Wind-blown dust and its impacts on particulate matter pollution in Northern China: current and future scenarios

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Keywords: dust, CMAQ, wind speed, climate change, particulate matter

Supplementary material for this article is available online

Abstract
Northern China experienced two intense dust storms in March 2021, leading to reduced visibility and excessive particulate pollution. Understanding the cause of such extreme phenomena is important for further prevention. This study successfully reproduced the extreme dust storms using the Community Multiscale Air Quality model with refined bulk density of different soil types and improved spatial resolution. The wind-blown PM_{2.5} and PM_{10} are estimated to be around 15 and 120 µg m^{-3} in dust source areas (equal 9.6% and 31.0% in average of China), resulting in 1.1 and 2.0 times increases in PM_{2.5} and PM_{10} concentrations in populated regions of the Middle Yellow River Basin and the Beijing-Tianjin-Hebei area. The critical threshold friction velocity is the key parameter to judge whether wind-blown dust occurs. Dust flux is sensitive to the bulk soil density (increased by 4.2% and 12.6% for PM_{2.5} and PM_{10} after refined soil bulk density) and resolution (increased by 13.5% and 3.5% for PM_{2.5} and PM_{10} from 27 km to 9 km). Such results demonstrated the strong correlation between wind speed, frequency, and intensity of dust phenomena from 2013 to 2021. The wind speed can be further enhanced in dust source areas even in the context of a decline in the national average, leading to more frequent and persistent dust storms in March 2050. Only relying on coordinated emission reductions to mitigate climate change, wind-blown dust in northern China still poses considerable potential risks to air quality. Urgent actions should also be taken to improve land-use and land-cover to reduce the area of dust sources.

1. Introduction

Dust storms occur frequently in arid and semi-arid areas such as Northwest China (Shao et al 2013), leading to reduced visibility (Chepil 1957, Lee et al 2021), excessive particulate matter (PM) pollution (Solomos et al 2011, Fu et al 2014), and significant modulation on climate (Sokolik et al 2001, Huneeus et al 2011, Smoydzin et al 2012, Sun et al 2012). The dust event is an important source of PM_{10} pollution in northern China, accounting for more than 30% of the same and mainly originating from the Gobi Desert and the Taklimakan Desert (Wang et al 2006, Guan et al 2019, Zhou et al 2020). Particularly for the populated regions like Middle Yellow River Basin and the Beijing-Tianjin-Hebei regions which are located closely to the dust source region and already suffer from serious PM pollution concentration exceeding several times the World Health Organization (WHO) standard, the extreme dust storms will exert additional challenges on air quality and PM-related human health (Jun et al 2016, Baek et al 2017). Though the current ambient air quality standard in China excludes dust days in order to unavoidable
natural influences, the actual impacts of wind-blown dust are real and unneglectable.

Dust activities in Northwest China are primarily driven by the cyclones affecting the Taklimakan and Gobi Deserts (Shao et al. 2013), exhibiting high sensitivity to meteorological factors such as temperature, precipitation, and soil moisture (Kim et al. 2014, Krasnov et al. 2016, Lababpour 2020, Liu et al. 2020a). Series of studies have summarized the dust trend and its relationship with wind speed in historical years. Chen et al. (2008) found that the frequency of dust storms in Northwest China increased slightly in the 1970s compared with the 1960s due to the continuous expansion of desertified land, and has been decreasing from the 1970s to the 1990s due to the weakening of the East Asian monsoon. Yao et al. (2021), Li and Zhong (2007), and Chen and Tang (2005) agreed that wind speed dominated the variation of dust over the East Asian dust source regions and their downstream areas based on analysis of the past few decades. The meteorological condition may vary significantly in the context of future climate change, suggesting potential changes to wind-blown dust emissions in the future. There are few studies that reported the prediction of dust in the future, and most predict that the global or Asia’s dust emissions will tend to decline in the future (Tegen et al. 2004, Hong et al. 2019, Lu et al. 2020). Zhang et al. (2020) revealed that the Mongolian Plateau has fallen into a dangerous cycle of heatwaves and droughts, which are the two factors conducive to the occurrence of dust storms. There are also studies that predict from the perspective of the strength of solar activity that there will be more dust storms in Northwest China in the 21st century (Li et al. 2004, Li and Zhong 2007). The predictions thus depend on the design of climate scenario and are not yet conclusive. In general, dust on a global scale tends to decrease, while stronger dust weather may still occur on a regional scale.

Numerous empirical- or physical-based numerical models have been developed to simulate the dust emission and associated impacts (Appel et al. 2017, Zender et al. 2003, Han et al. 2004, Wang et al. 2012a, Fu et al. 2014). The models usually calculate the emission flux based on the threshold friction velocity and wind speed using different model parameterizations (Shao and Dong 2006), resulting in a nearly 8 times difference in global dust emissions (514–4313 Tg y\(^{-1}\)) (Huneeus et al. 2011). A dust model Intercomparison project over Asia reported a 2–4 times difference in estimated maximum dust concentration (diameter < 20 µm) among eight dust models during two huge dust episodes in 2002 (Uno et al. 2006). So overall various models over the years have been used to simulate dust and the magnitude of dust reported may vary by a large degree.

Previous studies suggest that improved resolution of simulating domain may contribute to the model performance by capturing more details of the wind vector (Ming and Westphal 2001, Liu et al. 2003, Ridley et al. 2013). Regional models have added advantage of covering a wider domain apart from the ability to simulate very fine domain size. As a well-developed regional air quality model, the Community Multiscale Air Quality (CMAQ) model distributes dust particles into 19 aerosol species, simulates the emission, transformation, transport, and fate of the many different air pollutant species that comprise PM, including dust (Appel et al. 2013), exhibiting great advantage in examining natural dust and anthropogenic aerosols on air quality and regional climate (Appel et al. 2017, Fu et al. 2014, Dong et al. 2016), and thus was chosen in this study. Unfortunately, the underestimation of dust in CMAQ is frequently reported (Fu et al. 2014). The dust module in CMAQ has been constantly updated to narrow the degree of underestimation of wind-blown dust (Fu et al. 2014, Kok et al. 2014, Dong et al. 2016, Foroutan et al. 2017). However, its performance in representing wind-blown dust emissions in Northwest China is uncertain, which may be improved with localized parameters.

On 15 March 2021, northern China experienced the most intense and wide-ranging dust storm in the past 10 years due to the favorable thermal and dynamic conditions (Zhang 2021a), which aroused widespread concern and can be a good case for evaluating the model performance of CMAQ dust module, quantifying and projecting the wind-blown dust impacts in northern China. Based on the 2 °C and 1.5 °C warming targets under the Paris Agreement, China will meet the current air quality standards in Europe and the United States by 2050 (National Development and Reform Commission 2020). However, current policies focus on emission reduction and energy transition while ignoring the potential impact of natural dust (Luo 2020). Exploring the contribution of dust to PM in 2050 will help formulate more reasonable policies to reach pollutant standards.

This paper is organized as follows: section 2 describes research methods; section 3.1 analyses the results of dust reproducing during March 2021 using the CMAQ model; section 3.2 describes historical and future trends of wind-blown dust and their impact. The summary and conclusion are given in section 4.

2. Method

2.1. Model configuration

The CMAQ (version 5.3) model configured with the AERO6 aerosol module and the CB6 gas-phase chemical mechanism was used to estimate the wind-blown dust emissions and simulate the pollutant concentrations (Byun 1999). Detailed wind-blown dust emission treatment is described in Foroutan et al. (2017) and supplementary materials. The vertical dust flux is calculated as equation S1 (available online at stacks.iop.org/ERL/16/114041/mmedia), where u,
is friction velocity, and is positively correlated with the wind speed at 10 m (WS10).

The bulk soil density $\rho_s$ is set to 1000 kg m$^{-3}$ in CMAQ for all soil types (Foroutan et al 2017) because a change in $\rho_s$ does not have much effect on the vertical dust flux (Kang et al 2011). But this default value is too small for China regardless of soil types (Wen-Jie et al 2011, Han et al 2012, Yu et al 2015, Chai and He 2016, Guo et al 2019). Therefore, we decided to use 1550, 1350, 1450, and 1300 kg m$^{-3}$ for $\rho_s$ of sand, loam, sandy clay loam, and clay, respectively, in this study (Amer 2010, Yu et al 2015).

The Weather and Forecasting (WRF, version 4.2) model was used to simulate meteorological fields needed by CMAQ. The Model of Emissions of Gases and Aerosols from Nature (MEGAN, version 2.10) (Guenther et al 2012) was used to calculate biogenic volatile organic compound (VOC) emissions. The Meteorology-Chemistry Interface Processor (version 5.1) (Otte and Pleim 2010) was used to process meteorological data in the format required by the MEGAN and CMAQ. Land-use and land-cover (LULC) types and soil data come from the Moderate Resolution Imaging Spectroradiometer (MODIS). The year-specific leaf area index (LAI) data are from the 8 day MODIS LAI product (MOD15A2) (Hu et al 2017).

The modeling domain 1 (d01) covers East Asia, northern Southeast Asia, and northeastern India with a 27 km $\times$ 27 km grid resolution, the nest domain 2 (d02) mainly includes northern China with a 9 km $\times$ 9 km grid resolution, as shown in figure 1. Two populated regions, the Middle Yellow River Basin and the Beijing-Tianjin-Hebei region and locations of 427 major dust source grids (red) with the total monthly (March 2021) dust emission exceeding 200 t are marked. A Lambert projection with the domain origin of 34 °N, 110 °E and with two true latitudes of 25 °N and 40 °N was used (Zhao et al 2013). The vertical domain is divided into 23 layers (from 201 300–1000 Pa). A five-day simulation spin-up was performed to minimize the effects of initial conditions as in previous studies (Street et al 2007, Wang et al 2012b, Ding et al 2019, Liu et al 2019, 2020b). The main parameter settings of the WRF-CMAQ model are listed in table S1.

2.2. Simulation period and scenario design

The simulation periods cover March in the base year (2021) and future (2050) years under two shared socioeconomic pathways (SSP) scenarios (i.e. SSP126 and SSP585) developed by the Intergovernmental Panel on Climate Change (Bruyere et al 2015). The analysis of meteorological (the National Centers for Environmental Prediction Final Operational Global Analysis data, noted as FNL data) and observation data for the upper air and surface for base years (2013–2021) is based on the National Centers for Environmental Prediction datasets (dataset ds083.3, ds351.0, and ds461.0). The grid-nudging four-dimensional data assimilation method is used to approximate the reanalysis data for base year simulations. The climate goal for SSP126 is to stabilize the radiative forcing at 2.6 W m$^{-2}$ by 2100 under the path of sustainable development, and for SSP585 is to stabilize the radiative forcing at 8.5 W m$^{-2}$ by 2100 under the development path based on fossil energy. The results of a single climate model lack representativeness due to the large differences in the sensitivity of current climate models to radiative forcing from anthropogenic sources (Deser et al 2012). Therefore, this study uses the ensemble of five climate models in the sixth phase of the Coupled Model Intercomparison Project (Rasmussen et al 2011, 2014, Liu et al 2017, 2021) as a reference for the meteorological condition in 2050 (average of 2048–2052), including BCC-CSM2-MR (developed by China National Climate Center), CNRM-CM6-1 (developed by French National Meteorological Research Center), EC-Earth3, IPSL-CM6A-LR and MRI-ESM2-0 (Liu 2020).

The anthropogenic emissions inventory for China developed by the Tsinghua group, includes pollutants such as NO$_x$, SO$_2$, PM$_{10}$, PM$_{2.5}$, OC, black carbon, VOCs, NH$_3$ as detailed by Zhao et al (2018) and Ding et al (2019) and CO downscaled based on the ECLIPSE v5a (Stohl et al 2015). The anthropogenic emission inventory in 2017 was used instead of in 2021, due to the lack of emission information for the year 2021. Same anthropogenic emission inventory is used in the base year and future year simulations to ensure that only the effects of climate variables are examined.

Ten simulation cases are designed in this study, as listed in table 1. Simulations for 2021 can be divided into two groups: 27 km $\times$ 27 km grid resolution (cn27) and 9 km $\times$ 9 km grid resolution (cn9). Each group includes three dust module settings: without dust (nodust), default dust (def), and revised dust (rev) modules. Simulations for 2050 with cn27 resolution include two dust module settings: nodust and rev for each SSP scenario.

2.3. Evaluation of model performance

We compared the simulation results in March 2021 with observation results (including wind speed and wind direction levels at 10 m (WS10 and WD10), temperature and humidity levels at 2 m (T2 and Q2), surface concentrations of PM$_{2.5}$ and PM$_{10}$) from the National Climatic Data Center (www.ncdc.noaa.gov/data-access/land-based-station-data/) and the China National Environmental Monitoring Centre (http://beijingair.sinaapp.com/). Table S2 lists the model performance statistics for meteorological and chemical variables and benchmarks proposed by Emery et al (2001) which have been widely applied in many regional air quality modeling studies (Zha et al 2013, 2017, 2018, 2019). The error level of the WRF and
Figure 1. The modeling domain (d01) with a grid resolution of 27 km (182 × 232 cells) and the locations of the nest domain (d02) with a grid resolution of 9 km (184 × 403 cells). Three typical regions are marked.

Table 1. Design of simulation cases. The abbreviations for all simulation cases are listed in the last column.

| No. | Year | Modification | Objective | Resolution | Noted |
|-----|------|--------------|-----------|------------|-------|
| 1   | 2021 | Not using dust module | Base case without dust to calculate the impact of dust emissions | 27 km | cn27-nodust |
| 2   | 27 km | Adding dust module with default parameters | Taking difference with cn27-nodust to calculate the degree of improvement using refined bulk soil density | 27 km | cn27-def |
| 3   | 27 km | Adding dust module with revised parameters | Taking difference with cn27-def to calculate the degree of improvement using refined bulk soil density | 27 km | cn27-rev |
| 4   | 9 km | Similar to cases to No.1–3 except that it uses 3 times the resolution to estimate the effect of resolution on model performance | Reference case for SSP126 | 9 km | cn9-nodust |
| 5   | 9 km | Using meteorological data for SSP126 without dust module | To give dust predictions for SSP126 | 9 km | cn9-def |
| 6   | 9 km | Using meteorological data for SSP126 with revised dust module | Reference case for SSP585 | 9 km | cn9-rev |
| 7   | 2050 | Using meteorological data for SSP126 without dust module | To give dust predictions for SSP126 | 27 km | SSP126-nodust |
| 8   | 27 km | Using meteorological data for SSP126 with revised dust module | Reference case for SSP585 | 27 km | SSP126-rev |
| 9   | 27 km | Using meteorological data for SSP585 without dust module | To give dust predictions for SSP585 | 27 km | SSP585-nodust |
| 10  | 27 km | Using meteorological data for SSP585 with revised dust module | To give dust predictions for SSP585 | 27 km | SSP585-rev |

CMAQ model is considered to fall within acceptable limits for this study. Detailed descriptions can be found in supplementary materials.

To evaluate the model performance while simulating the wind-blown dust, in addition to the surface PM$_{2.5}$ and PM$_{10}$ concentrations, we also compared the simulated aerosol optical depth (AOD) with the satellite retrieved AOD. The value of AOD can be estimated by the concentration of aerosol components obtained by model simulation (Pitchford and Malm 1994, In et al 2009, Zhang et al 2009). We use the following equation to calculate the total integrated AOD for 23 layers from CMAQ simulation:

$$AOD = \sum_{l=1}^{23} \left( \sigma_{sp,l} + \sigma_{ap,l} \right) \times \Delta z_l \quad (1)$$

where $\sigma_{sp,l}$ is the aerosol scattering coefficient (unit: m$^{-1}$) and $\sigma_{ap,l}$ is the aerosol absorption coefficient (unit: m$^{-1}$) in layer $l$. $z_l$ is the full-layer height above ground (unit: m) in layer $l$. $\sigma_{sp,l}$ and $\sigma_{ap,l}$ are calculated based on equation S2 and equation S3, respectively.

The model-estimated AOD will be compared with the observed daily and monthly mean total MODIS AOD which is from the level-3 land-corrected MOD08 productions at 550 nm with a grid resolution of 1° × 1°. We use the observation information from the TERRA satellite (transit time is approximately 10:30 local time), and take the average of 10 and 11 o’clock for comparison when calculating the model-estimated AOD.
3. Results and discussions

3.1. Reproducing the March dust storms in 2021 using the CMAQ model

According to the report from the China Meteorological Administration, affected by the Mongolian cyclone and strong cold air winds, dust storms occurred in northern China on 14–16 March 2021. The visibility was about 1 km, which reduced to less than 300 m in some areas. The PM$_{10}$ concentration in most areas exceeded 2000 $\mu$g m$^{-3}$ (CCTV 2021). The area affected by this dust storm as visible from the satellite was approximately 466 000 km$^2$ in China (China Meteorological Administration 2021). On 27–29 March, northern China experienced another strong dust storm of similar origin (People’s Daily Online 2021). The dust storm that occurred on 15 March aroused widespread concern and can be a good case for CMAQ dust simulations. Therefore, we simulated the pollution in March 2021 considering different dust module settings in the CMAQ model.

The no-dust simulation (cn27-nodust) generally largely underestimated the PM pollutants in northern China (48.9% of PM$_{2.5}$ and 55.5% of PM$_{10}$) (see figure S2). The default dust module of CMAQ (cn27-def) can capture the dust phenomenon in dust source areas which were mainly located in Mongolia and the Gobi Desert in Xinjiang province. The impact of dust on regional PM concentration is also quantified (see figure S3). The total monthly dust emission in d01 (covering whole China) reached 306.6 kt, resulting in an increased PM$_{2.5}$ and PM$_{10}$ concentration by 9.6% and 31.0%, respectively, in March 2021. Since the particle size of dust is mostly concentrated in the coarse mode, the contribution of dust to PM$_{10}$ is far greater than that of PM$_{2.5}$, and its impact area is also wider. Due to horizontal transport, its impact expanded to nearly half of China and even affected the Yangtze River Basin. The dust can increase the monthly average PM$_{2.5}$ and PM$_{10}$ concentration in d02 (covering northern China) by $\sim$15 and $\sim$120 $\mu$g m$^{-3}$, causing pollution to far exceed the WHO recommended values (24 h average concentration $< 25$ and 50 $\mu$g m$^{-3}$). Taking the severe dust storm on 15 March as an example, figures S3(d)–(f) respectively show the contribution of dust to PM$_{10}$ before, during, and after the dust storm day. The average daily concentration of PM$_{10}$ in dust source areas can reach 2000 $\mu$g m$^{-3}$.

The simulated AOD with dust module (cn27-def) coincides with the trend of the observed AOD on the time scale (figure 2(a)), implying the ability of the default dust module of CMAQ in identifying the dust event. The results show that the AOD values around 15 and 27 March were significantly higher than other periods, which coincided with the two dust storm periods released by China Meteorological Administration. The wind-blown dust increased the model-estimated AOD by about 0.1–0.4 in Northwest China. However, there is still a large underestimation (27.0%) in the default simulation (cn27-def). To improve the model performance, the simulation with refined dust module parameters (cn27-rev) was conducted, which resulted in a 39.2% increase in dust emission (426.8 kt) when compared with cn27-def.

Considering the actual soil situation in Northwest China, cn27-rev can make the dust simulation results closer to the observed level. The monthly average concentrations of PM$_{2.5}$ and PM$_{10}$ in Northwest China can be increased by $\sim$6 and $\sim$50 $\mu$g m$^{-3}$, which is equivalent to 4.2% and 12.6%, respectively, in domain average level (d01) compared with cn27-def. Hereafter, results for 27 km are from simulation cn27-rev unless stated otherwise. Even for non-dust source areas, such as the densely populated downstream areas Middle Yellow River Basin and the Beijing-Tianjin-Hebei region (marked in figure 1), the contributions of dust to monthly averaged PM$_{2.5}$ and PM$_{10}$ concentrations reached 17.7% (6.5 $\mu$g m$^{-3}$) and 8.9% (3.7 $\mu$g m$^{-3}$), 47.4% (56.3 $\mu$g m$^{-3}$) and 36.5% (43.8 $\mu$g m$^{-3}$) in the two regions, respectively, and even exceeded 50% (as for PM$_{2.5}$) and 80% (as for PM$_{10}$) on some days, which are much higher than on normal days (less than $\sim$20% and $\sim$30%). Days when dust storms occurred are aptly represented by peaks of dust-contributed percentage in both two regions, as shown in figure 2(b). The Middle Yellow River Basin is closer to dust source areas and has fewer anthropogenic emissions than Beijing-Tianjin-Hebei (Huang et al 2021), so the proportion of dust-contributed PM concentrations are higher. Dust-contributed PM concentrations are usually instantaneous and can reach several times that of anthropogenic. After the occurrence of dust storm in source areas, the contribution to the downstream areas will continue for a period of time.

The improvement in the spatial resolution from 27 km (cn27-rev) to 9 km (cn9-rev) further increased dust emission by 5.3%, and made the AOD close to the observed value (figure 2(a)). Figure 3 compared the distribution of improvements from cn27-def to cn9-rev. Table S3 lists the average concentration of dust-contributed PM$_{2.5}$ and PM$_{10}$ and the difference from 27 km to 9 km resolution. After increasing the resolution by 3 times, the concentration of dust-contributed PM$_{2.5}$ and PM$_{10}$ may increase by $\sim$13.5% and $\sim$3.5% respectively.

Such results suggest the success of reproducing the extreme dust storms with the CMAQ model with refined bulk density of different soil types and improved spatial resolution.

This study uses constant LULC types and soil data, so the vertical dust flux is only related to WS10. The simulation of wind-blown dust is very sensitive to model resolution which needs to be as fine as possible to capture the details and strength of wind. The increase of dust simulation in cn9 is related to the fact that finer resolution can retain more vector wind
Figure 2. Daily average (a) simulated and observed AOD in d02 and (b) percentage of dust-contributed PM$_{2.5}$ and PM$_{10}$ to total PM in two populated regions in March 2021.

Figure 3. Distribution of total monthly dust flux (first row) and dust-contributed PM$_{2.5}$ (second row) and PM$_{10}$ (third row) concentrations 27 km × 27 km (first column) and 9 km × 9 km resolution (second and third columns).

details, which was proved in figure S4. A higher resolution simulation can reproduce more extreme vector wind, thereby having a larger friction velocity value and consequently more dust fluxes. We compared the simulation results of WS10 and friction velocity in d02 between 27 km and 9 km resolutions. In general, the WS10 simulated with two resolutions are similar, but the percentage of numbers with hourly average WS10 > 4 m s$^{-1}$ is 2.3% higher in cn9 and the maximum hourly average WS10 captured by cn9 is 1.1 times that of cn27. Mean and maximum friction velocity calculated by cn9 is also larger than that of cn27.

The China Meteorological Administration reported that temperatures in Mongolia and Northwest China rose in March, low precipitation along with suitable surface conditions provided a conducive environment for the occurrence of dust storms. Taking the dust storm that occurred in northern China on 15 March 2021 as an example, the strong cyclone in Mongolia provided good thermal and dynamic conditions for the occurrence of a dust storm (Zhang 2021a). To characterize the relationship between dust flux and wind speed, we extracted the average friction velocity (noted as U$^{*}$) of major dust source grids (noted as dust-grids, 427 in total, marked red in figure 1) with the total monthly dust emission exceeding 200 t to represent grids of dust source. We determine whether a grid should be included in dust-grids according to the contour gradient of the total monthly dust flux. The gradient becomes dense when it exceeds 200 t, as shown in figure S5(a). The dust-grids although account for less than 10% of the total number of grids that have generated dust flux, but they contribute more than 60% of the dust flux.
Figure 4. Daily average (a) wind speed in dust-grids and (c) dust-contributed concentration of PM$_{10}$ in Middle Yellow River Plain, and (b) total dust emission in d01 in March 2021.

(see figure S5(b)). We also estimate the daily average $U^*$ to compare the changes of $U^*$ over time. The trend of daily average $U^*$, dust emission in China and dust-contributed concentrations of PM$_{10}$ in the Middle Yellow River Basin are correlated with each, as shown in figure 4. That is because the dust emission and its contributed PM are directly related to friction velocity. This provides us with an idea for studying long-term dust phenomena: to determine the wind speed threshold during the period of dust occurrence, and to estimate the dust flux by counting the frequency and degree of wind speed exceeding the threshold over the years.

On basis of our comparison of dust and non-dust days in March 2021, we assumed the total daily dust emission of 30 kt as the threshold, and the corresponding daily average $U^*$ are 0.15 and 0.22 m s$^{-1}$, which can be used to divide into three levels: no dust ($U^* < 0.15$), moderate dust ($0.15 < U^* < 0.22$), and dust storm ($U^* > 0.22$). Note that the daily average $U^*$ is usually less than the ideal threshold friction velocity, because not all grids have dust flux at the same time. The value of friction velocity for each grid is determined by WS10 and surface roughness length, and we found that the average WS10 is about 27.2 times $U^*$ in dust-grids. Results suggest that when the daily average WS10 in dust-grids exceeds 4 m s$^{-1}$, moderate dust may occur, and when it exceeds 6 m s$^{-1}$, dust storm is likely to occur. The dust storm period also overlaps with the severe pollution period announced by the government, implying the credibility of the simulation results. The high value of dust-contributed PM$_{10}$ concentration in the Middle Yellow River Basin is delayed compared to in dust-grids, which represents the horizontal transmission of dust emissions from source to downstream. Apparently, wind speed is the most important meteorological factor which determines the calculation of the dust emission flux in the CMAQ model as well as the transport of pollutants from dust source areas to surrounding regions. It is reasonable to use wind speed to estimate wind-blown dust, which can consider both vertical dust emission flux and horizontal transportation.

3.2. Historical and future trends of wind-blown dust

To further verify the correlation between wind speed and dust flux, we compared the data of historical years. We analyzed the historical trend of wind-blown dust by using the WS10 to approximate the situation of dust emission.

The frequency of simulated hourly average WS10 in dust-grids was counted for March of the past 8 years from 2013 to 2021, as shown in figure 5. We also counted the frequency and duration of observed dust occurrences of different intensities in March from 2013 to 2018 recorded in the yearbook, as listed in table S4. In 2014, 2017, and 2019, the percentage of WS10 $> 4$ m s$^{-1}$ was the highest, and the yearbook did not record the occurrence of dust storm. A higher proportion of hours of high wind speed (WS10 $> 6$ m s$^{-1}$) may lead to frequent or stronger dust storms. Particularly in March 2021, the average
and maximum WS10 reached 4.44 and 10.97 m s\(^{-1}\) in dust-grids, respectively, which were also the highest value, implying the strongest wind-blown dust in past 8 years. Based on the simulated wind speed, the wind-blown dust trend in historical years is consistent with the yearbook record, indicating the rationality of using wind speed to predict the trend of wind-blown dust.

For future projections under global warming, both temperature and specific humidity tend to rise significantly. The average annual temperature of SSP585 in China is about 0.66 K higher than that of SSP126, while the average specific humidity of SSP585 is 0.044 g kg\(^{-1}\) higher than that of SSP126. The temperature increased the most in spring (by 0.82 K) corresponding to the dust season. The average WS10 in China in March 2050 is 0.1 m s\(^{-1}\) lower than that in 2021, but in dust-grids is 0.2 m s\(^{-1}\) higher than the average value from 2013 to 2021, and even higher than extreme dust year 2021, as shown in figure S6(a). The proportion of high WS10 (>6 m s\(^{-1}\)) in dust-grids reached 12.1% in 2050, higher than the 2013–2021 average value of 8.6%, which means that there is a greater possibility of higher intensity, wider range, longer duration dust phenomena in 2050. The difference in WS10 between SSP126 and SSP585 scenarios is very small (the latter is slightly lower), as shown in figure S6(b). This suggests that under the SSP scenario, the circulation status in 2050 predicted by different emission control policies is similar and is developing towards an unfavorable direction in terms of dust source areas. The SSP126 scenario, with a greater reduction of carbon emissions, has more extreme WS10 in dust-grids. As for SSP585, more greenhouse gas emissions and an increase in temperature may result in a smaller average wind speed, which is consistent with the research conclusions of Jiang et al. (2018) and Ming et al. (2006).

The changing WS10 in 2050 directly causes changes in dust emissions, as shown in figures 6(a) and (b). The dust emission fluxes in March under two scenarios will reach 1.54 and 1.41 Mt, respectively, which are much higher than the 2021 level. The only factor driving the simulation changes of dust emission fluxes in 2050 from 2021 is the wind speed conditions in the meteorological field. Due to the uncertainty of the future circulation, there is a possibility that the overall average wind speed decreases while it might increase in some areas in the future. Since the areas where WS10 increases in 2050 intersect with dust-grids, the final simulated dust emission fluxes in 2050 tend to be significantly higher than the base year. With the proposal of ‘carbon neutrality’, the SSP126 scenario is more likely to occur than the SSP585 scenario. We calculated the monthly average dust-contributed concentrations of PM\(_{2.5}\) and PM\(_{10}\) under the SSP126 scenario, which can reach ~40 and ~300 µg m\(^{-3}\), respectively, in dust source areas, as shown in figures 6(c) and (d). In the Middle Yellow River Basin and the Beijing-Tianjin-Hebei region,
the contribution of dust to monthly averaged PM$_{10}$ concentration reached 61.1% (126.2 µg m$^{-3}$) and 45.3% (88.2 µg m$^{-3}$), respectively, larger than in 2021. Similarly, such percentages for PM$_{2.5}$ in the two regions increase to 29.0% (16.4 µg m$^{-3}$) and 15.9% (9.5 µg m$^{-3}$), respectively. In conclusion, concentrations of dust-contributed PM$_{2.5}$ and PM$_{10}$ in 2050 have more than doubled from 2021.

The generation of dust storms requires dust sources, unstable thermal and dynamic conditions. Both the Chinese and Mongolian governments have been investing substantial resources into fighting desertification thus resulting in reduced frequency and strength of dust storms in northern China from 2012 to 2019 (Xinhua 2020). Although the desertification environment is an indispensable factor for the formation of dust storm (Qian et al 2006), atmospheric circulation is also one of the key factors which affect the occurrences of dust storm (Mao et al 2005). This is also the reason why strong dust storms in 2021 occurred despite substantial work on desertification control. The thermal conditions of high temperature and drought in Northwest China may remain the same or even worsen in the future (Stocker et al 2013). Global warming may help reduce global wind speed levels from the perspective of long-term circulation, but more frequent extreme weather may also result in a more violent collision of cold and warm fronts on the Mongolian Plateau. China may have entered a new cycle of strong winds in 2021 (Zhang 2021b), and it is best to be alert to the hazards of potential sandstorms. More relevant research is worthwhile.

Since in this study, the LULC types is considered to remain unchanged over the years, our results might seem to paint a more pessimistic picture. We found that future climate changes are still likely to cause an increase in dust emissions. Dust phenomena may be more frequent and last longer in 2050 due to temporarily unfavorable circulation conditions. Without changing the LULC types and anthropogenic emissions, only natural dust emissions may cause high PM concentrations in the future spring. Thus, the 'let us go with the flow' attitude may result in increased extreme weather in the future and cause worsening air pollution. Only relying on coordinated emission reductions to mitigate climate change to avoid extreme weather is not enough. Urgent actions should also be taken to improve LULC to reduce the area of dust sources. China and Mongolia governments still need to continue to cooperate to advance the work of combating desertification.

4. Summary

In this study, we refined the bulk density of different soil types in the CMAQ model and analyzed dust emissions and related PM concentrations during March 2021. The total monthly dust emission in whole domain reached 306.6 kt and further...
increased by 39.2% after the refinement of parameters. Dust-contributed PM$_{2.5}$ and PM$_{10}$ concentrations are around 15 and 120 µg m$^{-3}$ in dust source areas (equal 9.6% and 31.0% in domain average level of China) in cn27-def, and further increase by around 6 and 50 µg m$^{-3}$ after refinement of bulk soil density (equal 4.2% and 12.6% in domain average level of China) in cn27-rev, respectively. The monthly average contribution of dust to PM$_{10}$ concentration reached 47.4% and 36.5% in the Middle Yellow River Basin and the Beijing-Tianjin-Hebei region, respectively, and even exceeded 80% on some days. Our revised dust module in CMAQ should be mechanically reliable.

After increasing the model resolution by 3 times, total monthly dust emissions in d02 is 423.5 kt in cn9-rev simulation, which is 402.2 kt in 27 km resolution (cn27-rev). The concentration of dust-related PM$_{2.5}$ and PM$_{10}$ thus may increase by around 13.5% and 3.5%, respectively, which is related to the fact that finer resolution can retain more vector wind details. Our simulation results of wind speed from 2013 to 2018 show a strong correlation with the number and intensity of dust phenomenon recorded in the yearbook. Increasing the model resolution as much as possible is an effective method to obtain a simulation closer to the observation.

We also predict the response of dust emissions due to future climate change under two SSP scenarios (i.e. SSP126 and SSP585) with an ensemble of five climate models. The difference in wind speed between SSP126 and SSP585 scenarios is very small, while wind speed tends to increase in dust source areas in both scenarios compared with 2021. Dust phenomenon may thus become more frequent and last longer in March 2050. The dust emission fluxes in March under two scenarios will reach 1.54 and 1.41 Mt, respectively, which are much higher than the 2021 level (near 2018 show a strong correlation with the number and intensity of dust phenomenon recorded in the yearbook. Increasing the model resolution as much as possible is an effective method to obtain a simulation closer to the observation.

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Thus, without changing the types of LULC and anthropogenic emissions, only natural dust may cause high PM concentrations in the future spring. It is therefore urgent to improve LULC in order to shrink dust source areas and mitigate climate change to avoid extreme weather which aids in worsening dust-contributed air pollution. International cooperation to deal with extreme weather and dust pollution is thus required to be undertaken on a priority.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

This work was supported in part by the National Key R & D program of China (2017YFC0213005 and 2018YFC0213506), and the National Natural Science Foundation of China (4190070530 and 51861135102). This work was completed on the ‘Explorer 100’ cluster system of Tsinghua National Laboratory for Information Science and Technology.

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