Studies on a Severe Dust Storm in East Asia and Its Impact on the Air Quality of Nanjing, China

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ABSTRACT

Long-range transport of dust aerosol has severe impact on the atmospheric environment over vast areas. In this study, the features of a severe dust storm and its transport characteristics were investigated during the period from 28 April to 5 May 2011 in East Asia. The combined impact on Nanjing was studied with the observational PM10, PM2.5, visibility and meteorological data, and the numerical models of HYSPLIT and WRF/Chem. This dust storm was caused by a cyclone on 28 April over arid and semiarid areas in Mongolia and China, and then transported to broad downwind areas including northern, central, and eastern parts of China, the Korean Peninsula, and Japan. Among the available data, the highest hourly PM10 concentration reached 3.916 mg/m3 at Jinchang site near the source area. In East China, the coastal cities had poorer air quality than inland ones for two days. Dust aerosol arrived at Nanjing from the northwest, and then north, owing to the movement of synoptic system, mixed with local anthropogenic emissions, resulting in the highest PM10 concentration of 0.767 mg/m3 with PM2.5 level reaching 0.222 mg/m3. As the dust storm gradually turned eastward, the dust aerosol went over the seas in the east of the continent and then flowed back to Nanjing. Numerical simulations showed that dust aerosol affecting East China was mainly transported below the altitude of 2.5 km. The vertical profiles of PM10 and PM2.5 concentrations showed maxima at the altitude between 0.2 km and 1.3 km.

Keywords: Dust storm; Particulate matter; Transport path; Hysplit; WRF/Chem.

INTRODUCTION

There is a broad “dust belt” in the Northern Hemisphere from North Africa to East Asia where the largest and most persistent sources are located (Prospero et al., 2002). A number of studies on chemical, microphysical and optical properties of dust aerosols and the homogeneous or heterogeneous formation on dust aerosols have been carried out in last twenty years (Zhuang et al., 1992; Mori et al., 2002; Zhang et al., 2003; Schmechtig et al., 2011; Shen et al., 2011). Dust aerosol has implications for climate change mainly by direct and indirect radiative forcings (Sokolik and Toon, 1996; Winckler et al., 2008; Yue et al., 2009; Wu et al., 2010). Dust aerosol lifted into atmosphere and deposited to oceans can affect global biogeochemical cycles (Zhuang et al., 1992), and human health (Chen et al., 2004) as well. Dust storm events are divided into four types: severe dust storm, dust storm, blowing dust, and floating dust (Wang et al., 2005). Monitoring systems include remote sensing by satellite (Husar et al., 2001; Prospero et al., 2002; Huang et al., 2007) and lidar (Sugimoto et al., 2005) and synoptic observations. Much progress has been made in dust storms modeling and prediction, understanding and quantifying the dust processes and their impact on environment and climate (Han et al., 2004; Har et al., 2006; Shao et al., 2006; Zhao and Hao, 2006; Liu et al., 2011).

There are a number of sources in northeastern Asia including the Taklimakan Desert, Gobi (gravel), the Badain Jaran Desert, and the Loess Plateau (Dong et al., 2000; Prospero et al., 2002; Wang et al., 2008; Yang et al., 2009). Asian dust aerosols can be transported to vast downwind areas including large portions of China (Zhang et al., 2003; Han et al., 2004; Li et al., 2011; Liu et al., 2011; Zhao et al., 2011), Korean Peninsula (Stone et al., 2011), Japan (Mori et al., 2002), North Pacific (Gao et al., 1992), North America (Husar et al., 2001), and even the Arctic (Bory et al., 2002) and mixed with various aerosols during the long-range transport (Fan et al., 1996; Mori et al., 2003). Pure cold front, Mongolia cyclone and cold front, Mongolia high and cold front, and dry squall line are four important weather types for super severe dust storms (Zhang et al., 2010).

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With an area of 6600 km², a population of 8 million and over 1 million automobiles, Nanjing is one of the important megacities in the region of Yangtze River Delta. The rapid economic development and urbanization have caused poor air quality and visibility degradation during the past two decades (Deng et al., 2011). Dust storms, besides biomass burning (Li et al., 2010), fireworks setting, and general anthropogenic activities accompanied by unfavorable weather conditions (Xiao et al., 2011), can cause severe air pollution problems with high particular matter concentrations. The severe dust storm occurred on 28 April to 5 May 2011 in East Asia showed strong long-range transport as it swept Mongolia, northern, central, and eastern parts of China, Korean Peninsula, and as far as Japan. It seriously impacted air quality in Nanjing and adjacent cities for several days.

In this paper, we analyzed the features of the severe dust storm and its long-range transport during April 28 to May 5, 2011 in East Asia with observational data, and then reproduced the process by numerical simulations with HYSPLIT model and WRF-Chem model to study the spatial distribution and temporal evolution as well as its impact on Nanjing.

DATA AND METHODOLOGY

Observational and Reanalysis Data

Various meteorological and atmospheric environmental data were used to analyze the spatial distribution and temporal variation of this dust storm event. 3-hourly data records at surface stations in East Asia were documented on weather maps of the Meteorological Information Comprehensive Analysis and Process System (MICAPS). Daily average PM₅₀ concentrations at a number of monitoring sites of each Chinese province were deduced from Air Pollution Index (API) through a standard formula prescribed by the State Environmental Protection Administration (SEPA) of China and local environmental protection agencies (Bian et al., 2011). Hourly PM₁₀ concentrations at 120 sites of China were derived from the China National Environmental Monitoring Center (CNEMC). Hourly visibility observations and soundings at major cities of China were derived from the web of University of Wyoming (http://www.weather.uwyo.edu/). Hourly PM₁₀ and PM₂₅ concentrations and visibility observations at Nanjing site were obtained on the roof of a 24-storey building (118°46'29"E, 32°3'20"N) about 80 meters high in Gulou Campus of Nanjing University. 24-hour accumulated precipitation data at Chinese and global surface stations were from China Meteorological Data Sharing Service System and the web of NOAA (ftp://ftp.ncdc.noaa.gov/pub/data/gsod), respectively. Meteorological data at Nanjing were obtained from M3552 automatic weather station (118.769°E, 32.725°N).

6-hourly Final (FNL) Operational Global Analysis data with 1° x 1° resolution from the National Center for Environmental Prediction (NCEP) were used for diagnostic analysis and initial and boundary conditions of WRF-Chem.

Numerical Models

HYSPLIT Model

Online HYSPLIT model of NOAA Air Resources Laboratory (http://ready.arl.noaa.gov/HYSPLIT.php) was used to calculate the trajectories of air parcels to analyze the sources and pathway of dust aerosols with 1° x 1° resolution meteorological data. There are three types of trajectories can be calculated: normal, matrix, and ensemble. Trajectory Matrix is used to calculate trajectories from a matrix distribution of locations of a region, while Trajectory Ensemble is used to calculate multiple trajectories from one location by all-possible offsets in X, Y, and Z. The resolution of the meteorological field is one of the factors causing the modeling uncertainty. Therefore, Trajectory Ensemble was used to calculate all-possible trajectories at one point to reduce the uncertainty.

WRF/Chem Model

Weather Research and Forecasting/Chemistry model (WRF/Chem) version 3.2.1 was used to simulate the outbreak and transport process of dust and its impact on Nanjing with 4 nested domains. The model is one of the currently available models to investigate air quality and dust problems. This fully coupled meteorology-chemistry community model is developed by NOAA together with some other research institutions. At present, it is still under active development (Grell et al., 2005). It is suitable for simulating the chemistry, aerosols and dust from local to global scales. The meteorological and chemical sub-models are fully coupled online and they: (1) use the same horizontal and vertical coordinates, (2) use the same physical options, (3) there is no temporal interpolation and (4) there are feedbacks between the chemical and physical interactions (Jiang et al., 2012). The chemical sub-model contains both physical and chemical processes. It includes convective and advective transport of chemical; anthropogenic and biogenic emissions; dry and wet depositions; photolysis, gas and aqueous phase modules; aerosol chemistry and dynamics as well as the aerosol direct and indirect effects. Generally, it is suitable for use in a broad spectrum of applications across scales ranging from meters to thousands of kilometers. Simulations and real-time forecasting tests have indicated that the WRF model has a good performance on weather forecasts, and has broad application prospects (e.g., Done et al., 2004; Koch et al., 2004). The model configuration and domains designed in this study is shown in Fig. 1 and Table 1. The first domain is from 65.5° to 170.5°E, and 2.9° to 59.3°N with 81 km x 81 km horizontal grid resolution, including almost East Asia. The second domain is from 106.2° to 132.6°E, and 21.3° to 38.6°N with 27 km x 27 km horizontal grid resolution, including coastal areas of east and south China, and part of Korean Peninsula and Japan. The third domain is from 116.3° to 123.3°E, and 29.4° to 34.7°N with 9 km x 9 km horizontal grid resolution, including the whole Yangtze River Delta region. The forth domain is from 117.9° to 119.7°E, and 31.1° to 32.9°N with 3 km x 3 km horizontal grid resolution, including the whole administrative region of Nanjing City. 27 vertical layers stretch unequally from the ground to 100 hPa. Asian emission inventory in 2006 (Zhang et al., 2009), paved road dust emission estimated by AP 42 Emission Factors Model (US EPA, 2006 (Zhang et al., 2009), paved road dust emission estimated by AP 42 Emission Factors Model (US EPA, 2006).
Fig. 1. Nested domains of WRF/Chem model.

Table 1. WRF/Chem domain setting and configuration options.

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<th>DM 1</th>
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<th>DM 4</th>
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<tr>
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<td>RADM2 and MADE/SORGAM</td>
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SURFACE DUST-RISE AND METEOROLOGICAL OBSERVATIONS

Surface Dust-rise Observations in East Asia

From 28 April to 5 May, 2011, there was a dust storm remaining over East Asia for several days. Fig. 2 shows observed high PM$_{10}$ concentrations at Chinese sites and documented dust weather over East Asia. Fig. 3 presents the time series of surface PM$_{10}$ concentrations at Jinchang (102.10°E, 38.28°N), Baotou (109.49°E, 40.39°N), Chifeng (118.58°E, 42.17°N), Zhangjiakou (110.29°E, 29.08°N), Luoyang (112.27°E, 34.41°N), and Qingdao (120.33°E, 36.07°N) monitoring sites, China, as labeled in Fig. 1. Fig. 4 shows the spatial distribution and temporal evolution of PM$_{10}$ concentrations gridded by MATLAB v4 method (Sandwell, 1987) over East China. The dust storm was initiated from northwestern China and southern Mongolia on 28 April, 2011 (Fig. 2(a)), and then moved to broad downwind areas, lasting about 7 days, mainly influencing northern, central and eastern parts of China, Korean Peninsula and western Japan. The Jinchang, Baotou and Chifeng
Fig. 2. Observed high 24-hourly average PM$_{10}$ concentrations at Chinese sites and documented dust weather over East Asia during (a) 0400 UTC 28 April to 0400 UTC 29 April, (b) 0400 UTC 29 April to 0400 UTC 30 April, (c) 0400 UTC 30 April to 0400 UTC 1 May, (d) 0400 UTC 1 May to 0400 UTC 2 May, (e) 0400 UTC 2 May to 0400 UTC 3 May, and (f) 0400 UTC 3 May to 0400 UTC 4 May.

sites located along northern part of China observed high PM$_{10}$ concentrations sequentially in the first three days with maxima reaching 3.916 mg/m$^3$, 1.996 mg/m$^3$, and 1.813 mg/m$^3$, respectively (Fig. 3), indicating that the dust storm would sweep a large portion of northern China (Fig. 2(b)). The Luoyang site located in central China, the Zhangjiajie site located in a scenic area in central southern China, and the coastal Qingdao site observed maximum PM$_{10}$ concentrations in the following days in turn, reaching 0.844 mg/m$^3$, 0.334 mg/m$^3$, and 0.823 mg/m$^3$, respectively (Fig. 3), indicating that the dust storm had influenced broad downwind areas of China and would also transport to downwind countries continuously (Fig. 2(c)). East China, Korean Peninsula, and Japan observed suspended dust from the fourth day to the seventh day (Figs. 2(c) to 2(f)). Cities in northern and western East China were firstly influenced (Fig. 4(a)). Continuous higher PM$_{10}$ concentrations at the coastal cities in East China were observed compared to inland cities, especially Shanghai with daily average PM$_{10}$ concentrations higher than 0.600 mg/m$^3$ (Figs. 4(b) and 4(c)). As Yangtze River Delta region was one of the three major economic zones with mature urban construction, the significant urban canopy effect and other planetary boundary layer meteorological feathers made the high concentrations of dust aerosols diffuse more difficulty and thus led to higher PM$_{10}$ than in non-urban areas. The impact of the dust storm on East Asia gradually weakened on the seventh day (Figs. 2(f) and 4(d)).
Fig. 3. Time series of observed PM$_{10}$ concentrations at Jinchang (102.10°E, 38.28°N), Baotou (109.49°E, 40.39°N), Chifeng (118.58°E, 42.17°N), Zhangjiajie (110.29°E, 29.08°N), Luoyang (112.27°E, 34.41°N), and Qingdao (120.33°E, 36.07°N) monitoring sites of China from 0000 UTC 27 April to 2300 UTC 6 May, 2011.

Fig. 4. Gridded observed 24-hourly average PM$_{10}$ concentrations at intense sites over East China during (a) 0400 UTC 30 April to 0400 UTC 1 May, (b) 0400 UTC 1 May to 0400 UTC 2 May, (c) 0400 UTC 2 May to 0400 UTC 3 May, and (d) 0400 UTC 3 May to 0400 UTC 4 May.
**Temporal Variation of PM and Visibility**

**Temporal Variation of PM$\text{_{10}}$, PM$\text{_{2.5}}$, and Visibility in Nanjing**

The dust storm affected Nanjing for several days and caused severe degradation of air quality. Fig. 5 presents the time series of PM$\text{_{10}}$, PM$\text{_{2.5}}$, reciprocals of visibility, and the ratio of PM$\text{_{2.5}}$ to PM$\text{_{10}}$ during dust period; the relationship between visibility and PM$\text{_{2.5}}$. The dust-affecting process from 1200 UTC 30 April to 0500 UTC 4 May could be divided into three peaks, two platforms, and one interruption. Platform periods could be seen as time of a little fall of PM$\text{_{10}}$ after the peak periods with high mean PM$\text{_{10}}$ and PM$\text{_{2.5}}$ reaching approximately 0.300 mg/m$^3$ and 0.100 mg/m$^3$, respectively. During three peaks periods, the mean PM$\text{_{10}}$ and PM$\text{_{2.5}}$ were over 0.300 mg/m$^3$ and 0.090 mg/m$^3$, respectively. PM$\text{_{10}}$ maximum appeared in the second peak period, reaching 0.767 mg/m$^3$, with PM$\text{_{2.5}}$ level reaching 0.222 mg/m$^3$. There was an interruption time around 0080 UTC 3 May between the second platform and the third peak with characteristics of air quality similar to those of non-dust-affecting periods. As all the peaks arrived around 1200 UTC (local time 20 p.m.), it was difficult for PM$\text{_{10}}$ and PM$\text{_{2.5}}$ to diffuse due to the stable atmospheric stratification at night, leading to the simultaneous increase of concentrations. During non-peak periods, the ratio of PM$\text{_{2.5}}$ to PM$\text{_{10}}$ fluctuated substantially from 0.40 to 0.80, indicating that in which time random anthropogenic emission dominated. On the contrary, during peak periods, the ratio came down below 0.40 and stayed steady, indicating that dust aerosols with a large proportion of coarse particles were the main factors. The absolute value of slope in fitting visibility to PM$\text{_{2.5}}$ during dust affecting period was a little lower than that during non-dust affecting period. PM$\text{_{2.5}}$ below 0.100 mg/m$^3$ may degrade visibility to below 3 km during non-dust affecting period. However, only high PM$\text{_{2.5}}$ around 0.200 mg/m$^3$ could degrade visibility to 3 km during dust affecting period. The chemical components in PM$\text{_{2.5}}$ such as sulfate and nitrate are considered to be sensitive species to visibility variation (Yuan et al., 2006). Therefore, it can be inferred that local anthropogenic emissions dominated the visibility degradation, and the additional dust aerosols played a little role in degrading visibility.

**Comparisons of PM$\text{_{10}}$ and Visibility in Cities of East China**

Most of the cities in East China including Nanjing suffered...
from this dust storm. Fig. 6 presents the time series of observed PM$_{10}$ and reciprocals of visibility at the other affected by dust storm on 30 April among the four cities. Shanghai was the most seriously influenced with the highest three mega-cities, i.e., Shanghai, Hangzhou, and Hefei in East China. Hefei located in the westernmost was the first PM$_{10}$ reaching 0.897 mg/m$^3$. There were also 3 peaks of PM$_{10}$ at Shanghai, similar to that of Nanjing. Hourly PM$_{10}$ concentrations exceeding 0.300 mg/m$^3$ lasted for three days. Hangzhou and Hefei were least affected with maxima of PM$_{10}$ lower than 0.600 mg/m$^3$. Visibility was degraded to below 5 km in all cities.

**Synoptic System of Dust Storm**

Springtime synoptic system contributed to East Asian dust storm. Fig. 7 shows the synoptic pattern of sea level pressure (hPa), 10 m wind (m/s), as well as zones of 24-hour accumulated precipitation. Fig. 8 presents the sounding wind profile on the Beaufort Wind Scale and the hourly precipitation (mm) and relative humidity (%) at Nanjing. The Mongolian cyclone developed during 28 April and was heading eastward. The cold and fast moving northwesterly airstream of the cyclone transported dust from arid and semi-arid areas to the atmosphere and downwind areas, and East China was dominated by southerly airstream in the mean time (Figs. 7(a) to 7(c)). As the Mongolian cyclone moved to Sea of Japan on 30 April, Nanjing was in the edge of zones of precipitation (Figs. 7(d) and 8(b)) just before the local dominant wind direction began to change to the north followed by the arrival of dust aerosols (Fig. 5) along with the dry air (Fig. 8(b)). Nanjing was in a large zone of precipitation on 3 May (Figs. 7(f) and 8(b)), as the wind direction was turning easterly gradually (Fig. 8(a)), which agreed with the interruption in Fig. 5. Southerly airstream dominated East China again on 5 May, which gave the end to this dust event.

**NUMERICAL SIMULATIONS**

**Sources and Routes of Dust Storm with HYSPLIT**

Fig. 9 illustrates ensembles of the backward trajectories starting from the altitude of 250m over Nanjing. It shows that differences exist in the trajectories during different periods. During the first peak period (Fig. 9(a)) some air parcels came northwesterly from the remote West Siberia, Mongolia and Inner Mongolia and other northern provinces of China, while some came from the south. Air parcels during the second period (Fig. 9(b)) mainly originated from Mongolia and Inner Mongolia as northeast Asia was considered as a major source of dust aerosols which resulted in the highest PM$_{10}$ concentrations. It was noteworthy that the routes and the sources of air parcels were gradually offset easterly as the low-pressure system moved eastward to the Sea of Japan and even some of them were via the seas in the east of Jiangsu Province and turned back to Nanjing. As a large area of precipitation appeared in East China (Fig. 8(f)), a fall of PM$_{10}$ concentrations took place on 3 May. The air parcels to Nanjing on 4 May mainly came from the northern part of China via the seas and turned to Nanjing from the east and southeast, which agreed with the

**Fig. 6.** The time series of observed hourly PM$_{10}$ concentrations (mg/m$^3$), and reciprocals of visibility (km$^{-1}$) from 0000 UTC 27 April to 2300 UTC 6 May 2011 at Shanghai, Hangzhou, and Hefei.
Fig. 7. Sea level pressure field (hPa), 10 m wind vectors field (m/s), and zones of 24-hour accumulated precipitation (gray areas) at (a) 1200 UTC 28 April, (b) 1200 UTC 29 April, (c) 1200 UTC 30 April, (d) 1200 UTC 1 May, (e) 1200 UTC 2 May, (f) 1200 UTC 3 May, (g) 1200 UTC 4 May, and (h) 1200 UTC 5 May.
lowest third peak. This suggests that the sources and routes of suspended dust affecting Nanjing were different during the process under the influence of synoptic system.

**Simulation of Transport Process and Spatial Distribution with WRF/Chem**

**Validation of PM$_{10}$ and PM$_{2.5}$**

Fig. 10 shows the time series of simulated and observed hourly PM$_{10}$ and PM$_{2.5}$ at representative megacities in East China from 28 April to 5 May 2011. Fig. 11 shows the time series of simulated and observed hourly PM$_{10}$ in northern China. As sites in northern China aren’t intensive, 4 points which are 229 km (2.828 times the horizontal grid resolution in domain 1) away from the center in four directions are also selected for comparison. The peaks of dust aerosols were obviously presented and the order of magnitude of simulated maxima of PM$_{10}$ and PM$_{2.5}$ agreed well with that of observations in East China. The correlation coefficients between simulated and observed PM$_{10}$ in Nanjing, Shanghai, Hangzhou, Hefei, and PM$_{2.5}$ in Nanjing are 0.62 (N = 217), 0.66 (N = 169), 0.55 (N = 171), 0.67 (N = 143), and 0.46 (N = 217), respectively, and all are significant. Near the source regions, the timing of maximum particle concentrations was modeled well, but there were deviations in the magnitude of peak and slight biases in locations. At the westernmost Jinchang site, the simulated PM$_{10}$ in the northeast and southeast were closer to the observation. The simulated PM$_{10}$ in the southeast and southwest were better than that in the center at the Baotou site. The simulated PM$_{10}$ at the Chifeng site agreed well except a little shorter lasting time. The differences in positioning indicate that the source location may be estimated easterly and southerly, or the source strength near the middle Inner Mongolia may be slightly overestimated. At the Nanjing site, the model reproduced the second peak of PM$_{10}$ about 8 hours earlier and lost the third peak. The possible paths of dust aerosols may be northwest and north (Figs. 9(a) and 9(b)), in company with the early estimated peaks in Hangzhou and Hefei around 0000 UTC 1 May. It may be the reason that the deviation in location in the western part of Inner Mongolia leading to transportation of shorter distance, or the early simulated overestimated source strength mentioned before resulting in corresponding early simulated peaks in downwind areas. The simulated PM$_{10}$ from 2 May to 3 May at the easternmost Shanghai site was much less than observation. The underestimation of simulated PM$_{10}$ peak also appeared in Hangzhou on 3 May and Nanjing in late 3 May, but a little less, and didn’t appear in the westernmost Hefei site. With just the background emission sources without considering the erosion of soil in the upwind areas in use, the simulated PM$_{10}$ in East China varied diurnally as usual. Combined with the possible path that the airflow came from the eastern part of Mongolia and Inner Mongolia, and then went through the sea and coastal cities, turned to Nanjing via Shanghai (Figs. 9(c) and 9(d)), it could be considered that the missing parts of PM$_{10}$ in the three cities came from the same airflow. New source regions may be considered produced where there are high surface dust concentrations and the wind speed is strong enough to re-uplift the dust during transportation (Bian et al., 2011).
Therefore, there may be underestimation in one of the source areas or deviation in meteorological fields during transportation which would lead to the lower simulated PM$_{10}$. The second peak simulated PM$_{2.5}$ at the Nanjing site was reproduced earlier and the third peak got lost, same as those of PM$_{10}$. The PM$_{2.5}$ of dust aerosols is a little overestimated during the dust-affecting period. There are several reasons causing modeling uncertainty: (1) threshold values of friction velocity, soil or near-surface water content for various soil types are key points in initializing dust deflation (Han et al., 2004); (2) surface wind strength is important in new considered generated source regions with high surface dust concentrations during transportation (Bian et al., 2011); (3) model resolution deficiencies in the source region (Shaw, 2008); and (4) meteorological field during transportation.

**Simulated Transport Process**

Fig. 12 shows simulated evolutionary pattern of surface PM$_{10}$ in East China and agrees well with observations in Fig. 2 in terms of spatial pattern and temporal variation. Fig. 4(b) showed that at 0000 UTC 29 April, there was already a broad center of high PM$_{10}$ exceeding 2,000 mg/m$^3$ around Mongolia, Inner Mongolia, Gansu Province and adjacent provinces of China. The high concentration center moved eastward and got strengthened around the eastern part of China-Mongolian border on the next day. The center disappeared before 0000 UTC 1 May and the dust aerosols spread widely and was transported eastward to North Pacific and southward to South China following the synoptic flow.

Fig. 13 presents the evolutionary images of 3-dimensional distribution of PM$_{10}$ in East China. Fig. 14 illustrates the vertical profiles of PM$_{10}$ and PM$_{2.5}$ at Nanjing. In comparison with backward trajectories in Fig. 9, Fig. 13 showed similarities in routes of dust aerosols impacting Nanjing. The main body of dust aerosols impacting East China was transported below the height of 2.5 km. The dust firstly reached the northwestern and northern parts of East China with the center of high PM$_{10}$ concentration exceeding 1,200 mg/m$^3$ located at the height between 0.2 km and 1.5 km around 0000 UTC 1 May. Then the center of high PM$_{10}$ got weaken and was transferred lower and eastward to the sea while the dust was occupying the whole airspace below the altitude of 2.5 km over East China on 2 May. It was obvious that the concentrations in coastal areas were higher than those in inland areas through the airspace below the altitude of 1.5 km during 3 May. Then the near-surface concentrations returned to normal levels on 4 May. The simulated high concentration center of PM$_{10}$ at Nanjing was located at the altitude between 0.2 km and 1.3 km on the beginning of 1 May with the PM$_{10}$ exceeding 0.800 mg/m$^3$. 

![Fig. 9. Ensembles of backward trajectories starting from the height of 250 m over Nanjing calculated at (a) 0000 UTC 1 May, (b) 0000 UTC 2 May, (c) 0000 UTC 3 May, and (d) 0000 UTC 4 May.](image_url)
Fig. 10. The time series of simulated and observed hourly PM$_{10}$ concentrations (mg/m$^3$) for the period of 28 April to 5 May 2011 at (a) Nanjing, (b) Shanghai, (c) Hangzhou, and (d) Hefei, and (e) PM$_{2.5}$ concentrations (mg/m$^3$) only at Nanjing.

The simulated PM$_{2.5}$ maximum was located similarly to that of PM$_{10}$ with concentrations exceeding 0.300 mg/m$^3$, but lasted longer for two days (Fig. 14(b)).

CONCLUSIONS

We analyzed the long-range transport of a severe dust storm in East Asia and its impact on the air quality of Nanjing from 28 April to 5 May 2011. Nanjing started to be affected by the dust storm two days later after its outbreak, and continued suffering for several days. During the transportation from source regions to downwind areas, dust aerosol may arrive at Nanjing in different directions: directly from the northwest, later from the north when the main body of dust storm moved easterly, and at last from the east when the reflux of the dust aerosol passed through the seas, thus resulted in several peaks of PM concentrations. Dust aerosol, in company with local anthropogenic emissions, caused severe air pollution with maximum of PM$_{10}$ reaching to 0.767 mg/m$^3$ and PM$_{2.5}$ reaching 0.222 mg/m$^3$. WRF/Chem model simulated this dust storm event well in terms of spatial distribution and temporal evolution of dust aerosol, reflecting good capability in pollution prediction during dust storm period, thus can be taken as a reference in daily air quality forecast.

ACKNOWLEDGMENTS

This work was supported by the National Key Basic Research Development Program of China (2011CB403406,
Fig. 11. The time series of simulated and observed hourly PM$_{10}$ concentrations (mg/m$^3$) at Jinchang, Baotou, and Chifeng.

Fig. 12. Simulated spatial distribution of surface PM$_{10}$ concentrations (mg/m$^3$) and meteorological fields in East Asia for (a) 0000 UTC 29 April, (b) 0000 UTC 30 April, (c) 0000 UTC 1 May, (d) 0000 UTC 2 May, (e) 0000 UTC 3 May, and (f) 0000 UTC 4 May.
Fig. 13. Simulated 3-dimensional distribution of PM$_{10}$ concentrations (mg/m$^3$) in East China for (a) 0000 UTC 1 May, (b) 0000 UTC 2 May, (c) 0000 UTC 3 May, and (d) 0000 UTC 4 May.

Fig. 14. Simulated vertical distribution of (1) PM$_{10}$ and (2) PM$_{2.5}$ concentrations (mg/m$^3$) at Nanjing.

REFERENCES


Received for review, May 1, 2012
Accepted, August 17, 2012