic aerosols to particulate matter mass concentration was quantified, and the changes in aerosol chemical composition due to heterogeneous chemical reactions on dust surface were also identified. To our knowledge, this is the first study concerning mineral dust impact on particulate matter during the COVID-19 epidemic in China, which would provide valuable insights into aerosol evolution and composition in spring 2020 over east China.

The paper is organized as follows: model description and configuration and observations are introduced in section 2. Section 3 introduced dust model development and model validation for meteorological variables, PM$_{2.5}$, PM$_{10}$ and aerosol components. The evolution of dust events and dust contribution to particulate matter are analyzed and discussed in section 4. Section 5 summarizes model results and draws conclusions.

2. Model and observation descriptions

2.1. WRF

WRF (The Weather Research and Forecasting Model) version 3.8 is applied to provide meteorological fields for RAQMS, with four-dimensional data assimilation (4DDA) to enhance the prediction accuracy of meteorological variables. The hourly fifth-generation reanalysis data (ERA5) from European Centre for Medium-Range Weather Forecasts (ECMWF) with a spatial resolution of 0.5° × 0.5° was used as the initial and boundary meteorological conditions. Fig. 1 shows the study domain of concern and the observational sites for meteorology and aerosols.

The physical options used in WRF3.8 for this study are as follows: the Thompson microphysical scheme (Thompson et al., 2004), CAM shortwave and longwave radiation scheme (Collins et al., 2004), Tiedtke ensemble cumulus scheme (Zhang et al., 2011), Yonsei University (YSU) planetary boundary layer (PBL) scheme (Hong et al., 2006), revised MM5 Monin-Obukhov surface layer model (Jiménez et al., 2012), and the Noah-MP land surface model (Niu et al., 2011). More details on model settings and parameterizations in WRF3.8 are listed in Table S1.

2.2. RAQMS

The Regional Air Quality Model System (RAQMS) is a three-dimensional Eulerian model constructing on a spherical and terrain-following coordinate system. It contains a series of tropospheric physical and chemical processes of major chemical components, such as advection, diffusion, dry and wet deposition, multiphase chemistry. (An et al., 2002; Han et al., 2004, Han, 2007, 2008a). The gas-phase chemical mechanism includes 37 gas components and 91 chemical reactions based on CBM-IV (the Carbon Bond Mechanism IV) (Gery et al., 1989). The ISORROPIA model is applied to describe thermodynamic equilibrium processes of inorganic aerosols (Nenes et al., 1998). The generation of secondary organic aerosols is calculated by a volatility...
2.3. Model configuration

Han, 2016). In this study, aerosol distribution is divided into two size sections. Fine particle (Meng et al., 1998) is used to calculate gas/particle mass transfer. In this California/Carnegie-Mellon Institute of Technology) bulk equilibrium heterogeneous reactions on dust are assumed to take place when calcium content exceeds sulfate and nitrate produced on dust, and the calcium content of dust is assumed to be 5% by weight according to Dentener (1994). Heterogeneous reactions and uptake coefficients on the surfaces of aqueous particles and cloud droplets are represented by the formula from Jacob (2000). Heterogeneous reactions and uptake coefficients of gaseous species on dust surface are treated mainly based on Li and Han (2010), with the heterogeneous reaction of HNO₃ depending on RH, according to Vlasenko et al., 2005 (Table S2). Heterogeneous reactions on dust are assumed to take place when calcium content exceeds sulfate and nitrate produced on dust, and the calcium content of dust is assumed to be 5% by weight according to Dentener et al. (1996). RAQMS has participated in the Model Inter Comparison Study for Asia phase II (MICS-Asia II) project (Carmichael, 2008; Han et al., 2008b) and has been used in previous studies on tropospheric ozone, haze pollution, acid deposition, dust storms over East Asia (Han et al., 2006, 2008b; Li et al., 2011, 2018; Li et al., 2020, 2021; Li and Han, 2016).

2.4. Satellite and observation data

The National Meteorological Information Center (http://data.cma.cn) provides daily observations of meteorological variables, including air temperature and relative humidity at 2 m (T2 and RH2) above ground and wind speed at 10 m (WS10), and 16 monitoring sites in China are selected for model validation. The hourly observations for PM₂.₅ and PM₁₀ concentrations in the major cities of north and east China (shown in Fig. 1) are derived from the Air Quality Database of the Ministry of Environmental Protection (http://datacenter.mep.gov.cn). The observation for each city is an average of all sites in the city. Hourly concentrations of PM₂.₅ components are observed on the big tower of the Institute of Atmospheric Physics, which is located between the third and fourth ring road in Beijing.

The land use data with a 500-m resolution for the base year 2019 is derived from MODIS (Moderate Resolution Imaging Spectroradiometer Land Cover Type (MCD12Q1), https://search.earthdata.nasa.gov/search). The soil texture map (including sand, silt and clay contents with 30 arcsec resolution) is obtained from the Harmonized World Soil Database (HWSD: https://westdc.westgis.ac.cn/data) released by the United States Department of Agriculture (USDA) and the map in China is provided by the Institute of Soil Science, Chinese Academy of Sciences. The satellite soil moisture content data is obtained from AMSR2 (the Advanced Microwave Scanning Radiometer 2, https://search.earthdata.nasa.gov/search), which is improved based on AMSR-E by adding two channels with frequency of 7.3 GHz and 89.0 GHz. In this study, daily ascending orbit data from 1 to April 30, 2020 with a spatial resolution of 25 km were used.

2.5. Dust deflation model

The deflation, dry deposition and wet removals of dust particles are parameterized by the scheme of Han et al. (2004). Particles with diameters ranging from 0.43 to 42 μm are divided into 10 size bins. Three categories of underlying surface, i.e., bare ground, bare ground with little shrubs and plain with low grass are taken as potential dust deflation regions. Land use data are derived from DeFries and Townshend (1994). Dust flux is calculated by the following formula:

\[ F = C \times u_i^* \times \left(1 - \frac{u_i}{u_{i*}}\right) \times \left(1 - \sum f_i \times R_i \right) \times \left(1 - \frac{u_{ts}}{u_{ts*}}\right) \]

where \( u_i \) and \( u_i^* \) are the friction and threshold friction velocities and C is a constant (1.4 × 10⁻¹⁵). \( R_i \) and \( f_i \) are reduction factor for each land use type and fractional coverage of the \( f_{ts} \) type of vegetation in a model grid. The threshold friction velocities are set to 0.4, 0.5 and 0.65 m s⁻¹ for the three categories of source regions mentioned above, and the threshold relative humidity is set to 50%, 40% and 40% for the above three land use types. Dust deflation is allowed in the above regions when near-surface friction velocity and relative humidity are larger and smaller than the threshold friction velocity and threshold relative humidity. The total dust emission flux is assigned to each size bin based on field measurements of size distribution of vertical dust flux over major Chinese deserts during the Aerosol Characterization Experiment–Asia (ACE-
ASIA). More details refer to Han et al. (2004). The dust model exhibits a good ability in reproducing strong dust storms in past decades, such as the dust storms in the spring of 2002, 2006, 2009 and 2010 (Han et al., 2004; Li et al., 2011; Li and Han, 2015). However, in some cases, the model performance is not satisfactory, especially for moderately strong dust storms originated from arid areas other than the Gobi deserts, which could be associated with potential changes in land use, dust deflation regions or with uncertainties in controlling factors for dust deflation.

In this study, the dust model is developed as follows: first, land use is updated with the up-to-date MODIS retrievals, in which barren land and grassland are taken as potential dust deflation regions (Fig. 4). Second, soil texture and fraction (Fig. 5) are introduced into the dust model, which is derived from the HWSD database. The calculation of the dust emission flux is revised to:

$$F_j = F \times \sum S_j \times a_i$$

where $F_j$ is the dust emission flux calculated by formula (1), $S_j$ is the fraction of sand, silt and clay in each model grid (Fig. 5), $a_i$ is the dust deflation efficiency factor of different soil textures, which are taken as 1.0 for sand, 0.6 for silt and 0.2 for clay according to Liu et al. (2007).

Third, soil moisture content is a key factor determining dust deflation. Li et al. (2004) found that there existed a threshold value, approximately 16.3%–19.5%, below which dust can be deflated. So, a threshold soil moisture of 17% is assigned to be a parameter determining dust deflation.

Fourth, most dust storms influencing north and east China originated mainly from the Gobi deserts in southern Mongolia and northern inner Mongolia. Besides the broad Gobi deserts, the HunshanDake desert (HSDK) (Fig. 1) is also a major dust source region and has considerable influence on air quality as well because it is closer to the NCP region than the Gobi desert. Previously, the threshold friction velocity is set to a constant for each of the three dust source regions. In this study, the field measurement of friction velocity (Zhang et al., 2007) was applied to the HunshanDake desert, with $u_{vt}$ being 0.4 m s$^{-1}$, smaller than 0.65 m s$^{-1}$ in the previous dust model.

From 1 to April 30, 2020, three dust events occurred in north China, which were mainly originated from the eastern parts of the China-Mongolia border, the Gobi desert around the China-Mongolia border and the Hunshandake desert in eastern Inner Mongolia. To examine the dust model improvement, five model simulations are conducted as shown in Table 1. The base case refers to model simulation with the old land use scheme, Exp1 applies the up-to-date land use data from MODIS instead of the old land use from U.S. Geological Survey (USGS), Exp2 introduces soil texture distribution based on Exp1, Exp3 takes threshold soil moisture into account based on Exp2, and Exp4 is the same as Exp3 except that new threshold friction velocity derived from field experiment is used for the Hunshandake desert. Exp4 presents the final model results by considering all the above improvements.

| Experiments | New land use data | Soil texture | Threshold soil moisture | New threshold $u_{vt}$ for HSDK |
|-------------|------------------|--------------|------------------------|-------------------------------|
| Base        |                   |              |                        |                               |
| Exp1        | ✓                | ✓            |                        |                               |
| Exp2        | ✓                | ✓            | ✓                      |                               |
| Exp3        | ✓                | ✓            | ✓                      | ✓                             |
| Exp4        | ✓                | ✓            | ✓                      | ✓                             |

3. Results and discussions

3.1. Model validation

3.1.1. Meteorological variables

The statistics for comparison between the WRF simulated and observed daily mean surface meteorological variables at 16 ground monitoring sites (note: meteorological data in Shijiazhuang and Zhengzhou are not available during the study period) in April 2020 are presented in Table 2. The overall meteorological prediction is generally satisfactory, with the correlations coefficients (R) of 0.96 for temperature, 0.92 for relative humidity and 0.71 for wind speed. The correlation coefficients for air temperature and relative humidity for all sites were 0.96–0.98 and 0.81–0.96, respectively. The model apparently predicted lower temperature and higher relative humidity in Zhangjiakou and Hohhot, with the normalized mean biases (NMB) of −36–38% and 41%–45%, respectively. The model performance for wind speed was generally good, with R of 0.54–0.90, and NMB of 23–78%. The overall statistics for all sites exhibit a generally good ability of WRF in predicting meteorological variables, with NMBs of −7.4%, 6.4% and 10.9% for near-surface air temperature, relative humidity and wind speed, respectively.

3.1.2. Soil volume water

Fig. 2 presents the monthly mean soil volume water content from the AMSR2 product and WRF simulation at 14:00 LST (the time when satellite passes over east China). The comparison shows the model can capture the major features of the spatial distribution of soil water content, with low values of ~13% over southern Mongolia, western and central Inner Mongolia and northern parts of Gansu province. However, WRF model tends to predict somewhat lower values than the satellite retrievals in the above dust source regions.

3.1.3. PM$_{10}$ concentrations

Fig. 3 presents the observed and simulated (from Exp4 and the base case) hourly surface PM$_{10}$ concentrations at 8 surface monitoring sites during the study period. There were three dust events of different magnitude in April 2020, with the maximum values of 288.7 μg m$^{-3}$, 194.0 μg m$^{-3}$ and 470.1 μg m$^{-3}$, on 4–5 April, 15–16 April and 24–25 April in Beijing, respectively. Therefore, these dust events are of moderate strength, compared with previous typical dust storms in 2002, 2006 and 2010. Among the three events, it is interesting to note that the maximum PM$_{10}$ concentrations occurred on 4 April in Tianjin (639.8 μg m$^{-3}$), Tangshan (594.3 μg m$^{-3}$) and Shijiazhuang (406.3 μg m$^{-3}$), on 16 April in Zhangjiakou (496.3 μg m$^{-3}$), Hohhot (830.0 μg m$^{-3}$), and Ulán Qab (634.5 μg m$^{-3}$), whereas the maximums appeared on 24 April in Beijing (470.1 μg m$^{-3}$) and Zhangjiakou (733.8 μg m$^{-3}$), suggesting different dust source regions and transport pathways.

The comparison shows that the base case generally captures the dust storms (4–5 April, 15–16 April, 24–25 April), but there are some biases in the model simulation compared with observations, e.g. missing the first dust event at most sites, overprediction of the PM peaks in the upwind cities during the second event, underprediction of peaks in the third event, and fake “dust events” from the Hunshandake desert on 20–22 April were predicted. Regarding the above model limitation, the dust model was improved and relevant sensitivity model simulations were presented as follows:

In Exp1, the old land use is replaced by the up-to-date MODIS data. The proportion of barren land reached 90% in the southern China-Mongolia border, central Inner Mongolia and parts of Gansu and Qinghai provinces. Grassland coverage reached more than 90% in northern and central Mongolia, eastern Inner Mongolia, southern Qinghai, western Sichuan and Tibet (Fig. 4), which had wider arid or semi-arid areas than former land use, resulting in larger dust emission flux (Fig. S1b) and higher dust concentration than those from the base case (Fig. S1a, Fig. 6).

Previous studies indicated that high clay content might prevent dust...
deflation (Fecan et al., 1999; Wu et al., 2018). Fig. 5 shows that the content of sand soil is about 50% in the Gobi Desert of southern Mongolia with clay content being about 10%–35%. However, sandy soil contains more than 80% and clay content is less than 10% in the Badain Jaran Desert, the Tengger Desert, and the Hunshandake desert of Inner Mongolia. By taking soil texture into account, Exp2 yields lower dust emission flux (Fig. S1c) than that in Exp1 and reduces the high biases at both the upwind sites (OD, HH, UQ, DT) and downwind sites (BJ and TJ) compared with that in Exp2 (Fig. S1d) and the fake emission flux over the Hunshandake desert (Fig S1e) and increasing dust concentrations to 418.0 μg m⁻³ and 744.6 μg m⁻³ in Beijing and Zhangjiakou, respectively, much closer to the observations of 470.1 μg m⁻³ and 735.8 μg m⁻³. The improvement in Tianjin and Tangshan was relatively smaller, the results from Exp4 are better than those from most cases in the two cities.

In all, the dust model is improved by applying up-to-date land use, soil texture map, soil water content and field measurements for threshold friction velocity (Fig. 3). Table 3 presents the statistics for model performance for PM₁₀ concentrations in major cities from upwind desert regions to downwind areas of east China for the entire study period of April 2020. The Exp4 which includes all the above improvements yields an overall R of 0.50 and NMB of −7.4% for PM₁₀ concentration, better than those (with R of 0.38 and NMB of −9.1%) from the base case. For the dust events, the improvement is more evident, with R increased from 0.52 to 0.62, and NMB decreased from −15.6% to −11.6%. The revised dust model evidently improves model simulation for PM₁₀ during dust events and consequently enhances the model ability for PM₁₀ concentration for the entire study period.

Table 4 presents the performance statistics for PM₂.₅ concentrations in megacities of east China in April 2020. The model well reproduced...
Fig. 3. The observed (gray shades) and simulated hourly mean PM$_{10}$ concentrations from the base case (blue line) and Exp4 (red line) in 8 cities during the study period.
PM$_{2.5}$ concentration in Beijing, with $R$ of approximately 0.5 and NMB of 2%, but somewhat underpredicted PM$_{2.5}$ observations by 14–25% in Tianjin and Tangshan. The model performances in southern North China Plain (NCP) are satisfactory (i.e., SJZ, JN, ZZ), with NMBs around ±6%. The model tends to overpredict observations in the Yangtze River Delta (i.e., NJ and SH, with NMBs around 40%) and in the portions of south China (i.e., NC, GZ, WH and CS, with NMBs of 30–69%). In all, the model is able to reasonably reproduce the distribution and magnitude of PM$_{2.5}$
concentrations, with the overall R of 0.5 and NMB of 13.7%.

### 3.1.4 Aerosol chemical components

Fig. 9 shows the simulated (from Exp4) and observed hourly concentrations of PM$_{2.5}$ chemical components in Beijing. The model reasonably reproduces the temporal variation of aerosols, including aerosol evolution from clean to haze periods. However, the model tends
to generally underpredict the magnitude of secondary aerosol components, which was often seen in current chemical transport model simulations and could be mainly attributed to the uncertainties in chemical mechanisms. So far, most chemical models consistently predict lower sulfate concentration, especially during haze episodes (Fu et al., 2016; Zheng et al., 2015), suggesting missing chemical pathways for sulfate formation. Although a VBS approach with semi-volatile and intermediate volatile organic compounds (S/IVOC) primary emissions and aging mechanisms was applied, SOA concentration is also underpredicted. Potential uncertainties in emission inventory, meteorological simulation, as well as model grid resolution may also contribute to the model biases. The overall model performance for sulfate, nitrate, ammonium, BC and OM are 0.42, 0.55, 0.56, 0.60 and 0.54 for R, and −43.6%, 1.2%,

![Graph showing observed and model simulated hourly concentrations of sulfate, ammonium, nitrate, BC, POA, SOA, OM and PM$_{2.5}$ in Beijing during the study period.](image)

**Fig. 9.** The observed (at the big tower) and model simulated (Exp4) hourly concentrations of sulfate, ammonium, nitrate, BC, POA, SOA, OM and PM$_{2.5}$ in Beijing during the study period.

| Component | $C_{\text{obs}}$ ($\mu g m^{-3}$) | $C_{\text{sim}}$ ($\mu g m^{-3}$) | R | MB ($\mu g m^{-3}$) | NMB (%) |
|-----------|-------------------------------|-------------------------------|---|----------------|--------|
| BC        | 1.4                           | 0.82                          | 0.60 | −0.57          | −40.9 |
| SO$_2^+$  | 3.4                           | 1.9                           | 0.42 | −1.5           | −43.6 |
| NO$_3^+$  | 7.2                           | 7.3                           | 0.55 | 0.09           | 1.2   |
| NH$_4^+$  | 3.5                           | 2.6                           | 0.56 | −0.95          | −27.2 |
| POA       | 2.7                           | 2.1                           | 0.56 | −0.57          | −21.4 |
| SOA       | 9.9                           | 6.3                           | 0.49 | −3.6           | −36.7 |
| OM        | 12.6                          | 8.4                           | 0.54 | −4.2           | −33.4 |

**Table 5** Performance statistics for PM$_{2.5}$ chemical components in Beijing during the study period from Exp4.
4. Model results

4.1. Spatial and temporal distributions of dust and PM$_{10}$ concentrations

Fig. 10 presents the spatial distributions of simulated concentrations of mineral dust (diameter < 10 µm) and PM$_{10}$ averaged over the three dust events and over the entire month of April 2020 (in contours in Fig. 10) represent the percentage contribution of dust to PM$_{10}$ concentrations. The first dust event influencing the NCP was originated from the portions of eastern Inner Mongolia in the vicinity of China-Mongolia border, with the maximum PM$_{10}$ concentration of 500 µg m$^{-3}$. It is interesting to note that the dust plume moved southward in a clockwise direction, and led to apparent increases in PM$_{10}$ concentrations in Tianjin, Tangshan, Shijiazhuang and Jinan, but relatively small PM$_{10}$ increase in Beijing due to the clockwise circulation bypassing Beijing (Fig. 10a). The influence of this dust event was mainly confined within northeast China and the NCP, with dust contribution to PM$_{10}$ of 50–80% (Fig. 10e). Meanwhile, dust deflation occurred in western China, with PM$_{10}$ concentration exceeding 1000 µg m$^{-3}$ and dust plumes were transported southeastward by northwesterly, affecting broader areas from central China to the lower reaches of the Yangtze River, with dust fraction in PM$_{10}$ of 30–50% in the above regions.

The second dust event affecting east China was originated from the Gobi desert of southern Mongolia (Fig. 10b), with the maximum PM$_{10}$ value above 1000 µg m$^{-3}$ over dust source regions. It swept over broad areas from the central Inner Mongolia to the NCP and the lower reaches of the Yellow River. PM$_{10}$ concentrations were generally above 300 µg m$^{-3}$ in Inner Mongolia and ranged from 50 to 150 µg m$^{-3}$ in downwind regions. It was striking that most areas of north China were dominated by dust, with dust fraction of PM$_{10}$ exceeding 80% over the middle reaches of Yellow River and most of Inner Mongolia. The impact of this dust event is relatively weak over the NCP because southerly wind prevailed in this region, reducing the southeastward transport of dust plumes, resulting in dust fraction of 30–50% in the NCP (Fig. 10f).

On 24 April, dust deflation occurred in the Gobi desert around the southern China-Mongolia border and the Hunshandake desert (Fig. 10c), with the maximum dust concentration up to 500 µg m$^{-3}$ in the deserts. The Gobi dust influenced large areas in the middle and lower reaches of the Yellow River, whereas Beijing and the NCP were directly influenced by the southward dust transport originated from the Hunshandake desert. Dust dominated most regions of north China, with fraction in PM$_{10}$ larger than 80%, and accounted for approximately 50% of PM$_{10}$ mass along the Yangtze River except for the Yangtze River Delta (the areas around Shanghai) (Fig. 10g). This dust event exerted the largest influence on PM$_{10}$ concentration over east China.

The monthly mean distribution of dust concentration was characterized by high values over the western inner Mongolia (up to 800 µg m$^{-3}$) and the southern China-Mongolia border (up to 200 µg m$^{-3}$), and moderate values of 50–100 µg m$^{-3}$ over the deserts of eastern Inner Mongolia including the Hunshandake desert. Vast areas from the NCP and the middle reaches of the Yellow River to the middle reaches of the Yangtze River were evidently influenced by dust events, resulting in dust concentrations above 20 µg m$^{-3}$. It was noteworthy that the PM$_{10}$ concentrations exceeded 50 µg m$^{-3}$ over most of east China including the NCP, and over 75 µg m$^{-3}$ in portions of central China and in the middle to lower reaches of the Yangtze River (color bar in Fig. 10h).

Mineral dust dominated PM$_{10}$ mass (>80%) over the Gobi deserts in north and west China, it comprised approximately 50% of PM$_{10}$ over wide regions from the NCP to the middle reaches of the Yangtze River, and it even accounted for approximately 30–50% of PM$_{10}$ in the lower reaches of the Yangtze River.

Fig. 11 clearly illustrates the relative contributions of dust and anthropogenic aerosols to total PM$_{10}$ mass concentration in major cities along the dust transport pathway averaged over the three dust events and over the entire study period of April 2020. During the dust events, the dominant component of PM$_{10}$ was mineral dust in the upwind regions close to Gobi deserts, with dust fractions of 97.3%, 98.8% and 97.4% in Ordos, Hohhot and Ulanqab, respectively. The dust fraction decreased to 89–93% in Beijing, Tangshan and Datong, and further decreased to approximately 71–78% in the major cities (Tianjin, Shijiazhuang, Jinan, Zhengzhou) over the NCP, indicating the dominant component of mineral dust in north China. In terms of monthly mean, dust also contributed more than 80% of PM$_{10}$ mass in those upwind cities and contributed 56–80% of PM$_{10}$ in the big cities of NCP including Beijing. It is noted that the dust fraction of PM$_{10}$ in Zhengzhou was 76%, larger than those in the NCP, which can be explained by the different pathway of dust transport mainly coming from the Gobi desert near the China-Mongolia border. The domain and monthly mean dust fractions in PM$_{10}$ were estimated to be 46.7% and 43.1% over the NCP and east China (110–123 E, 22–42 N), respectively, which indicated that dust comprised about half of PM$_{10}$ mass over the NCP in April.

4.2. Spatial and temporal distributions of PM$_{2.5}$ and its components

Fig. 12 presents the spatial distributions of monthly mean near-surface concentrations of PM$_{2.5}$ and its major components over the study domain. During April 2020, the distribution of mineral dust in fine model (diameter < 2.5 µm) (DS$_{2.5}$) resembled that of DS$_{10}$ (Fig. 10d). DS$_{2.5}$ concentrations ranged from 50 to 200 µg m$^{-3}$ over the deserts of western China, 10–20 µg m$^{-3}$ in the middle reaches of the Yellow River and Yangtze River, and 5–10 µg m$^{-3}$ over broad areas of east China (EC), including the NCP and the Yangtze River Delta. It is noticed that DS$_{2.5}$ concentrations were 10–50 µg m$^{-3}$ over the Gobi desert, the Hunshandake desert and the eastern part of Inner Mongolia, which were the sources of the three dust events mentioned above (Fig. 12a). High concentrations of 18–28 µg m$^{-3}$ for secondary inorganic aerosols (including sulfate, nitrate and ammonium) (SIA) were distributed from the middle to lower reaches of the Yangtze River (Fig. 12b). It was also found that higher SIA concentration appeared over the Bohai Bay, downwind of the North China Plain. It is interesting that sulfate (DS$_{a}$) and nitrate (DS$_{b}$) concentrations produced by heterogeneous chemical reactions on fine dust surface were relatively high (1.2–3.2 µg m$^{-3}$) over wide regions downwind of the deserts, including the middle and lower reaches of the Yellow River and Yangtze River, where both mineral dust and anthropogenic gaseous emissions were abundant (Fig. 12c). The concentrations of carbonaceous aerosols (including BC, POA and SOA) (CA) were in a range of 10–40 µg m$^{-3}$ along the Yangtze River (Fig. 12d), similar to the distribution pattern of SIA. Primary PM$_{2.5}$ concentration (PMP$_{2.5}$) was lower than SIA and CA concentrations, with 4–10 µg m$^{-3}$ over most of east China, and 4–7 µg m$^{-3}$ in the NCP (Fig. 12e). The relatively higher PMP$_{2.5}$ concentration in southwest China was possibly caused by southeast Asia emissions, in which biomass burning emission could be high in springtime. Fig. 12f shows the spatial distribution of PM$_{2.5}$ concentration and the percentage contribution of mineral dust to PM$_{2.5}$ during April 2020. The distribution of PM$_{2.5}$ resembled that of PM$_{10}$, with 40–180 µg m$^{-3}$ in western China and 20–80 µg m$^{-3}$ over east China. High PM$_{2.5}$ concentration of 40–80 µg m$^{-3}$ occurred in wide areas along the Yangtze River and portions of central China, exceeding the Grade II National Ambient Air Quality Standard (35 µg m$^{-3}$ in terms of annual mean). It is interesting to note that the simulated maximum PM$_{2.5}$ value occurred in Chang Sha, which was also reflected in observations (Table 4). Impressively, mineral dust dominated PM$_{2.5}$ mass (>50%) over western China and parts of north China and accounted for approximately 20% of PM$_{2.5}$ in portions of the NCP and central China. Even in the areas from the lower to middle reaches of the Yangtze River. This indicated that mineral dust played an important role in particulate matter in spring 2020 when the COVID-19 epidemic was prevailing.

Table 6 presents the simulated fractions of major aerosol components in PM$_{2.5}$ mass averaged over the specific domains (the NCP and east China).
Fig. 10. The model simulated (a)–(c) average dust concentrations (overlapped with wind vector) during the three dust events and (d) in April 2020; (e)–(h) corresponding PM$_{10}$ concentrations (overlapped with contours representing percentage contribution of dust to PM$_{10}$, unit: %) (red dot denotes Beijing, the unit of concentration is μg m$^{-3}$).
During the dust events, the dominant component of PM$_{2.5}$ was mineral dust in NCP, with a fractional contribution of 50.8%, followed by SIA (22%) and CA (15.7%). $\text{D}_{\text{sul}} + \text{D}_{\text{nit}}$ totally accounted for 15% of SIA and 3.7% of PM$_{2.5}$ over the NCP. The contributions to SIA of heterogeneous reactions on dust surface were approximately 9% and 13% of SIA in the NCP and east China, respectively, and their contributions to PM$_{2.5}$ were just about 5% over east China, which can be ignored in the study period.

In all, during dust events, mineral dust dominated PM$_{2.5}$ mass over the NCP, and accounted for approximately 26% PM$_{2.5}$ over east China. For April 2020, mineral dust can contribute up to 22% and over 20% of PM$_{2.5}$ mass over the NCP and east China, respectively, which indicated that nitrate and sulfate formed on fine mode dust surface accounted for up to 17% and 11% of total nitrate and sulfate mass concentration during the dust events in March 2015. For east China, dust aerosol contributed approximately 26% of PM$_{2.5}$, comparable to the contributions from SIA (31%) and CA (30%).

For the entire study period of April, SIA was the dominant component of PM$_{2.5}$ in both NCP (40%) and east China (35%), dust fraction (22%) was comparable to CA fraction (24%) in the NCP, but it (21%) was lower than CA fraction (32%) for east China. The contributions to SIA of heterogeneous reactions on dust surface were approximately 9% and 13% of SIA in the NCP and east China, respectively, and their contributions to PM$_{2.5}$ were just about 5% over east China, which can be ignored in the study period.

In all, during dust events, mineral dust dominated PM$_{2.5}$ mass over the NCP, and accounted for approximately 26% PM$_{2.5}$ over east China. For April 2020, mineral dust can contribute up to 22% and over 20% of PM$_{2.5}$ mass over the NCP and east China, respectively, which

Table 6
Model simulated time-domain average fractions of major aerosol components in PM$_{2.5}$ mass concentration during dust events and April 2020 over the North China Plain (NCP) and east China (EC) (unit:%) (The values in brackets denote the fraction of sulfate and nitrate produced by heterogeneous reactions in SIA).

|          | Dust | SIA | $\text{D}_{\text{sul}} + \text{D}_{\text{nit}}$ | CA | PPM$_{2.5}$ |
|----------|------|-----|---------------------------------------------|----|------------|
| Dust events | NCP  | 50.8| 22.0 (15.4) | 3.7 | 15.7 | 11.4 |
| EC          | 26.1 | 31.4 (12.4) | 3.9 | 30.4 | 12.1 |
| April       | NCP  | 22.1| 40.0 (8.5) | 3.6 | 24.0 | 13.9 |
| EC          | 20.5 | 34.6 (12.9) | 4.5 | 31.9 | 13.0 |
demonstrated the considerable impact of mineral dust on particulate matter.

5. Conclusions

A dust deflation model was developed by using up-to-date land use and soil texture data, by introducing soil moisture as a controlling factor for dust deflation, and by using experimental based threshold friction velocity in the Hunshandake desert. A regional air quality model system (RAQMS) including this dust model was applied to investigate evolutionary processes of dust aerosols and contribution of dust aerosols to PM and its chemical components during the COVID-19 epidemic in April 2020. The validation against observations indicated that the model was capable of reproducing meteorological variables and aerosol concentrations reasonably well. The revised dust model apparently improved PM$_{10}$ simulation for dust event days, with R increased from 0.52 to 0.62, and NMB decreased from $\sim 15.6$ to $\sim 11.6$, and consequently improved PM$_{2.5}$ simulations for the entire study period of April, with R increased from 0.38 to 0.50, and NMB decreased from $\sim 9.1$ to $\sim 7.4$. There were three dust events influencing NCP in April 2020, which were originated from deserts in eastern Inner Mongolia, the Gobi desert of southern Mongolia, and the Hunshandake desert, respectively, although there were also dust events in western China. During dust events, the maximum hourly PM$_{10}$ concentrations exceeded 1000 $\mu$g m$^{-3}$ in the dust source regions and reached 700 $\mu$g m$^{-3}$ in downwind cities over the NCP. In term of monthly mean, dust concentration was as high as 800 $\mu$g m$^{-3}$ over the western inner Mongolia, up to 200 $\mu$g m$^{-3}$ in the vicinity of China-Mongolia border, and in a range of 50–100 $\mu$g m$^{-3}$ over the deserts of eastern Inner Mongolia including the Hunshandake desert. In April, mineral dust dominated PM$_{10}$ mass (>80%) over the Gobi deserts in north and west China, while it comprised approximately 50% of PM$_{10}$ over wide regions from the NCP to the middle reaches of the Yangtze River, and it even accounted for approximately 30–50% of PM$_{10}$ in the lower reaches of the Yangtze River. The domain and monthly mean dust fractions in PM$_{10}$ were estimated to be 46.7% and 43.1% over the NCP and east China, respectively.

In April 2020, average D52.5 concentrations ranged from 35 to 200 $\mu$g m$^{-3}$ over western deserts, 10–20 $\mu$g m$^{-3}$ in the middle reaches of the Yellow River and Yangtze River, and 5–10 $\mu$g m$^{-3}$ over broad areas of east China (EC), including the NCP and the Yangtze River Delta. It dominated D52.5 mass (>50%) over western China and parts of north China and accounted for approximately 20% of PM$_{2.5}$ in portions of the NCP and central China, and even in the lower to middle reaches of the Yangtze River. In terms of domain and period average, mineral dust dominated D2.5 mass over the NCP (51%), and accounted for approximately 26% PM$_{2.5}$ over east China during dust events, whereas for April 2020, mineral dust contributed up to 22% and 21% of PM$_{2.5}$ mass over the NCP and east China, respectively. Sulfate and nitrate produced by heterogeneous chemical reactions on fine dust surface totally accounted for 9% and 13% of SIA concentration in April over the NCP and east China, respectively.

This study revealed the significant contribution of mineral dust to PM mass concentration in north China, and the considerable impact of mineral dust on PM$_{2.5}$ level even in east China during the COVID-19 epidemic in spring 2020, when human activity and anthropogenic emissions were reduced by government’s strict control measures. More efforts will be made to continuously develop dust model and to explore evolution and interaction of anthropogenic and natural aerosols over east Asia in the future.

Credit author statement

Lin Liang: Methodology, Investigation, Formal analysis, Writing - Original Draft. Zhiwei Han: Conceptualization, Writing - Review & Editing, Supervision. Jiawei Li; Software, Data Curation. Mingjie Liang: Figures, Data Curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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