Observation study of aerosol spectrum and meteorological conditions under dust weather in Nanjing

Fei Wang1,2,5, Qi Jiang3 and Bin Zhu4

1 Key Laboratory for Cloud Physics, Chinese Academy of Meteorological Sciences, Beijing, 100081, China;
2 State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Global Change and Earth System Science, Beijing Normal University, Beijing, 100875, China;
3 National Meteorological Center, Beijing, 100081, China;
4 Key Laboratory for Aerosol-Cloud-Precipitation of China Meteorological Administration, Nanjing University of Information Science & Technology, Nanjing, 210044, China.

5 Email: feiwang@cma.gov.cn

Abstract. In this paper, the characteristic of aerosol spectrum and meteorological conditions of a dust storm was analyzed on May 2011. To compared with different weather background, another 3 day of aerosol properties were discussed. The results showed that the dust storm was originated in southern Mongolia and central Inner Mongolia, influenced Nanjing through Beijing and Shandong from the direction of southeast. The local pollution was serious before the dust intrusion and the ultrafine particles mainly ≤0.08μm. The coarse particles ≥0.5μm mainly occurred during and after the dust intrusion. Compared with other pollution and clean days in the same season, the aerosol concentration affected by dust storm and local pollution was five times higher than that in the clean days in Nanjing. By the influence of local pollution, the diurnal variation of aerosol showed double peaks which located at about 10:00 and around 20:00, respectively. Dust and precipitation had great influence on aerosol diurnal variation. The dry and wet removal process affected the time of the aerosol concentration peaks.

1. Introduction
Dust aerosol (or mineral aerosol) is a key component of aerosol in troposphere [1, 2]. In 1968, the estimated global generation rate of dust aerosol was about 500 Tg/year, ranking third behind the aerosol generated by gas-particle conversion and sea-salted aerosols [3]. After 2000, the generation rate of dust aerosol was up to 2150 Tg/year [4]. Simulation results of global aerosol models have been assembled in the framework to estimate the globe mineral dust emission in recent years. In different dust emission schemes used in the models, the amount of dust emission was estimated with great uncertainty, depending on the details of the dust parameterization [5, 6]. The magnitude of global dust cycle, usually estimated with climate model, has recently been suggested to be between 1500 and 2600 Tg/year [7]. Due to the increasing concentration of dust aerosol in the atmosphere, which seriously affects the environment and climate, the research on it has been paid close attention [8-11]. Sandstorm is a common disastrous weather that is harmful to the East Asian region including northern China, especially in spring and autumn [12].
Dust aerosol directly affect the radiation budget of the earth-atmosphere system by absorbing and scattering solar radiation, absorbing and emitting long-wave radiation [13]. This causes direct climatic effects, which is mainly reflected in the "Umbrella Effect" of dust aerosols. Dust aerosol also produces indirect climate effects by affecting precipitation probability and microphysical properties of clouds [14]. In addition, dust aerosol can also influence the dynamic and thermal structures of the atmosphere through the radiative effects, thereby affecting the weather and climate around the globe [15, 16]. Due to the absorption of radiation, dust aerosol particles in clouds heat the atmosphere, which caused “burning effect” on clouds and thus reduce the cloud cover on earth [17, 18]. This is called semi-indirect effect of dust aerosol [19]. The fourth way that dust aerosol may affect climate change is its transportation to the ocean will affect the ocean’s primary productivity, thereby affect the marine carbon cycle process, which cause the variation of CO₂ concentration in atmosphere. The land use and land cover caused by sandstorm or other dust related weather will also indirectly affect global climate. There is still much uncertainty about the estimation of dust aerosol on climate forcing. The third IPCC report concludes that the value is between -0.6w/m² and +0.4w/m² [20], meaning that its positive (warming) or negative (cooling) effects has not yet conclusive, and the uncertainty of dust aerosol on indirect climate effect is even greater.

Dust storms occur frequently in China, especially in Loess Plateau and Northern Deserts, which contribute most of dust aerosols to Asia. The study of dust weather in China since 1970s, which mainly focused on statistics and analysis of weather background, lacking systematic exploration of the dynamic mechanics of dust event. Since a serious dust storm in northwest China in May 1993, which lead life, property and economic construction suffered great losses. The dust storm and its related research attract the interest of scientists, which become a hot topic of meteorological science. The dust aerosol brought by strong dust storms can not only affect China and neighboring East Asian countries, such as Korea and Japan, but also cross the Pacific Ocean to North America. It has significant impacts on global climate by changing the balance of radiation budget and the chemical cycles of microorganisms. Therefore, the study of dust weather and related dust aerosol originated from China has been paid more attention by scientists, and a number of research programs have been implemented in recent years [21-25].

There is different characteristics between the dust aerosol originated from the northern part of China and those from other regions (such as Saharan Africa). A field experiment with dust aerosol measurement was conducted at Mauna Lao station in Hawaii where far from the dust sources of Asia (about 1.1×10⁴km) [26]. The results show that the peak diameter of dust aerosol originated from Asia is much larger than that from Sahara regions, and it raised with the increase of aerosol mass concentration to a larger value. High concentration of dust aerosol particles has magnitude impact on atmospheric visibility and radiation transfer, and through altering the thermal stability of atmosphere, thereby affecting local circulation and climate, which is a direct contribution to atmospheric environment and air quality.

Since April 29, 2011, a series large scale dust storm originated from southern Xinjiang Basin, successively attacked western Gansu Province and western Inner Mongolia region in northern China, which was the most intensity and extensive dust weather in 2011. Affected by the dust to the south region of China, Yangtze River Delta have experienced varying degrees of dust floating and blowing weather. This study focuses on the variation of concentration and size distribution of dust aerosol and also includes the dust weather characteristics and back-trajectory analysis.

2. Data and methods
The air quality index (AQI) data used in this study was from the data center of the Ministry of environmental protection of China. The region of this study mainly focused at Nanjing and its surrounding areas, and the in-situ measurement was located at the northern suburban of Nanjing. The weather station in Nanjing University of Information Science & Technology provides the surface meteorological data. Aerosol sampling is located in the meteorological building, where is about 1km from weather station. A wide-range particle spectrometer (WPS, produced by MSP Company, USA)
provides highly sensitive aerosol number concentration (Nₐ) and spectrum measurement with a range of 0.01~10μm. The sampling frequency is about 5 minutes. Its observation principle and uncertainties have been well documented [27]. A visibility measurement instrument (VFP730, Observator Group, Netherlands) with a range of 0.01~75km was used in this study. To understand the sources and transport pathways of dust aerosols, we calculated isentropic air mass back trajectories for 48h using the NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model [28, 29]. The HYSPLIT model (http://ready.arl.noaa.gov/HYSPLIT.php) was used along with the National Center for Environmental Prediction’s Global Data Assimilation System 1°×1° meteorological database to calculate backward trajectories terminated at Nanjing region.

3. Results and discussion
In May 2011, the Yangtze River Delta including Nanjing, Suzhou, Shanghai and Ningbo suffered a serious dust storm. Especially in Nanjing, such a severe dust storm has been the first time in this century. The AQI is a simple and generalized way to describe air pollution level in China. It is calculated from concentrations of sulfur SO₂, NO₂ and PM₁₀. An individual score is assigned to the level of each pollutant and the final AQI is the highest of those three scores. Figure 1 represents the AQI data (primary pollutant is PM₁₀) measured at the path of dust intrusion from April 30 to May 3. The AQI data in Nanjing and its surrounding areas was sharply decreased from 5:00 from May 1. Until 10:00, the AQI even once exceeded to 300. The concentration of dust aerosol declined after 12:00 and returned to light pollution level in the afternoon of May 2. Besides Nanjing, the air quality of Shanghai (AQI 307), Suzhou (AQI 330), Nantong (AQI 413) and Ningbo (AQI 334) also achieved severe pollution level, Yangzhou, Zhenjiang, Hangzhou and Hefei were moderately polluted. Jiaxing, Xuzhou, Changzhou, Wenzhou, Huzhou, Shaoxing and Taizhou were also suffered slight pollution.

3.1. Characteristics of weather condition and atmospheric circulation
Based on the statistical analysis of the meteorological data since 1951, it is concluded that the dust weather appeared in 15 years in total in Nanjing, generally about 3 days per year. The most frequent occurrences of dust weather were from 1953 to 1957, suffered 5 dust storms and including twice in 1953. Until the 1970s, the dust weather increased from 11 days to 15.3 days per year due to the growing number of dust floating weather. However, the floating dust decreased obviously since 1980s. The dust weather averaged 4.8 days a year in the 1980s, and dropped to 0.9 days a year in the 1990s. There was no large scale of dust weather in Nanjing until the end of 2009.

Figure 1. The variation of AQI (primary pollutant is PM₁₀) measured at the path of dust intrusion from April 30 to May 3.
Figure 2 showed the sea level pressure field at 8:00 on May 1 and 2, 2011. On May 1, the ground was in the form of a saddle field. The two high-pressure zones on the ground were located in outer Mongolia and the Pacific, respectively. The cold tongue of outer Mongolia high pressure extended deep into the west of Hetao and East China. The two low pressures on the ground were located in the Sichuan Basin and the Sea of Japan respectively. On May 2, the ground low pressure center in the Sea of Japan moved to the Pacific Ocean. The center located in the outer Mongolian area moved to the Hetao area and the intensity weakened. The cold high pressure extended to East China gradually evolved into reverse tank and extended southward to South China. Nanjing was affected by the front of the cold tongue centered in outer Mongolia and accompanied with strong winds and temperature reduction. The maximum wind speed reached to 6.5m/s. The dust storm reached in Nanjing and gradually strengthened on May 1. The next day, Nanjing area was affected by the ground denatured high pressure and the outer periphery of the inverted trough with the maximum wind speed exceeds 7m/s. On the night of May 2, the dust weather ended accompanied with the precipitation gradually.

Figure 2. Surface pressure of East Asia at 08:00 on May 1 (a), and May 2 (b), 2011. (Nanjing represents by red star).
3.2. Influence of dust weather on \( N_a \) and aerosol spectrum in Nanjing area

3.2.1. The variation of aerosol number concentration. To better distinguish dust aerosol particles, we divide the aerosol range measured by WPS into 4 particle segments, including nucleation mode (0.01–0.02μm), Aitken mode (0.02–0.1μm), accumulation mode (0.1–1μm) and coarse mode (1–10μm). The diameter of dust aerosol was mainly range of 0.5–1μm, which located in the accumulation mode and coarse mode (Figure 3). The \( N_a \) of nuclear mode, Aitken mode and accumulation mode decline significantly, while the coarse mode without marked change since 15:00 May 1, 2011. About 21:00 the concentration of coarse mode aerosol sharply increased. The maximum concentration was about 60 cm\(^{-3}\) at 22:35, then slowly declined and back to a normal level around 12:00 on May 2. Aerosol number concentration except coarse mode slowly raised after it decreased to a trough value around 3:00 on May 2. The minimum value of \( N_a \) was about 6300 cm\(^{-3}\) (0.01~10μm). Under a blowing dust weather condition, the dust \( N_a \) with the diameter of 0.5~1μm was about 83~148 cm\(^{-3}\) measured at Otindag Sandy Land, Inner Mongolia. In this study, the maximum value of dust \( N_a \) was about 114 cm\(^{-3}\), which was an exceptionally dust weather over past several years in Nanjing. Aerosol size distribution affected by the strong dust intrusion mainly concentrated on the fine particles with the diameter ≤ 0.08μm and the coarse mode aerosols with the diameter>0.5μm (Figure 4). For the fine particles (D ≤ 0.08μm), the \( N_a \) before the occurrence of dust storm is about an order of magnitude higher than that during and after the dust intrusion. After the dust storm, the hourly averaged \( N_a \) with D≤0.02μm is higher but \( N_a \) with 0.02μm<D<0.8μm is lower than that during the dust storm. Mainly because the scavenging of fine particles by the gale with an average speed of more than 4.5m/s under a dust weather condition. Wind speed declined gradually with the removal the dust aerosol. But the fine particles from local emission gradually accumulated, which can be regarded as the formation of new particles. The variation of \( N_a \) before, during and after the dust storm was quite similar at 0.08μm<D<0.5μm, which indicated the dust aerosol has little effect on this range of aerosol particles. The dust aerosol (D>0.5μm) dramatically increased, and the hourly averaged \( N_a \) values of dust aerosol during the event is much higher than that after or before the intrusion.

![Figure 3. Time series of 4 modes aerosol number concentration in Nanjing during the dust storm (May 1, 12:00 ~ May 3, 6:00, 2011).](image)

![Figure 4. Distribution of aerosol spectrum before, during and after dust intrusion.](image)

3.2.2. Transport route of dust aerosol. To study the source and transport route of the dust intrusion in Nanjing, the 48h backward trajectory of hourly air mass movement was analyzed from May 1, 12:00 ~ May 2, 12:00, 2011 (see figure 5). The horizontal component of the trajectory indicated the paths where the dust air mass passing by. According to the length of the trajectory, the speed of air masses movement can be judged. The dust storm originated from southeastern Mongolia and central Inner Mongolia. Wind erosion and desertification are serious in these areas, and the resources of sand and
grains are abundant. Coupled with less precipitation, rapidly raised temperature, and strong wind speed in this season, the dust storm formed and developed frequently. The dust air mass moved southeastward from April 29, passing Hebei and Shandong on April 30, and turn to Nanjing direction at northern Jiangsu and Shanghai region on May 1. From the AQI measurement at the transport paths of dust air mass (figure 1), the dust storm can be clearly captured. The sudden large amount of dust and the accumulation of local pollution dramatic weaken the air quality in Nanjing eventually.

![Figure 5](image_url)

**Figure 5.** The 48h back trajectory calculated hourly in Nanjing region from 18:00 on May 1 to 12:00 on May 2.

### 3.3. Meteorological condition and aerosol characteristic comparison among dust, pollution and clean days

![Graphs](image_url)

**Figure 6.** Diurnal variation of surface pressure (a), RH (b), visibility (c), wind speed (d) and wind rose (e) on dust, pollution and clean days.
Dust weather is rare in Nanjing. Different from the characteristically atmospheric conditions in this area, dust storm caused meteorological factor, aerosol spectrum and its diurnal variation uncommonly. To study the influence of this dust event on the atmospheric environment and local aerosol properties, three typical weather (including heavy pollution day on April 10 and 15, which were short for P1 and P2; and clean day on April 12, which was short for C1) in this season were selected for comparison in Nanjing (see Table 1). April 10 was a foggy day with a small wind speed (about 2.4m/s) and low visibility, the calculated AQI is 139. With a cold air mass brought strong wind developed, the ambient temperature sudden decline at night. Also, the pollutants and aerosols were gradually dissipated at all. Due to the dominate by cold high, RH dramatically decreased, the wind speed turned small and the background condition became clean until April 12. On April 15, the stable boundary layer caused local pollution. With a strong cold air arrived at night, brought fresh gale and 5.2mm precipitation from 20:00 to 22:00, which helped on removal of polluted aerosols in the atmosphere.

Table 1. Weather phenomena and the corresponding meteorological elements in Nanjing.

| weather phenomena      | temperature (°C) | wind speed (m/s) | RH (%) | visibility (m) | AQI |
|------------------------|------------------|------------------|--------|----------------|-----|
| May 1                  | floating dust    | 21.5             | 4.5    | 37.9           | 5190.4 | 307 |
| April 10               | fog              | 19.1             | 2.4    | 47.1           | 3052.1 | 139 |
| April 12               | clear            | 14.8             | 2.3    | 31.2           | 10177.2 | 69  |
| April 15               | light rain 20:00~22:00 | 19.2         | 3.8    | 39.0           | 10310.1 | 105 |

From the diurnal variation of \( N_a \) on dust day, pollution day and clean day, it can be concluded that, the variation tendency of \( N_a \) in spring is quite different in this area. The daily averaged \( N_a \) on dust day and pollution days \( (N_a=5\times10^4 \text{cm}^{-3}) \) is 5 times higher than that of clean day \( (N_a=1\times10^4 \text{cm}^{-3}) \). In the dust day, the \( N_a \) rapidly decreased after the dust weather pass by. The concentration achieved its lowest level around 0:00 on May 2 and its value even lower than clean day, approximated to the \( N_a \) after precipitation on the early morning of April 15. It can be considered that, strong wind and precipitation are the most effective ways to remove aerosol particles in Nanjing, both of them minimized the \( N_a \) to below \( 1\times10^4 \text{cm}^{-3} \). The course mode \( N_a \) on dust day (May 2) is higher than that of pollution day (April 15), resulted the visibility with great difference (figure 6 and 7). Pollution day (April 10) represents a most common diurnal variation of aerosol in spring in Nanjing. The dual peak values appeared at about 10:00 and 20:00, respectively. It always corresponds to higher RH, lower wind speed and visibility, stable boundary layer and surface pressure. It shows a typical pollution and meteorological characteristic of Nanjing in this season. With a low-level concentration of aerosol, the diurnal variation shows apparent in clean day (April 12). The dust airmass affected Nanjing from east and northeast, which was similar with clean day (April 12) and pollution day (April 15), while pollution day (April 10) was mainly influenced by local air flow from south area (figure 5).

Aerosol particles are comprised of different components and size. The average spectrum is an important physics characteristic used to describe aerosol numbers and size distribution. Aerosol particles show different spectrum properties under different weather conditions. Time series of aerosol spectrum are showed from 18:00 to 12:00 of the next day under dust (May 2), pollution (April 10 and 15) and clean (April 12) conditions (figure 8). It can be seen the significant variation of aerosol particles, especially nuclear and Aitken mode, during the day and night. The first peak of \( N_a \) is about 18:00 and then gradually decreased at night. With the increased human activities, the \( N_a \) gradually raised at 6:00 and another peak appeared around 10:00. However, dust and polluted conditions have certain effects on this aerosol diurnal variation. For example, if there was a significant scavenging by wind or precipitation of the day before, the \( N_a \) will dramatically decrease and its peak value delay in all possibility on the second day. Under clean condition, the particle size which corresponding to the peak of \( N_a \), gradually shift to large scale. However, with the accumulation of pollutants, the clean weather condition has a tendency change to the polluted condition.
Figure 7. Diurnal variation of $N_a$ on dust day (May 2), pollution days (April 10 and 15), clean day (April 12) and comparison of coarse mode (1~10μm) $N_a$ on dust (May 2) and pollution (April 15) day.

Figure 8. Time series of aerosol spectrum in a: dust day; b: pollution day; c: clean day; d: pollution day.

4. Conclusions
In this study, a serious dust event in Nanjing area was discussed. Including affected areas, meteorological condition, and aerosol characteristics were comparative analyzed with polluted and clean days in this season. The following conclusions can be drawn:

During the dust weather, Nanjing was controlled by cold high and inverted trough which characterized by high wind speed, low visibility and heavy pollution. With the enrichment of dust aerosols, the coarse mode $N_a$ sharply increased. HYSPLIT trajectory analysis showed that the dust storm originated in southern Mongolia and central Inner Mongolia, influenced Nanjing through Beijing and Shandong from southeast direction.

The low-visibility weather condition was not only affected by the northern dust air mass, but also involved local pollution, such as automobile exhaust and factory emissions, etc. Enrichment of fine particles (D<0.08μm) made local pollution serious. During and after the dust weather, the coarse mode aerosol (D>0.5μm) was dominated.
Compared with the aerosol properties of pollution and clean days in this season, $N_a$ in dust and pollution day was about 5 times higher than that of clean day in Nanjing area. Influence by local pollution, the diurnal variation of $N_a$ showed dual-peak distribution at 10:00 and 20:00, respectively. Dust and precipitation were important to $N_a$ diurnal variation which made the scavenging process would impact the time at which the peak $N_a$ occurred.

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