



Article

Trans-Boundary Dust Transport of Dust Storms in Northern China: A Study Utilizing Ground-Based Lidar Network and CALIPSO Satellite

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Abstract: During 14–16 March 2021, a large-scale dust storm event occurred in the northern region of China, and it was considered the most intense event in the past decade. This study employs observation data for PM_{2.5} and PM₁₀ from the air quality monitoring station, the HYSPLIT model, ground-based polarized Lidar networks, AGRI payload data from Fengyun satellites and CALIPSO satellite Lidar data to jointly explore and scrutinize the three-dimensional spatial and temporal characteristics of aerosol transport. Firstly, by integrating meteorological data for PM_{2.5} and PM₁₀, the air quality is assessed across six stations within the Lidar network during the dust storm. Secondly, employing a backward trajectory tracking model, the study elucidates sources of dust at the Lidar network sites. Thirdly, deploying a newly devised portable infrared 1064 nm Lidar and a pulsed 532 nm Lidar, a ground-based Lidar observation network is established for vertical probing of transboundary dust transport within the observed region. Finally, by incorporating cloud imagery from Fengyun satellites and CALIPSO satellite Lidar data, this study revealed the classification of dust and the height distribution of dust layers at pertinent sites within the Lidar observation network. The findings affirm that the eastward movement and southward compression of the intensifying Mongolian cyclone led to severe dust storm weather in western and southern Mongolia, as well as Inner Mongolia, further transporting dust into northern, northwestern, and northeastern parts of China. This dust event wielded a substantial impact on a broad expanse in northern China, manifesting in localized dust storms in Inner Mongolia, Beijing, Gansu, and surrounding areas. In essence, the dust emanated from the deserts in Mongolia and northwest China, encompassing both deserts and the Gobi region. The amalgamation of ground-based and spaceborne Lidar observations conclusively establishes that the distribution height of dust in the source region ranged from 3 to 5 km. Influenced by high-pressure systems, the protracted transport of dust over extensive distances prompted a gradual reduction in its distribution height owing to sedimentation. The comprehensive analysis of pertinent research data and information collectively affirms the precision and efficacy of the three-dimensional aerosol monitoring conducted by the ground-based Lidar network within the region.



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1. Introduction

Aerosols refer to the collective term for solid and liquid (cloud) particles suspended in the atmosphere. Atmospheric aerosols are mainly distributed in the troposphere, with

the majority concentrated in the boundary layer and diameters ranging from 0.001 to 100 μm . The atmospheric aerosol [1], influencing climate variations through radiative forcing, results in atmospheric environmental pollution. This phenomenon not only affects human health [2] and well-being but also poses significant challenges to societal development, attracting widespread attention [3]. On the one hand, certain solid particles can remain suspended near the ground and, when inhaled during human respiration, may enter the lungs. The presence of viruses carried by these solid particles poses the potential risk of respiratory infections and may even contribute to the development of lung cancer. On the other hand, atmospheric aerosol pollution is a significant factor contributing to the occurrence of dust storms and haze weather [4–7]. This pollution exerts substantial pressure on transportation systems. Aerosols possess the ability to scatter, absorb, and transmit both solar and terrestrial radiation. Scattering induces the deflection and dispersion of light in the atmosphere, impacting its transparency, optical thickness, and energy balance, consequently influencing radiative transfer, atmospheric temperature, and the water cycle. Moreover, aerosols can serve as cloud condensation nuclei, promoting cloud formation and growth. This alteration affects the optical thickness and brightness of clouds, subsequently impacting their radiative properties and the overall atmospheric radiation balance. Furthermore, aerosols can influence the quantity and size of cloud droplets, thereby influencing cloud precipitation processes and the spatial-temporal distribution of precipitation, ultimately impacting the surface water cycle. Dust represents a prominent aerosol type in the atmosphere, and its optical properties hold significant implications for various aspects including the atmospheric energy balance, climate change, air quality, and weather forecasting. A thorough comprehension of the optical characteristics of sand and dust is crucial for enhancing our understanding of their transport, dispersion, and deposition mechanisms in the atmosphere. This understanding, in turn, contributes to improved accuracy in monitoring and predicting sand and dust storms, assessing their environmental and public health impacts, refining climate models, and thereby enhancing climate prediction and environmental protection strategies.

Extreme events such as dust storms and haze have profound effects on normal human activities [8,9]. Dust storms, characterized by their extremity and adverse meteorological nature, have been enduring subjects of scholarly scrutiny. Simultaneously, scholars employ diverse scientific methodologies to scrutinize dust storms, encompassing the utilization of observational and model data from the vantage point of atmospheric dynamics to elucidate the genesis of dust [10], analyzing the distribution, transport, and ramifications on air quality through the integration of satellite data and models [11,12], and exploring the vertical diffusion of long-distance dust transport by amalgamating perspectives on atmospheric turbulence with regional dust enhancement observational data [13]. For this dust event, numerous researchers have employed various approaches for comparative validation to collectively unveil the source, transport, and development trends of the dust storm. Filonchyk, M et al. [14] analyzed data from ground-based sensors, satellites, and atmospheric models to conclude that the dust event affected not only the source area but also a wider territory. He, Yun et al. [15] integrated space-based and ground-based observations to elucidate the horizontal distribution of the dust storm, its transport paths, dissipation, and its impact on surface air quality. Gui, Ke et al. [16] characterized the optical, microphysical, and radiative properties of dust aerosols and their meteorological drivers using sun photometer observations and a comprehensive set of multi-satellite (including MODIS, VIIRS, CALIOP, and Himawari-8) and ground-based observations (including CMA Visibility Network and AD-Net) combined with atmospheric reanalysis data. Liang, Peng et al. [17] conducted isotope analysis of fresh dust from various locations in the dust storm area and combined satellite images with real-time meteorological data to quantify the source of the dust storm.

Currently, air quality monitoring in major Chinese cities primarily relies on ground-level air quality monitoring stations [18,19]. However, due to the limited sampling range of these ground-level stations, they can only acquire one-dimensional time series array

information near the ground, and their distribution is constrained. Additionally, these air quality stations cannot provide comprehensive coverage for certain regions, resulting in blind spots when monitoring air quality over larger areas. Therefore, relying solely on data from ground monitoring stations makes it challenging to fully comprehend the overall trend of air quality changes.

Lidar [20], owing to its heightened sensitivity, precise temporal resolution, robust coherence, superior directionality, and its ability to capture and quantify target information in three-dimensional space [21,22], finds wide-ranging applications in atmospheric structure detection and environmental pollution monitoring [23–26]. Currently, aerosol Lidars are capable of effecting three-dimensional detection of cloud and aerosol, adeptly meeting the observational requisites for aerosol spatiotemporal evolution in confined spatial scales. Dust storms represent the spatial and temporal evolution of dust aerosols on a large scale. While aerosol Lidar can monitor aerosols in three dimensions and the polarization channel can identify dust aerosol from other aerosol species, these capabilities are primarily suited for monitoring aerosol evolution on small scales. In the case of large-scale aerosol cross-border transport, such as during dust storms, a single Lidar is insufficient for comprehensive monitoring, making it challenging to discern the aerosol transport patterns. Therefore, a network of aerosol Lidar-based observations is beneficial for elucidating the sources, types, transport, and development of sand and dust aerosols. Ground-based Lidar networks, concomitant with ground-level air quality monitoring data, satellite payload data, and spaceborne Lidar data, can proficiently delve into the three-dimensional spatial and temporal characteristics of aerosol transport. This approach unveils the origins, transport dynamics, and developmental trends of pertinent aerosols. Prominent Lidar observation networks comprise EARLINET, NDACC, AD-NET, MPLNET, LALINET, GALION [27–33], and others. Many scholars have successfully integrated Lidar observation networks with studies on dust, yielding promising results. A. Ansmann et al. [34] conducted an analysis of the mass distribution of dust and fine particulate matter in central Europe following the eruption of the Eyjafjallajökull volcano in Iceland. They utilized observations from the European Lidar Network (EARLINET), thereby providing valuable insights into the spatial distribution and transport processes of volcanic ash and dust. Jeffrey S. Reid et al. [35] conducted an analysis of Saharan dust measurements during the Puerto Rico Dust Experiment (PRDEX) utilizing airborne and ground-based remote sensing methods. This study involved the use of Navajo aircraft, AERONET sun photometer data, and MPLNET Lidar data to elucidate the vertical distribution characteristics and transport processes of the dust. Tomoaki Nishizawa et al. [36] introduced multi-wavelength Raman Lidar and High Spectral Resolution Lidar (HSRL) technologies to enhance the investigation of the optical and microphysical properties, as well as the motion mechanisms, of sand, dust, and air pollution aerosols in Asia. They also plan to utilize AD-NET for validation and data assimilation of Earth CARE satellite observations, aiming to evaluate air pollution and sand and dust aerosol emissions in East Asia.

The solar photometer operates independently of direct contact with sand and dust, rendering it unaffected by variables such as particle size and shape. Consequently, it can maintain stable operation over extended periods during dust studies, minimizing maintenance expenses and experimental inaccuracies. Unfortunately, the absence of data from these six sites in AERONET and SONET precludes more robust comparative observations.

Given the recurrent incidence of dust storms in northern China during spring, this study is centered around a substantial dust storm event that unfolded in the northern region of China from 14 to 16 March 2021. This paper offers a comprehensive analysis of the dust event by leveraging Lidar network observations and satellite remote sensing data. The Lidar network furnishes detailed characteristics of the dust, including species and concentration. Meanwhile, satellite data provides remote sensing attributes of the dust, such as coverage area and optical thickness of the dust cloud. By integrating these two datasets, researchers can conduct multi-scale monitoring of sand and dust, spanning from

local to global scales. This approach facilitates a more comprehensive understanding of the spatial distribution and temporal variation of sand and dust phenomena.

The remaining sections of this article are as follows: In Section 2, we will introduce the data, dust source tracing model, and specific technical solutions captured by various instruments and equipment on multiple platforms during this intense sand and dust event. Section 3 focuses on the data processing of information collected from multiple platforms and the comprehensive analysis of data products. Section 4 shows a summary of the conclusions.

2. Methods and Approaches

2.1. Ground-Level Air Quality Monitoring Data

In 2012, China enacted the “Ambient Air Quality Standards”, initiating the establishment of more than 1400 air quality monitoring stations across 338 prefecture-level cities nationwide from 2013 onwards. Sophisticated instruments, at each station ensure continuous surveillance of urban air quality throughout the day, with real-time data transmission to the China National Environmental Monitoring Center (CNEMC) (<http://www.cnemc.cn/> (accessed on 13 March 2021)). The dataset, encompassing metrics such as the Air Quality Index (AQI), PM_{2.5} (Particulate Matter), PM₁₀, CO, NO₂, among others, is systematically reported at hourly intervals. The air quality monitoring data provides essential references to relevant government departments, assisting people in better understanding and addressing air quality issues during different time periods. Ground-level air quality monitoring data have been extensively utilized by researchers. Some have employed ambient air quality monitoring data to analyze the spatial and temporal distribution of ground-level ozone and to study the population exposure to it [37]. Others have utilized pollutant levels, such as PM_{2.5} (Particulate Matter), NO₂, SO₂, and CO, monitored at ground-level stations to conduct comparative experiments with data from onboard monitoring, enabling comprehensive analyses of air quality [38]. This paper utilizes data from the site’s beta-ray nuclei counting particulate matter monitor [39], which employs beta-ray nuclei counting technology to measure the concentration of suspended particulate matter in the air. Typically, this type of monitoring instrument comprises a detector, counter, amplifier, and data processing system. During operation, the detector converts detected beta-ray events into electrical signals, which are then counted by the counter. The signals are subsequently amplified, and the data processing system is responsible for recording and analyzing the monitoring data. With advantages such as high sensitivity, good stability, adaptability, and ease of operation, this detector serves as an effective means of monitoring suspended particulate matter in the atmosphere. It finds widespread applications in environmental monitoring, air quality assessment, and pollution source monitoring.

2.2. HYSPLIT Model

The HYSPLIT model [40,41], collaboratively developed by the National Oceanic and Atmospheric Administration (NOAA) in the United States [42,43], represents an advanced simulation and computational system. Its functionalities encompass the computation of transport dynamics for dust pollutants during dust storm events [44], providing valuable insights into potential sources. Moreover, the model excels in calculating air mass trajectories, enabling the simulation of intricate dispersion and deposition processes associated with phenomena like dust storms, volcanic ash, and wildfires [45]. Utilizing the analytical capabilities of the HYSPLIT model involves specifying parameters such as the geographical coordinates of the study location, start time, analysis duration, trajectory height, and more. This flexibility empowers researchers to generate comprehensive forward and backward trajectory analysis reports. Forward trajectories contribute to forecasting, while backward trajectories play a pivotal role in source identification and trace-back analyses. The HYSPLIT backward trajectory analysis model in this paper was employed at four different altitudes (3000 m, 1000 m, 500 m, 200 m) for a duration of 48 h, spanning from 14 March to 16 March, at our Lidar site.

2.3. Ground-Based Aerosol Lidar Network Data

The ground-based aerosol Lidar network consists of six aerosol Lidars. Figure 1 displays the distribution of these six Lidar sites and the CALIPSO transit trajectory (the yellow line), among which Beijing, Jinan, and Hefei deploy independently developed portable infrared Lidars (mIRLidar) [46]. The Lidar system comprises an Nd:YAG laser, receiving optics and subsequent optical units, signal detection unit, hardware control and data processing software. The laser emits at a wavelength of 1064 nm with a spatial resolution of 7.5 m and a temporal resolution of 20 s. The detector uses a sensitive-to-visible Si-APD and near-infrared bands with a bandwidth of 200 MHz. The Lidar system boasts compact dimensions of $200 \times 200 \times 420$ mm, demonstrating robust capabilities for extended outdoor operation. Its lightweight design, weighing a mere 13.5 kg, ensures ease of maintenance and installation. This Lidar system can transmit collected data and equipment status to a cloud server in real-time, where data quality control, the extinction coefficient and depolarization ratio are shown. Additionally, it can be connected to smartphones, computers, and other smart devices for remote control. Wuzhong, Xi'an, and Handan are equipped with three micro-pulse Lidars [47] emitting green light at a wavelength of 532 nm, featuring a polarization channel, spatial resolution of 7.5 m, and a temporal resolution of 1 min. The relevant parameters of the two types of Lidars are shown in Table 1.

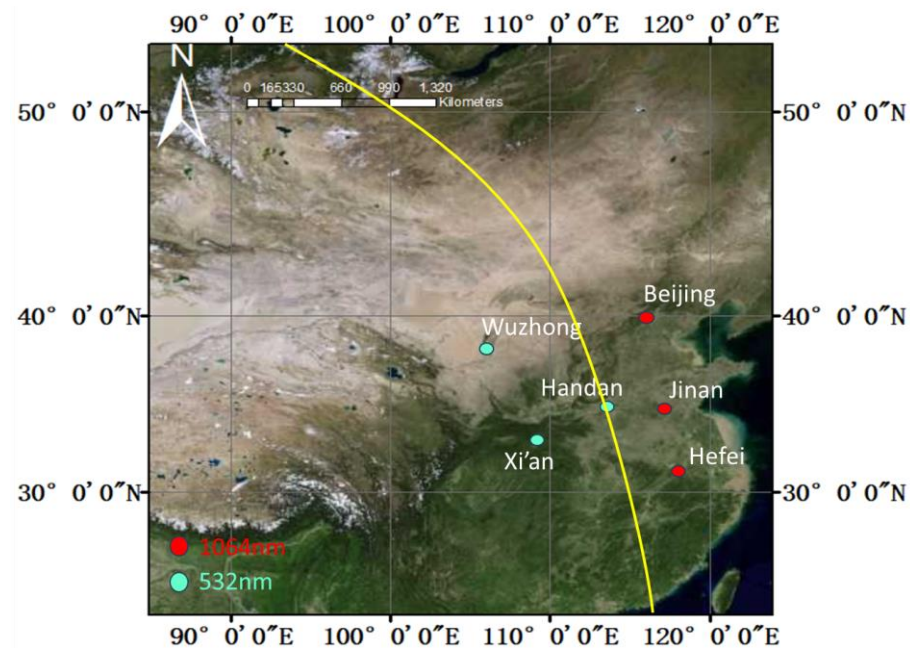


Figure 1. Distribution of Lidar Detection Sites and the CALIPSO transit trajectory (the yellow line).

Table 1. Technical parameters of Lidar at two wavelengths.

Parameter	mIRLidar	Micro Pulse Lidar
Wavelength	1064 nm	532 nm
Pulse energy	15 μ J	400 μ J
Pulse repetition frequency	5 kHz	5 kHz
Telescope diameter	100 mm	160 mm
FOV	1.5 mrad	1.5 mrad
Range resolution	7.5 m	7.5 m
Vertical detection range	0~6 km	0~5.2 km

FOV: field of view.

Due to the irregularity of atmospheric aerosol particles, the backscattered signal will exhibit varying degrees of depolarization compared to the original polarization direction. The depolarization coefficient can be utilized to analyze the type of aerosol, including

sand, dust, soot, and more. The mIRLidar has a polarization channel that synchronizes the parallel and perpendicular components of the backscattered signal $P_p(Z)$ and $P_s(Z)$ during atmospheric sounding. The gain coefficient k is obtained through the experimental method. Then, the depolarization ratio can be obtained by calculating the following Equation (1).

$$\delta(Z) = K \frac{P_s(Z)}{P_p(Z)} \quad (1)$$

To ensure consistent monitoring signals for the same pollutant across all sites, the quality control standards of the European Network of Lidar Observatories for Aerosol Research (ENLORAD) [25] and the test methods from the European Space Agency (ESA) in the ATLID project [48] were implemented to test and calibrate the Lidar equipment before deployment at the six radar sites. This involved various tasks including zero calibration, overlap factor calibration, dark noise testing, symmetry testing, linearity testing, and channel gain factor calibration. Despite using the same model and batch of photodetectors, amplifiers, and acquisition cards for both channels in the Lidar system, differences in photoelectric signal conversion, gain, and A/D conversion parameters are inevitable. Moreover, due to variations in the aging rate of electronic devices, the signal value discrepancy between the two channels and their rates of change may differ, leading to inaccuracies in the collected data and detection of depolarization ratio. Therefore, it is crucial to calibrate the electron gain coefficient (k) of the two channels of the Lidar. The experimental method is employed to determine the polarization gain coefficient (k) of the system, typically achieved by placing one-half of a waveplate in front of the polarizing prism. However, in this paper, one-half of the waveplate is fixed at the laser emission because the design of the lidar structure does not allow for the placement of the waveplate in the subsequent optical path. To determine the polarization gain coefficient, the angle of the one-half waveplate needs to be rotated. Initially, the angle is adjusted to maximize the signal strength of the parallel channel, and the corresponding detection data are recorded. Subsequently, the angle of the one-half waveplate is further adjusted to maximize the signal strength of the perpendicular channel, and the data are recorded again. The gain ratio profile of the two polarization channels is then computed by dividing the signal of the parallel channel from the first set of detection data by the signal of the perpendicular channel from the second set of detection data. Finally, the gain ratio coefficient profile is analyzed to determine a stable gain coefficient k .

The process of processing Lidar data at the six sites is as follows: Upon acquiring raw data from the Lidar at each site, the system initiates quality control procedures to remove invalid data. These scenarios leading to invalid Lidar detection data include adverse weather conditions (such as rain, snow, sandstorms, dense fog), presence of low-altitude clouds (typically a few hundred meters), and hardware failures (including optical path deviation, detector malfunctions, and significant laser energy attenuation). Subsequently, the average value of the last kilometer signal of the Lidar signal serves as the background value. This value is subtracted from the Lidar signal, deducting the DC bias of the signal. A denoising algorithm is then applied to minimize noise in the original data, thereby enhancing signal quality and the accuracy of data product inversion. Following this, the geometric factor of the Lidar is determined through experimental methods, and each radar signal is accordingly corrected. Finally, the corresponding inversion algorithm is employed to derive the depolarization ratio.

2.4. Satellite Remote Sensing and Spaceborne Lidar Observational Data

This study predominantly relies on image products from the Fengyun-4A (FY-4A) satellite. Launched successfully from Xichang on 11 December 2016, the satellite achieved geostationary orbit positioning over the equator on 17 December 2016. A key payload aboard FY-4A [49], the Advanced Geostationary Radiation Imager (AGRI), is dedicated to cloud image acquisition. AGRI captures high-frequency Earth cloud images across

more than 14 spectral bands, enabling the creation of vibrant satellite cloud images and facilitating the generation of regional observation images in as little as 1 min.

While the Lidar observation network furnishes valuable spatiotemporal distribution information on the atmospheric vertical structure, boundary layer, and cloud height characteristics, its observational scope is constrained by various factors. Harsh conditions in areas such as deep oceans, deserts, and polar permafrost regions pose significant challenges to the deployment of Lidar networks. Thus, achieving global coverage for Lidar networks remains a formidable task for humanity [50]. In contrast, the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) Lidar, mounted on the CALIPSO satellite [51], can detect thinner cloud layer information and atmospheric vertical structure parameters globally. CALIOP's released data products [52], encompassing depolarization ratio, backscatter coefficient, and aerosol classification, facilitates the analysis and exploration of aerosol vertical and horizontal structures [53].

2.5. Technical Approach

We established a Lidar network at six stations: Beijing, Wu Zhou, Handan, Jinan, Xi'an, and Hefei, facilitating networked observations through Lidar. Utilizing the detection data from the Lidar network and integrating it with satellite cloud imagery, ground-level air quality monitoring data, spaceborne Lidar detection data, and the HYSPLIT backward trajectory analysis system, we conducted an analysis of the origin and progression of a severe dust storm event in northern China from 14 March to 16 March 2021.

3. Results and Discussion

3.1. Overview of Haze Pollution in China from 14 to 19 March 2021

From the night of 14 March to the morning of 16 March (Beijing time), extensive sandstorms swept through the most northern regions of China, influenced by a cyclone from Mongolia and cold air. This marked a significant sandstorm event, the most notable in the past decade [54], leading to widespread haze pollution covering large parts of China. The impact was particularly felt in the northern, central, and eastern regions, significantly affecting air quality. Figure 2 illustrates the variation in particle concentrations in cities where the observation sites of the Lidar network are located. The concentration trends of PM_{2.5} and PM₁₀ at six sites shows remarkable consistency. In Beijing, Jinan, Handan, and Hefei, the PM_{2.5} concentrations were 401 $\mu\text{g}/\text{m}^3$, 292 $\mu\text{g}/\text{m}^3$, 277 $\mu\text{g}/\text{m}^3$, and 89 $\mu\text{g}/\text{m}^3$, respectively. The corresponding PM₁₀ concentrations were 6450 $\mu\text{g}/\text{m}^3$, 2397 $\mu\text{g}/\text{m}^3$, 2315 $\mu\text{g}/\text{m}^3$, and 382 $\mu\text{g}/\text{m}^3$. The PM_{2.5}/PM₁₀ ratios were all less than 0.2 (except for Hefei), indicating that fine particulate matter constituted a small proportion during this sandstorm event, with coarse particles being predominant. At the Wuzhong observation site, there was a brief increase in PM_{2.5} and PM₁₀ concentrations from 9:00 to 12:00 on 14 March. From 4:00 on 15 March, PM_{2.5} and PM₁₀ concentrations began to sharply increase simultaneously. PM_{2.5} reached its peak at 1454 $\mu\text{g}/\text{m}^3$, and PM₁₀ reached its first peak concentration of 2185 $\mu\text{g}/\text{m}^3$ at 8:00. Subsequently, both concentrations experienced a certain decrease. At 15:00, PM₁₀ sharply increased again, reaching a peak concentration of 3435 $\mu\text{g}/\text{m}^3$ and maintaining a high concentration level for the next few days. On 15 March, as the sand dust arrived in Wuzhong and Beijing, there was no significant increase in PM_{2.5} and PM₁₀ concentrations at the Xi'an site. Instead, PM₁₀ concentrations began to gradually increase on 16 March, while PM_{2.5} concentrations remained relatively stable. Intense sand dust began to affect Beijing at 8:00 on 15 March, causing PM₁₀ mass concentrations to soar to 6450 $\mu\text{g}/\text{m}^3$. The extremely high PM₁₀ concentrations were of short duration and returned to pre-sandstorm levels by 16 March. In Jinan and Handan, around 16:00 on 15 March, PM₁₀ mass concentrations rapidly increased to 2397 $\mu\text{g}/\text{m}^3$ and 2315 $\mu\text{g}/\text{m}^3$, respectively. The period of high concentration was brief, gradually decreasing to normal levels afterward. Due to its distance from the northern sand source, Hefei experienced minimal growth in particle mass concentrations during this sandstorm event. Around 6:00 on 16 March, PM₁₀ concentrations began to gradually increase to 382 $\mu\text{g}/\text{m}^3$, and

there was a slight increase in PM_{2.5} concentrations, but the amplitude was not significant. Hefei was less affected during this sandstorm event compared to other cities, with Beijing experiencing the greatest impact on air quality and Wuzhong having the longest duration of impact.

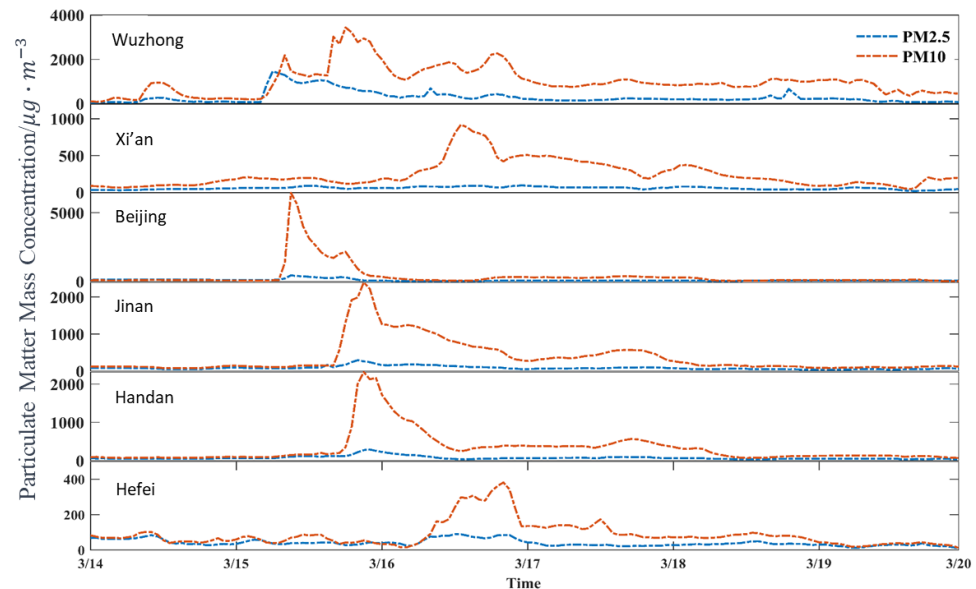


Figure 2. Variations in PM_{2.5} and PM₁₀ mass concentrations at six sites in China from 14 to 19 March 2021.

3.2. HYSPLIT Backward Trajectory and Dust Source Analysis

The primary conditions for the genesis of dust storms involve sand sources, robust winds, and thermally unstable atmospheric stratification. Northwestern China hosts numerous desert and desertification regions, such as deserts and the Gobi, characterized by soft surfaces, extensive exposure, and sparse vegetation. Consequently, these areas emerge as pivotal sources of dust storms during the autumn and winter seasons, with the predominant dust storm migration routes aligning westward, northwestward, and northward [55]. As illustrated in Figure 3, to ascertain the origin of dust, the HYSPLIT model was employed to scrutinize the backward trajectories of dust at six Lidar network sites across varied altitudes. Vertical profiles of dust at these six sites are discernible from Figure 4. Intense dust at the Wuzhong, Beijing, Jinan, Handan, and Hefei sites predominantly concentrate below 1500 m, while in Xi'an, it is confined below 3000 m. Accordingly, trajectory analysis was executed at heights of 3000 m, 1000 m, and 500 m for Xi'an and at heights of 1000 m, 500 m, and 200 m for the other five sites.

In Figure 3a, the backward trajectory of Wuzhong city delineates that the 1000 m high-altitude dust aerosol particle layer traverses Wuzhong from the southeast, distinctly differing from the dust sources at the other two altitudes. The 1000 m high-altitude dust aerosol particle layer, owing to its relatively abbreviated trajectory and gradual elevation, is inferred to have originated from the southeast direction, having resided there before 15 March, gradually dispersing to higher altitudes, and reaching an altitude of approximately 1000 m by 16 March upon arrival at Wuzhong. Hence, the 1000 m high-altitude dust in Wuzhong during this severe dust storm emanated from the southeast direction. The 500 m and 200 m low-altitude dust aerosol particle layers entered Wuzhong from Mongolia's 2000–5000 m altitude in a northeast direction, gradually descending into the lower atmosphere along with high-pressure airflow and local urban aerosol particles. This phenomenon aligns with the non-spherical characteristics of dust measured by the Lidar network. In summary, the high-altitude dust during this severe dust storm in Wuzhong originated from the southeast direction, while the low-altitude dust derived from the deserts and Gobi regions of Inner Mongolia and Mongolia.

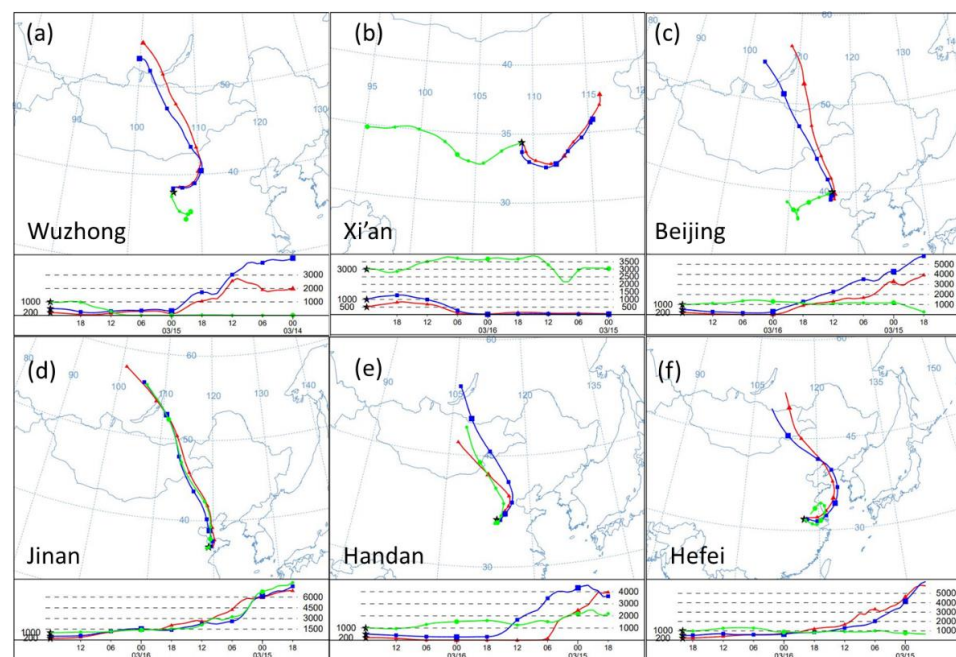


Figure 3. The 48 h HYSPLIT backward trajectory of different stations at different heights, Wuzhong (plane (a)), Xi'an (plane (b)), Beijing (plane (c)), Jinan (plane (d)), Handan (plane (e)), and Hefei (plane (f)).

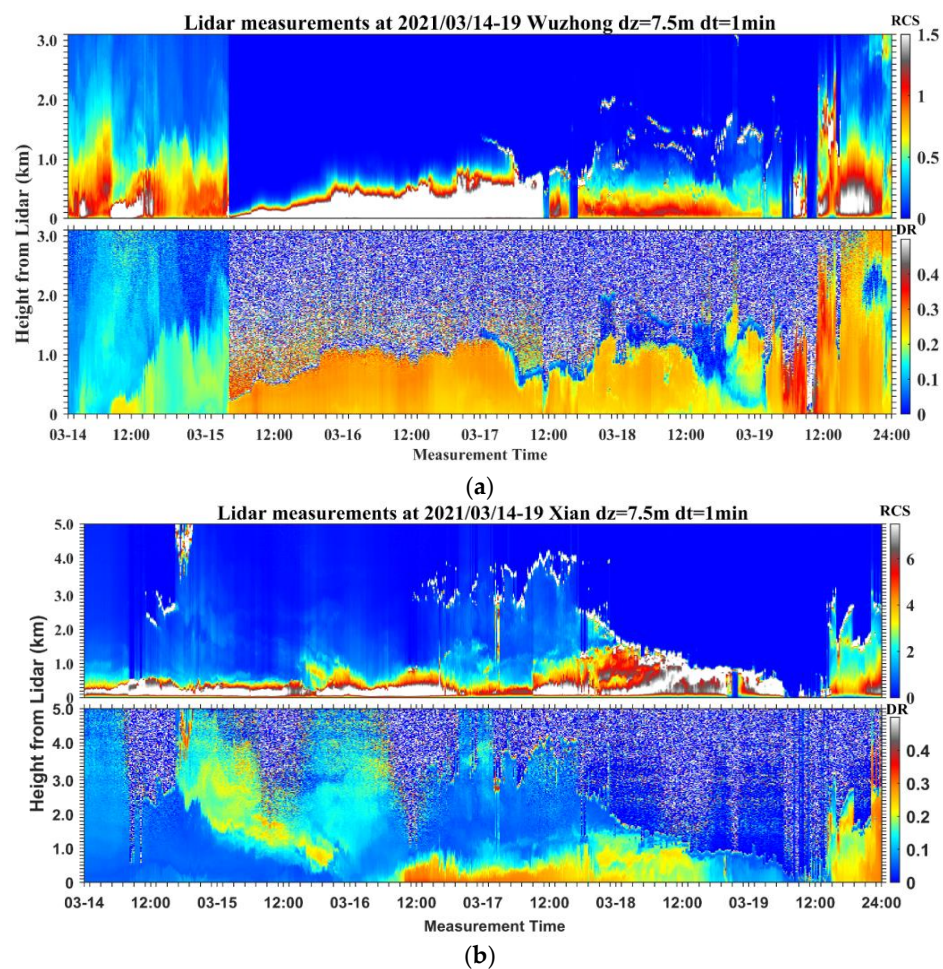


Figure 4. Cont.

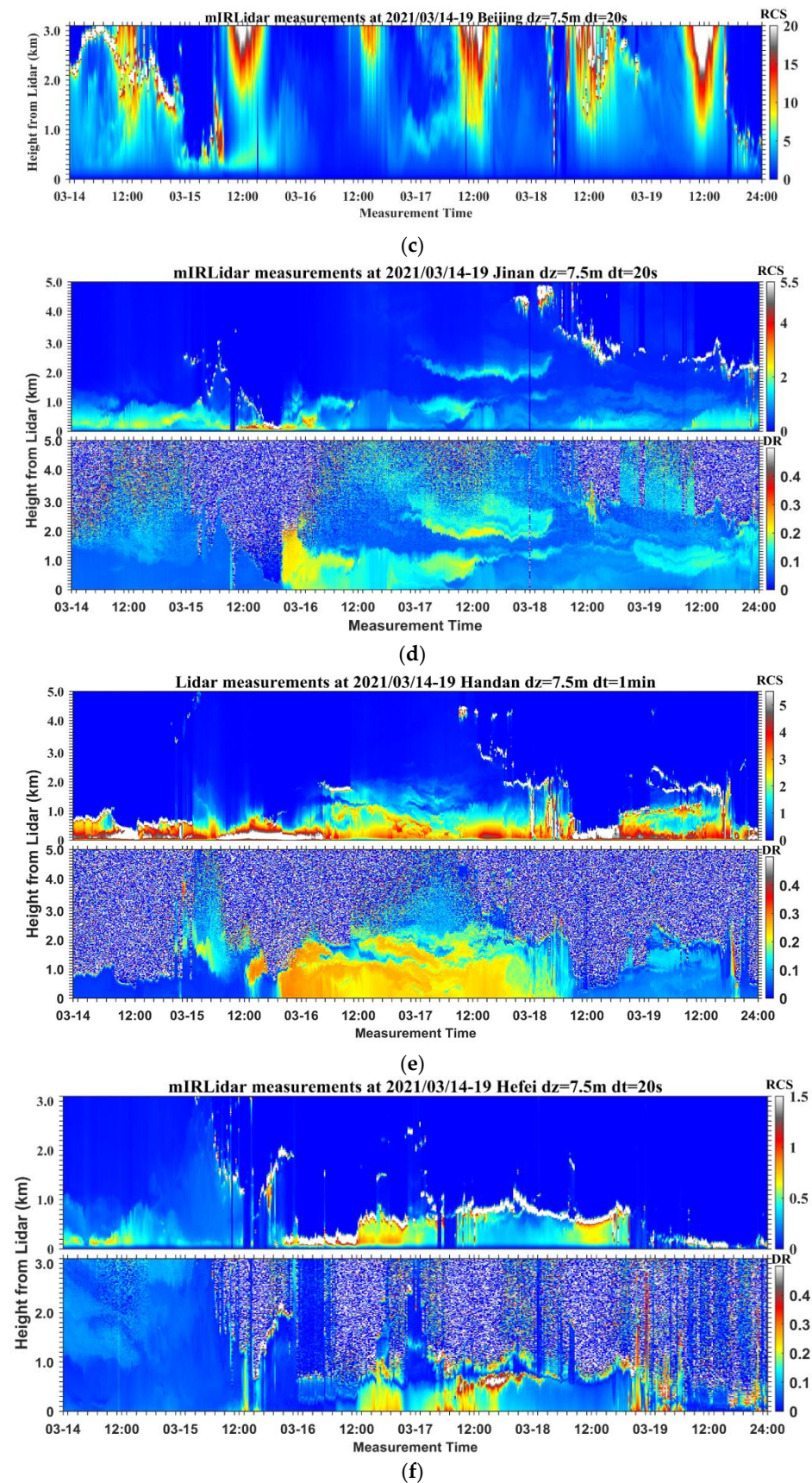


Figure 4. Lidar range corrected signals and depolarization ratio signals at different sites in the Lidar network: Wuzhong (panel (a)), Xi'an (panel (b)), Beijing (panel (c)), Jinan (panel (d)), Handan (panel (e)), and Hefei (panel (f)).

Figure 3b depicts the backward trajectory of Xi'an, revealing that the dust aerosol particle layers at three different altitudes originated from diverse locations. Considering geographical location, it is deduced that the 3000 m high-altitude dust aerosol particle layer originated from the Qaidam Desert in the west, undergoing protracted transport and descending from 3000 to 5000 m altitude to the ground in Xi'an by 15 March. The 500 m and 1000 m dust aerosol particle layers primarily originated from Henan and Shandong. Over time, the dust aerosol particle layers descended after settling and then ascended. Therefore, the intense dust weather in Xi'an during this period mainly originated from the dust in the Qaidam Desert, with additional contributions from land-based aerosol particles from Henan and Shandong.

In Figure 3c, the backward trajectory of Beijing indicates that the 1000 m high-altitude dust aerosol particle layer originated from the southwest of Beijing, remaining stable at around 1000 m altitude during transportation to Beijing, gradually descending to the ground. The 500 m and 200 m dust aerosol particle layers cover a long and wide area trajectory, signifying robust winds, high wind speeds, and substantial pressure differences in the low-altitude dust aerosol particle layer, engendering favorable diffusion conditions. The low-altitude dust aerosol particle layer primarily originated from the dust at 4000–6000 m altitude in Mongolia, gradually spreading and settling in the lower atmosphere after long-distance transport. In conclusion, during this severe dust storm in Beijing, the high-altitude dust aerosol particle layer primarily originated from the southwest of Beijing, while the low-altitude dust aerosol particle layer mainly originated from the deserts and Gobi regions of Inner Mongolia and Mongolia.

Figure 3d–f, respectively, depict the backward trajectories of Jinan, Handan, and Hefei. At these three altitudes, the dust aerosol particle layers of the three cities predominantly traverse in a south-east direction, with relatively protracted backward trajectories. Consequently, it can be inferred that the dust aerosol particle layers in these three cities originated from the high-altitude dust aerosol layer in the central and eastern parts of Inner Mongolia and the eastern part of Mongolia. Jinan and Hefei exhibit a segment of the dust trajectory over the ocean, while Handan's dust trajectory is entirely over land. Owing to the greater distance of the dust from Hefei, the intensity of the dust when it passes over Hefei is weaker compared to Jinan and Handan.

By analyzing the backward trajectories from six Lidar stations located in Wu Zhong, Xi'an, Beijing, Jinan, Handan, and Hefei, we successfully predicted the origin of this severe sandstorm weather. The predominant source of the intense sandstorm is still the sparsely vegetated deserts in the northwest of China, encompassing the Gobi Desert in the northern region of Inner Mongolia and the southern part of Mongolia. The backward trajectory paths from these six stations all revealed severe sandstorm weather of varying intensities, originating from different dust sources at various altitudes. The primary transmission routes predominantly lie in the northern and northwestern directions.

3.3. Lidar Observation Network Detects Sandstorm Processes

The comprehensive observation network of ground-based aerosol Lidar captured the entire process of this dust weather event. The range corrected signal (RCS) of the Lidar can reflect changes in atmospheric aerosol concentration [56], providing an intuitive description of the sandstorm transit process. The non-spherical nature of dust particles results in a relatively large linear depolarization ratio, making it a useful parameter for identifying dust aerosols [57]. Figure 4 presents each station and the the top panel is the range-corrected signal (RCS) in arbitrary units and the bottom panel (except for Beijing, because the APD of the parallel detection channel of the Lidar in Beijing was damaged during this dust process resulting in missing data, and thus the depolarization ratio of the Beijing area is not reflected) is the vertical depolarization ratio and the X-axis shows the universal time.

The RCS from the Wuzhong station Lidar reveals elevated aerosol concentrations from 0:00 on 14 March 2021, at 0–1.7 km, with a depolarization ratio ranging from approximately 0.12 to 0.2, primarily attributed to local urban spherical aerosol particles. After 5:00 on 15 March, the Lidar captures sand and dust, the RCS suddenly increases, and the detection range plummets to 0.3 km. The depolarization ratio also increased to around 0.3 and persisted until the 19th indicating the dust transit during these days. According to the RCS, after 12:00 on 17 March, the signal weakened, and dust concentration began to decrease, primarily below 1 km. By around 22:00 on 18 March, the dust gradually dispersed, forming a layer between 0.2 km and 1 km, subsequently rising to approximately 2 km. Over time, around 16:00 on 19 March, the dust gradually dispersed to 0.5 km, finally disappearing near the ground.

The RCS from the Xi'an station Lidar indicates dust distribution around 16:00 on 14 March; sand dust was distributed between 2.3 km and 5 km. The dust gradually settles to the ground over time and spreads in the process. By around 22:00 on 15 March, the dust had weakened considerably, and the depolarization ratio decreased from 0.36 to 0.12. According to data, the dust entered Xi'an around 4:00 on 16 March, with a sudden increase in the depolarization ratio to around 0.3, persisting until around 16:00 on 18 March. Considering the timing of dust transit in Xi'an and the geographical location of the Xi'an station, it is evident that the dust from 16 March to 18 March is from a different source.

Based on the Lidar detection data in Beijing, the dust storm entered around 8:00 on 15 March. Due to Beijing's higher latitude compared to Wuzhong, the arrival time of this dust storm was slightly later. Before the dust storm entered, the aerosol concentration near the ground in the Beijing area was low. At 8:00 on 15 March, the dust storm entered, sharply increasing the RCS until around 0:00 on 16 March, when the dust concentration returned to pre-arrival levels. The intense dust storm lasted roughly 18 h.

According to Lidar detection data in Jinan and Handan, the dust entered almost simultaneously, affecting both cities. On 14 March, low aerosol concentrations were observed below 1 km in the sky over Jinan, and aerosols from 1.1 km to the ground were observed over Handan. The depolarization ratio in both places was around 0.1. Typically, fine spherical particles (such as water droplets, ice crystals, etc.) exhibit a relatively low depolarization, close to 0, while coarse mineral particles (like sand, dust, etc.) display a relatively high depolarization, close to 1. A depolarization ratio of approximately 0.1 suggests that the scattering particles observed by Lidar may comprise a mixture of fine spherical particles and coarse mineral particles. This occurs because a depolarization ratio between 0 and 1 indicates that the scattered particles possess some non-spherical characteristics but are not exclusively composed of coarse mineral particles. Thus, when the depolarization ratio is around 0.1, it can be inferred that the observed particles constitute a complex mixture of particles with various shapes and sizes, potentially including a mixture of fine spherical particles along with coarse mineral particles. From 16:00 on 15 March, the dust began to transit in Jinan, with the dust aerosol height at about 2 km, and the depolarization ratio at 0.2–0.3. Around 4:00 on 16 March, the dust aerosol height dropped to about 1.5, and the depolarization ratio was between 0.1 and 0.2. Over time, the dust gradually dispersed until around 12:00 on 17 March, when most of the dust had disappeared near the ground, leaving few fine particles near the ground. From the Lidar detection data of Handan, it can be seen that the dust entered on 15 March. Around 12:00 on 15 March, the dust intensity at the station began to reach its peak at a height of about 2 km, with the depolarization ratio around 0.25–0.3. Around 4:00 on 18 March, the dust intensity began to decrease, with the depolarization ratio decreasing to less than 0.1. At this time, the aerosols are no longer dust but fine particles in the city.

Due to the distance and long-distance transmission of dust storms, when the dust storm reached Hefei, the intensity had considerably weakened. According to the RCS in the Hefei area, starting from 16 March, the dust began to transit, with a sustained height of about 0.5 km. At 12:00 on 16 March, the dust intensity increased, with the depolarization ratio between 0.16 and 0.35, and the dust height at about 1 km. Until 19 March, most of the dust had dispersed.

In summary, the six-site lidar observation network provided comprehensive information on this dust transit event. Analysis of data from these six stations revealed that dust heights in Wuzhong, Beijing, Jinan, Handan, and Hefei were mainly concentrated within 2 km. In Xi'an, the dust was primarily concentrated within 1 km and originated from higher altitudes. The depolarization ratio decreased as the dust entered and transited, likely due to the faster settling of dust aerosols compared to other aerosols. The cause of this disparity is inextricably linked to aerosol terminal velocity. The terminal velocity of aerosols refers to the constant rate of descent of these particles in the air under the influence of gravity [58]. This velocity is contingent upon various factors including particle density, size, and shape. Density stands out as a pivotal factor impacting terminal velocity, with higher densities resulting in greater gravitational force acting on the particles and consequently higher terminal velocities. Additionally, particle size plays a significant role in determining terminal velocity. Typically, larger particles exhibit higher terminal velocities owing to their inertia. Moreover, particle shape also influences terminal velocity, as different shapes encounter varying levels of air resistance. For instance, spherical particles generally experience lower terminal velocities compared to particles with jagged edges, attributed to the relatively lower resistance encountered by spherical particles.

3.4. Satellite Remote Sensing and Spaceborne Lidar Observation of Dust Transport

The dynamic evolution of dust storm weather and frontal cloud processes is intricately connected. Cold fronts and warm fronts combine to create frontal cloud systems, which, along with low-pressure systems at the ground level, form frontal cyclones. Due to the low water vapor content in the warm frontal cloud system, precipitation formation is challenging. Consequently, the sand and dust carried by the cold air mass from the north behind the cold front takes advantage of this situation and moves along with the frontal cyclone, resulting in sand and dust weather.

Figure 5 shows cloud imagery captured by the Fengyun satellite during this dust storm event. Panel a, b, and d display images obtained from the 12 μm channel, while panel c presents an RGB composite image using wavelengths of 830 nm, 650 nm, and 470 nm. Analyzing Figure 5a, at 12:30 (UTC) on 14 March 2021, a band-shaped cold front cloud system stretches from the eastern part of Xinjiang to the northeast part of Inner Mongolia. This cold front cloud system exhibits an eastward and southward trend with notable intensity. By around 20:15 (UTC) on 14 March, as depicted in Figure 5b, a spiral cloud system forms over northern China, showing a significant increase in intensity compared to noon on 14 March. At this time, the tail of the cloud system is located in Inner Mongolia, accompanied by the emergence of dust rain. On 15 March, as depicted in Figure 5c, the cold front cloud system continues its movement through the eastern and southern regions of China. Dust storms started to emerge in Inner Mongolia and across most of northern China. In addition, Figure 5c is a color image, so it records the details of the areas where the dust storms passed through more clearly than the other three figures. As time progresses, the cold front cloud system further develops, as shown in Figure 5d, and the northern and southeastern coastal regions of China also come under the influence of this dust storm.

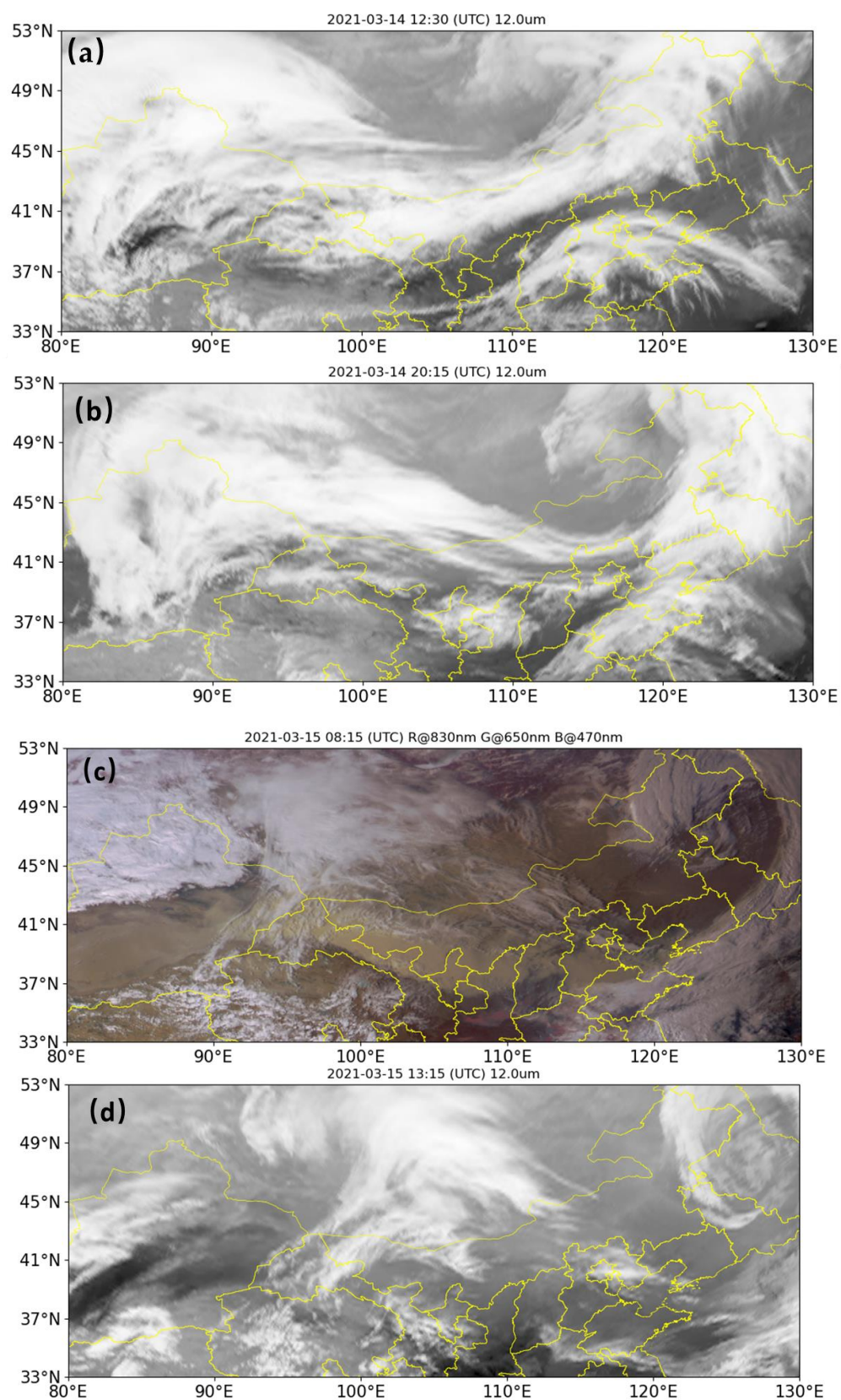


Figure 5. Cloud images of the dust process captured by the Fengyun satellite on 14 March 2021, at 12:30 (plane (a)), 20:15 (plane (b)), 15 March at 8:15 (plane (c)), and 13:15 (plane (d)).

Figure 6 depicts the trajectory of CALIPSO as it transited through the impacted region of the severe dust storm on 16 March 2021 at 5:55 a.m. The trajectory primarily traversed the source areas of this potent dust storm, including Mongolia, Inner Mongolia, Ningxia, Shanxi, and Shaanxi. Area A mainly covers the south-central regions of Ningxia, Shanxi, Shaanxi and Inner Mongolia, while Area B mainly includes northern Inner Mongolia and most of Mongolia. Area A, B in Figure 6 and A, B in Figure 7 are the same Area. These provinces were significantly affected by the dust storm. As shown in Figure 7, it becomes apparent that CALIOP detected dust aerosols while passing through Inner Mongolia, Ningxia, Shanxi, Shaanxi, and Mongolia. In Figure 7, Area A predominantly covers the central and southern regions of Ningxia, Shanxi, Shaanxi, and Inner Mongolia, while Area B mainly includes the northern part of Inner Mongolia and most regions of Mongolia. According to the data presented in Area A of Figure 7a, as the satellite passes over Ningxia, Shanxi, Shaanxi, and the central and southern regions of Inner Mongolia, a continuous aerosol layer is evident below 4 km. The backward scattering coefficient for this aerosol layer exceeds $5 \times 10^{-3} \text{ km}^{-1} \cdot \text{sr}^{-1}$, indicating a notably high aerosol concentration. Among these regions, Ningxia, Shanxi, and Shaanxi display the highest aerosol concentrations. In Area B of Figure 7a, where the satellite primarily traverses Mongolia, a layer of aerosols with a heightened concentration is observed near the surface, approximately 1.2 km above ground level. The backward scattering coefficient for this aerosol layer reaches $1 \times 10^{-2} \text{ km}^{-1} \cdot \text{sr}^{-1}$. Relative to the aerosols in Area A, those in Area B exhibit significantly higher concentrations and a broader range of variation. The combination of Figure 7a,b reveals that the dust aerosol heights in Ningxia, Shanxi, and Shaanxi range from approximately 0.4 km to 3.2 km, with the dust cloud tops in the central and southern parts of Inner Mongolia ranging from about 2 km to 4 km. In the northern part of Inner Mongolia and Mongolia, dust aerosol heights range from 1 km to 4.2 km, with a relatively uniform distribution. The intensity, prolonged duration, and extensive impact of this severe dust storm weather are evident. The signals detected by CALIPSO during its transit from northern Inner Mongolia to entering Mongolia indicate the presence of a high-altitude dust belt at around 3 km from south to north. It can be preliminarily determined that Mongolia is one of the main source regions for this intense dust storm weather.

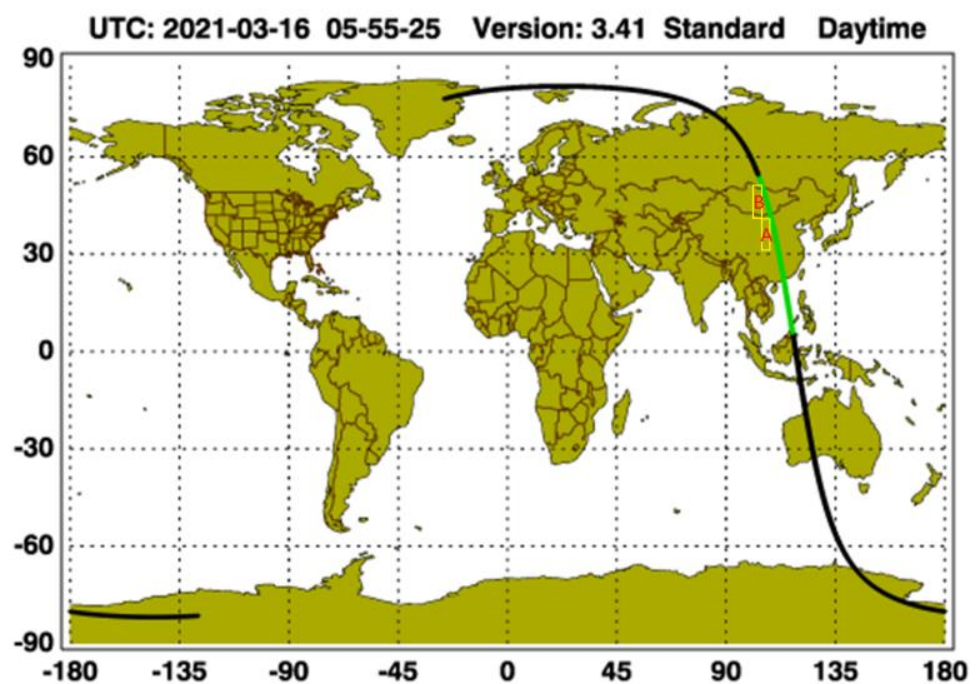


Figure 6. CALIPSO transit trajectory on 16 March 2021.

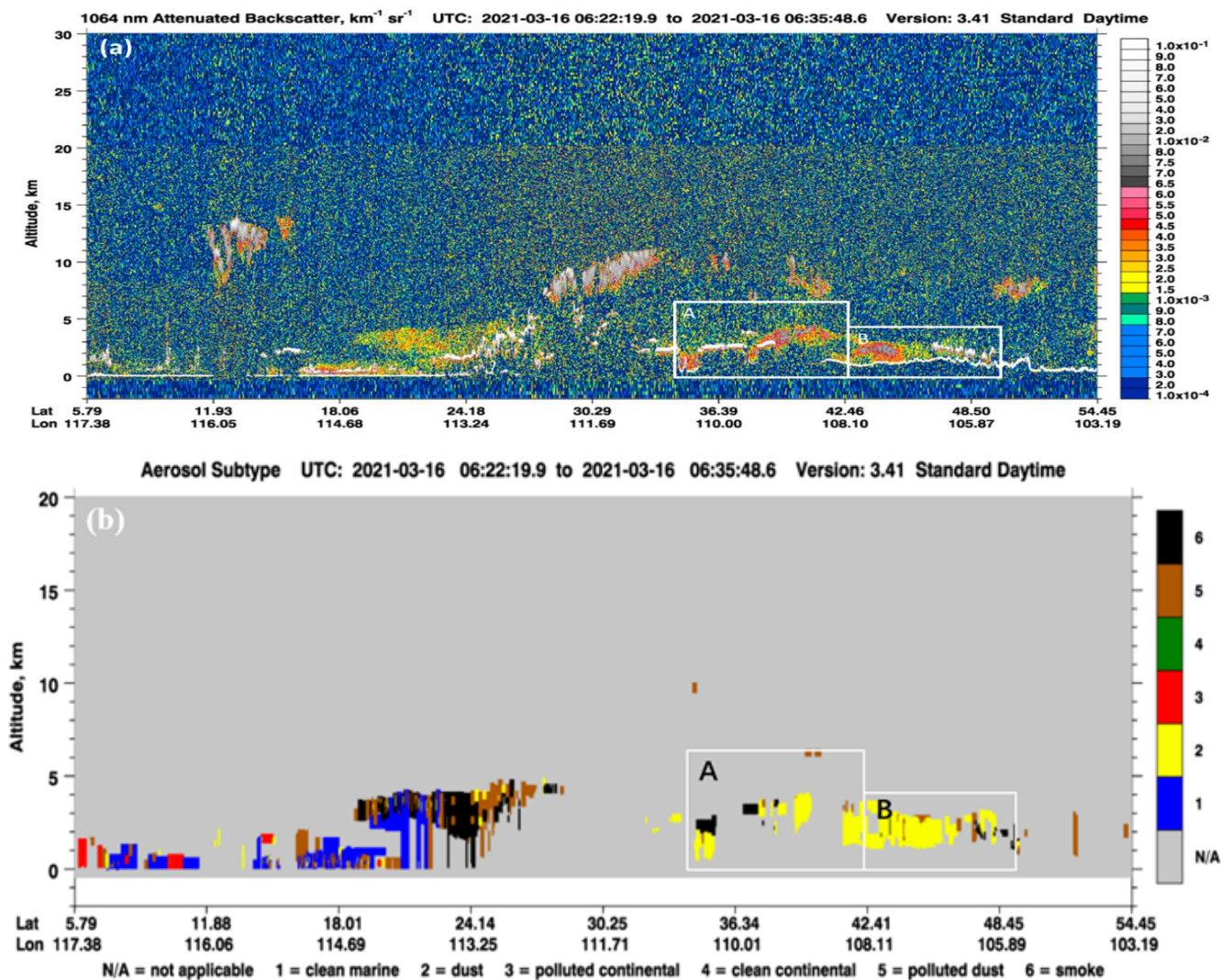


Figure 7. CALIOP data products on 16 March 2021: (a) Attenuated Backscatter Coefficient at 1064 nm wavelength, (b) vertical profile of aerosol classification.

4. Conclusions

In this paper, an investigation into the transboundary transport of dust aerosols during a severe dust storm event in China in March 2021 was conducted. The research utilized meteorological observations of PM_{2.5} and PM₁₀, HYSPLIT model for backward trajectory analysis, ground-based Lidar detection, Fengyun satellite AGRI payload data, and CALIPSO satellite Lidar data. The key findings are summarized as follows.

Firstly, spanning from 14th to 16th March 2021, a notable dust storm event affected large parts of Northern China, resulting in the widespread coverage of haze pollution. During this episode, concentrations of PM_{2.5} and PM₁₀ were relatively elevated, with a significant prevalence of coarse particles. The air quality in five cities—Wuzhong, Xi'an, Beijing, Jinan, and Handan—experienced significant impacts, with Wuzhong enduring the longest duration of influence. Notably, due to its considerable distance from the dust source, Hefei was relatively less affected during this intense dust storm. Secondly, the ground-based Lidar observation network, encompassing six Chinese cities (Wuzhong, Jinan, Xi'an, Handan, Beijing, and Hefei), provided a comprehensive depiction of the entire process of the dust storm. Throughout the dust storm period, the heights of the dust aerosol particle layers at the six sites were predominantly concentrated within 2 km. Additionally, the depolarization ratio exhibited a gradual decrease as the dust particles moved from entry to transit. Among these stations, the Xi'an site encountered two instances of intense sandstorm

weather, and notably, the origins of these two events differed. The recorded entry times for dust at each Lidar station closely align with the entry times provided by authoritative agencies, serving as indirect evidence of the authenticity and precision of the Lidar network observations. Thirdly, CALIPSO satellite observations unveiled a high-altitude dust belt distributed at heights ranging from 3 km to 5 km, extending from the northern part of Inner Mongolia to the central region of Mongolia. Substantial transboundary transport of high-altitude dust aerosols was observed in the northern part of Ningxia, the central and northern parts of Inner Mongolia, and most regions of Mongolia. Backward trajectory analysis using HYSPLIT and cloud image analysis from Fengyun satellite indicated that the dust originated from the Gobi Desert in Mongolia and the deserts in Northwestern China. The primary transport routes were identified as the northern and northwestern directions.

In this context, the ground-based Lidar observation network, equipped with the capability to discern aerosol vertical characteristics, overcame limitations inherent to one-dimensional air quality monitoring from ground stations and two-dimensional observation images from satellites. This breakthrough facilitates a more nuanced understanding of the transboundary transport dynamics of dust storms. Through the integration of sky and ground measurements utilizing satellites, ground monitoring stations, and a Lidar network, the entire process of this severe sandstorm weather event was unveiled. This comprehensive approach not only disclosed the temporal and spatial distribution details of the strong sandstorm but also offered substantial data support for the analysis of the sources and species of dust and aerosols in the region. The insights garnered from this in-depth research and application of the ground-based Lidar observation network and CALIPSO satellite during this severe dust storm lay the groundwork for advancing fine-scale three-dimensional atmospheric detection, enhancing air pollution control measures, and fortifying disaster prediction capabilities on a broader scale.

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