

Dear Editor and reviewers,

Thanks for the valuable comments, which help to improve significantly the quality of the paper. In this revision, we addressed the majority of the reviewer comments especially in terms of the study objective, figure clarity and sentence grammars rephrased. The detailed replies are listed below point by point in red.

Best regards,

Lu She on behalf of all authors

Interactive comment on “Investigation of severe dust storms over the Pan-Eurasian area using multi-satellite observations and ground-based measurements” by Lu She et al.

Anonymous Referee #1

This manuscript describes a severe dust episode originating from Gobi desert on early May 2017. The authors present the event properties based on satellite, in-situ and model back trajectory data. The manuscript is well written and the data are clearly described. However I do not recommend publication in NHESS. The reason is that at this stage it looks more like a report rather than a scientific paper and there is no clear justification of the contribution of this study to the relevant literature (e.g. unique properties of the particular event, explanation of the system behavior, impact, etc.). A simple presentation of measurements does not really contribute to our understanding on these events nor to the improvement of forecasting or mitigation activities. Similar measurements and observations are routinely performed worldwide. For example the origin and the evolution of this specific event has been forecasted by operational atmospheric dust models (e.g. <http://www.bsc.es/ess/bsc-dust-daily-forecast>) so there is really no need to perform HYSPLIT back trajectories.

Response: In this revision we have clearly stated our research objective in the beginning of the last introduction paragraph, which is to “picture a comprehensive view of dust event using different satellite and ground measurements with a recent heavy dust storm over northern China and southern Mongolia from 3 to 8 May 2017 as an example”. Note the reviewer 2 commented that “...the authors combine advantages of satellite data and ground-based data, giving readers a comprehensive and detailed view for this dust event, including its transport trajectory, horizontal and vertical properties of storm,

and its influence on aerosol properties. It can be expected that the study provides a useful contribution to dust transport and related to this Journal.” And the reviewer #3 stated that “the authors used diverse sources of observations to generate the knowledge on origin, timing and spatial coverage of the dust storm, overcoming setbacks of one observational system with other sources of measurements, leaving no room for uncertainties in created hypothesis on this event.”

We have also changed the title and abstract to reflect clearly the objective of this study. We made full use of diverse sources of observations to capture the spatial-temporal distribution of the dust storm, as a single observational system is usually unable to provide such information. Observations from both polar-orbit and geostationary satellites, from active and passive remote sensing, and from ground based measurements were used. In addition, intensive ground-based PM measurements are not derived from the optical method and thus free from the influences of clouds and can even provide measurements during night-time. This complements to the blind areas of satellite observation affected by cloud and in the night time.

We agreed with the reviewer that the operational atmospheric dust models can provide dust-forecast. For example, there are four forecast models from MACC-ECWMF, NGAC-NCEP, KMA (Korea Meteorological Administration), and CMA (China Meteorological Administration), respectively, for the dust storm forecasting for East Asia. However, as stated above, the purpose of this study to demonstrate that combining different models/observations can capture a comprehensive view of dust event. In addition, this case study presented here may be used “in further numerical models development and verification” as stated by Reviewer #3.

Dear Editor and reviewers,

Thanks for the valuable comments, which help to improve significantly the quality of the paper. In this revision, we addressed the majority of the reviewer comments especially in terms of the study objective, figure clarity and sentence grammars rephrased. The detailed replies are listed below point by point in red.

Best regards,

Lu She on behalf of all authors

Interactive comment on “Investigation of severe dust storms over the Pan-Eurasian area using multi-satellite observations and ground-based measurements” by Lu She et al.

Anonymous Referee #2

In this paper, authors use multi-satellite observations and ground-based measurements to analyses a strong dust storm occurred in East Asia during 3 - 8 May 2017, the long-distant transport of the strong dust storms and the properties of dust aerosols were analyzed. The paper investigated the sources and different transport directions of the dust storms from different satellite observation (OMI, CALIPSO, and AHI) and particle matter (PM) measurements from ground-stations, and the HYSPLIT model were used to calculate the backward trajectories of air masses. The aerosol properties and its variation during no-dusty and dusty days were compared using AERONET data. The paper is clearly structured and logical. The authors combine advantages of satellite data and ground-based data, giving readers a comprehensive and detailed view for this dust event, including its transport trajectory, horizontal and vertical properties of storm, and its influence on aerosol properties. It can be expected that the study provides a useful contribution to dust transport and related to this Journal. However, the language of the paper requires some improvements. There are some sentences that are unclear or too long to follow. There are also some redundancies that should be removed. But I realize the authors' first language is not English, and this is not a criticism of them. I would recommend publication if my following comments/suggestions can be adequately addressed. Some comments and questions are given as follows:

Major comments:

1. The core of this paper, in my opinion, is to clearly describe the dust transport process

and the dust affected areas. The authors used long length to explain the transport of dust storm based on multi observations, but it would be better to see a more compact analysis with clearer connections between different observations.

Response: This has been improved in the revision in two aspects: (1) The depiction of dust transports revealed from different satellite time series observations was shortened as most of them exhibit the same pattern. (2) We added several sentences to illustrate the correspondence among different satellite observations. For example, the OMI observations and the CALIPSO were used together to confirm the dust area. The backward trajectories from the HYSPLIT were used to determine the dust source and the dust storm propagation direction. The PM measurements were collected as an effective complement for cloud affected area in the satellite observations, e.g., the south dust transport direction was mostly affected by cloud.

2. The authors should define the scientific aims of this study in more detail than what is done in the last paragraph of the introduction.

Response: The objective of this paper has been stated in the beginning of the last introduction paragraph as “This study tried to picture a comprehensive view of dust event using different satellite and ground measurements with a recent heavy dust storm over northern China and southern Mongolia from 3 to 8 May 2017 as an example.”

The objective is based on the observation that “...few studies have been carried out to fully examine the source, distribution, transport, optical properties of the dust storm. This is possibly because each observation system can only characterize one or several aspects of them.”

3. The authors point out that the dust transported to Korean Peninsula and Japan, but I don't see much analysis supporting these findings, especially for Korean Peninsula. Please check this claim more carefully.

Response: Thanks for this reminder. We have added the following sentence in the first paragraph of Section 3.1. “Furthermore, there is a small portion of the high AI values in the Japan Sea on 7 May (Fig. 2e) indicating that there is a second dust transport path of all the way east and the Korean Peninsula and Japan were affected.”

We have revised the following sentence in the third paragraph of the Section 3.1 as below:

“The HYSPLIT backward trajectory analysis revealed that the air masses that reached the Bering Sea (Fig. 5a), the Kamchatka Peninsula (Fig. 5b), the Sea of Okhotsk (Fig. 5c), and the Japan Sea (Fig. 5d), originated from the Gobi Desert.”

4. The authors have also analyzed the aerosol property variation using four AERONET

sites measurements. The variations in the AOD (440 nm) and Ångström exponent at four sites are shown, but why just show the VSD and SSA at Beijing and Baotou, what about Xuzhou-CUMT and Ussuriysk?

Response: There was no VSD and SSA inversion product for Xuzhou-CUMT and Ussuriysk sites during May 3 – 8, 2017. We have specified this in Fig. 14 caption.

5. There are some sentences and points which are confusing and invalid, even misleading readers. I suggest authors polish those important sentences to make your analysis more useful and clear.

Response: We have throughout checked the paper and revised our English writing carefully.

6. It is hard to read the figures, because some figures are heavily digitized. So I suggest authors to re-plot them or upload un-compressed manuscript.

Response: This has been improved. Details are in blow responses.

Detailed comments:

1. Line 53, 'mm' should be ' μm '

Response: This has been corrected.

2. Fig.2, suggest to use "brown" or other color scheme to represent the UV_AI within 0-1. In addition, the labels on the color bar almost cannot be read! Please enlarge.

Response: This has been corrected. The labels have been enlarged and the color scheme has been modified so that the extreme high AI values pop up better.

3. Fig.3 the PM sites cannot be read. Please enlarge. We can barely read what is written.

Response: The letters have been enlarged. Note the contents of this Figures have been moved to other figures and the PM sites the reviewer concerned were now shown in Fig. 9 with enlarged labels.

4. Fig.4 the orbit tracks is not clearly depicted, please enlarge or just deleted, as the trajectories have been shown in Fig.3

Response: The orbit tracks have been moved to Fig. 2 and were shown with a clear dark blue color.

5. Line 191, 'over the region of northern China on 6 May', it seems that the overpass trajectory of 6 May didn't pass over northern China, see fig.4d. Please check it

Response: It should be 5 May, and we have corrected it in this revised version.

6. Line 212-215, sentence structure needs to be revised.

Response: We have changed this sentence to be “The HYSPLIT backward trajectory analysis revealed that the air masses that reached the Bering Sea (Fig. 5a), the Kamchatka Peninsula (Fig. 5b), and the Sea of Okhotsk (Fig. 5c), and the Japan Sea (Fig. 5d), originated from the Gobi Desert.”.

7. Line 231, ‘true-colour’ should be ‘true color’

Response: This has been corrected.

8. Fig.6 and Fig.7 are somewhat blurred, it’s hard to tell the ‘dust clusters’ that described in line 235, as well as the dust transport.

Response: This has been improved. We have marked out the ‘dust clusters’ in Fig. 6 and Fig.7, and the dust transport direction have been marked with arrows.

9. Line 233-247: This section is a bit confusing, it should be rephrased to make it clearer.

Response: This part has been rephrased in the revised version.

10. Line 262 ‘caused a high PM10 concentration (>500) in south-central China (e.g., Hunan Province)’ It would be better to specify the fig.- rather ‘Hunan province’, as it’s not shown on the map, it is just a new city name to reader.

Response: This has been improved.

11. The authors should clearly conclude the transport process of dust, including different transport directions in ‘Result’ section.

Response: This has been improved. The dust storm propagation in different directions has been added in Fig.1. Furthermore, different data sources have different advantages to reveal the propagation in different directions. Consequently, we have following sentences in the results section

“The OMI-AI revealed one of the long-distance transport path of the strong absorbing aerosols that originated from the Gobi Desert and moved towards the east and then northeast (hereafter referred to as northeast direction for simplicity).”

“Furthermore, there is a small portion of the high AI values in the Japan Sea on 7 May (Fig. 2e) indicating that there is a second dust transport path of all the way east and the Korean Peninsula and Japan were affected.”

“Part of the dust plume over southwestern Inner Mongolia moved along the edge of the Qinghai-Tibet Plateau and then finally reached the northern Sichuan basin (Fig. 6c), revealing the third path of the dust transport. This path of the dust transport is not revealed in the OMI AI time series maps possibly because the dust in this path is not very severe. ... High-frequency observations from the AHI presented more information about this severe dust storm, revealing multi-plumes propagation and several different transport directions, including southeastward, eastward and northeastward. The longest-distance transport occurred in the northeastward direction, as OMI-AI and

CALIPSO-VFM illustrated in the previous section, and finally arrived at the Bering Sea.”

“In this section, the temporal variations in the PM_{2.5} and PM₁₀ mass concentrations over mainland China were analysed and the third path of the dust transport, i.e., towards south, is obvious.”

Dear Editor and reviewers,

Thanks for the valuable comments, which help to improve significantly the quality of the paper. In this revision, we addressed the majority of the reviewer comments especially in terms of the study objective, figure clarity and sentence grammars rephrased by a colleague living in an English-speaking country. The detailed replies are listed below point by point in red.

Best regards,

Lu She on behalf of all authors

Interactive comment on “Investigation of severe dust storms over the Pan-Eurasian area using multi-satellite observations and ground-based measurements” by Lu She et al.

Anonymous Referee #3

Received and published: 5 July 2018

General comments

The Study presented in this manuscript analyze in details large-scale heavy dust storm during May 2017 over Asia. Airborne dust originated from Gobi desert dispersed in several dust plumes, which propagated for several days in different directions. The authors used diverse sources of observations to generate the knowledge on origin, timing and spatial coverage of the dust storm, overcoming setbacks of one observational system with other sources of measurements, leaving no room for uncertainties in created hypothesis on this event. Scientific significance, scientific and presentation quality are good. Presented subject is of great significance because of the popularity of the topic, large impact of dust on climate system, but still not well understood and poorly represented in numerical models. Case study described here may be well used in further numerical models development and verification, since it is hard to correctly capture and describe fully any dust storm. This reviewer recommends this manuscript for publishing, after consideration of the following comments.

Specific comments

1) The title mentions in plural “dust storms”, but in the manuscript is analyzed one dust storm that dispersed in several dust plumes. In the text is also mixture in mentioning dust storm as single event and dust storms as plural. To avoid confusion the authors should decide to define this event as one dust storm that has divided in several dust

plumes or to define this event as severe airborne dust transport, which consists of several dust storms with the same origin. This reviewer suggests defining described event as severe dust storm that has complex multi-plume propagation. Whatever the authors decide, title and the mentioning in the text of the manuscript should be changed accordingly. In the title should be the date of the event, to outstand that the study covers specific study case.

Response: The title has changed to be “Towards a comprehensive view of dust event from multiple satellite and ground measurements: exemplified by the East Asia May 2017 dust storm” in response to this and also to the Reviewer #1 and 2’s concerns on the paper objective.

We have referred to the event as one dust storm that has divided in several dust plumes.

2) In the manuscript there is no analysis of meteorological parameters to be able to understand the atmospheric conditions that produced this severe large-scale dust storm.

It is very important, to fully understand the event, to provide information about synoptic situation. To simplify this request it is enough to add the information on surface wind velocity and direction in the source region at the time of dust emission (or surface wind field), and to provide wind fields at representative height and/of geopotential heights (for example 500mb level) in representative times for later days. This would additionally explain the atmospheric circulation that carried dust particles. Data can be used from reanalysis fields.

Response: We have added the spatial distribution of wind velocity and direction, and geopotential height fields (Fig.3). Related analysis has also been added.

3) Add information about source of input data for HYSPLIT model that produced backward trajectories.

Response: Information about the input data for HYSPLIT mode have been added the revised version in section 2.7.

4) It would be very useful to add an image that presents hypothesis about dust storm propagation in different directions (or mark with arrows in Fig. 1), which is proved using many observations. It is hard to follow in case the geography of the region is not well known.

Response: This has been improved. See Fig.1.

Technical corrections

1) line 26: change “10 mm” in “10 _m”

Response: This typo has been corrected.

2) line 55: change “10 mm” in “10 _m”

Response: This typo has been corrected.

- 3) line 59: change “Many studies have been carried out to study different aspects of dust plumes from deserts using...” in “Many studies have been carried out to study different aspects of airborne dust transport from deserts using...”

Response: This sentence has been rephrased as “Many literatures have studied desert dust from different perspectives using different satellite data, ground-based observations and model simulations (Badarinath et al., 2010; Wang et al., 2013; Teixeira et al., 2016)”.

- 4) line 120: change “that can used to...” in “that can be used to...”

Response: This has been corrected.

- 5) line 123: change “It has been suggested that...” in “It has been evaluated that...”

Response: This has been corrected.

- 6) line 136/137: change “The inversion products includes both microphysical parameters ...” in “The inversion products include both, microphysical parameters ...”

Response: This has been corrected.

- 7) line 146: change in “... during both, day-time and night-time.”

Response: This has been corrected.

- 8) line 149/150: change in “...were collected to evaluate the dust-affected areas and to further analyse the transport of the dust plume.”

Response: This has been corrected.

- 9) line 172: is it correct to have easterly wind in “... swept through the North China plain on 4 May 2017 due to a strong easterly wind,...”? It is not likely to have east wind, maybe west wind, which means that circulation was eastward?

Response: This has been corrected. It should be west wind, and we have also added the information about wind direction, see Fig. 3

- 10) line 215: exclude “The” at the beginning of “The This result is ...”

Response: This has been corrected.

- 11) line 254: In the following sentence “Fig. 8 depicts the PM10 concentration distribution...” add an information about PM data values, are they hourly average of what? how many stations are considered?

Response: More information about PM data has been added in the revised version. The PM values are hourly average, and all the valid observations from 1350 stations located in mainland China were used. The PM values are real-time measurement, the air stations make the measurements every hour.

12) Letters in some Figures are too small, and require large zoom to be readable, especially Fig. 2, Fig. 4 and Fig. 9. If possible, use different rearrangement of plots and landscape mode.

Response: This has been corrected. The letters in figures were enlarged, and the figures have been rearranged in the revised version.

Investigation Towards a comprehensive view of ~~severe~~ dust storms over the Pan-Eurasian area using multi-event from multiple satellite observations—and ground-based measurements: exemplified by the East Asia May 2017 dust storm

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Abstract. ~~The deserts in~~ One or several aspects of the source, distribution, transport, optical properties of airborne dust have been characterized using different types of satellite and ground measurements each with unique advantages. In this study, a dust event occurred over the East Asia are one of the most influential mineral dust source regions in the world. Large amounts of dust particles are emitted and transported area in May 2017 was exemplified to distant regions. A super demonstrate how all the above mentioned aspects of a dust storm characterized by long distance transport occurred over the Pan-Eurasian Experiment (PEEX) area in early May 2017. In this study, multi-satellite/sensor observations and ground event can be pictured by combining the advantages of different satellite and ground measurements. The used data included the Himawari-8 satellite Advanced Himawari Imager (AHI) true-colour images, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aerosol vertical profiles, the Aura satellite Ozone Monitoring Instrument (OMI) aerosol index images, and the ground based measurements combined with the HYbrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model were

used to analyse the dynamical processes of the origin and transport of the strong dust storm. The optical and microphysical properties of the dust particles were analysed using Aerosol Robotic Network (AERONET) aerosol properties and the ground station particulate matter (PM) measurements. From the multi-satellite/sensor (AHI, CALIOP and OMI) time series observations, the dust storms were suggested storm was found to have originated/originate from the Gobi Desert on the morning of 3 May 2017, and it transported dust/transport northeastward to the Bering Sea, eastward to the Korean Peninsula and Japan, and southward to southern-Central/south-central China. The air quality in China drastically deteriorated as a result of this heavy dust storm; drastically: the PM₁₀ (particulate matter less than PM₁₀ < 10 μm in aerodynamic diameter) concentrations measured at some air quality stations located in northern China reached 4000–4333 $\mu\text{g}/\text{m}^3$. During the dust event At the AOE Baotou, Beijing, Xuzhou-CUMT, and Ussuriysk AERONET sites, the maximum AOD/aerosol optical depth values reached 2.96, 2.13, 3, 2.3, 2.87, and 0.65 with sharp drops in and the extinction Ångström exponent (EAE) dropped to 0.023, 0.068, 0.03, and 0.097 at AOE Baotou, Beijing, Xuzhou-CUMT, and Ussuriysk, respectively. The dust storm introduced great variations in the also induced unusual –aerosol property, causing totally different spectral single-scattering albedo (SSA) and volume size distribution (VSD). The combined observations revealed comprehensive information about the dynamic transport of dust and the dust-affected regions, and the effect of dust storms on the aerosol properties.

1. Introduction

Dust storms are prevalent in East Asia due to the large scale of deserts. Large amounts of dust particles are emitted from the deserts in western/northern China and southern Mongolia every year, especially in the spring (Shao et al., 2011). As one of the major mineral dust sources on Earth, the annual dust emissions of eastern Asia reach approximately 25% of the total global dust emissions (Ginoux et al., 2004). These massive emissions produce significant influences on the Earth's radiation balance, climate, ambient air quality and human health (Goudie, 2009; Shao et al., 2011; Rodríguez et al., 2012). Dust aerosols exert both direct and indirect effects on the climate system. Dust can directly scatter and absorb solar radiation over ultraviolet, visible, and infrared wavelengths, resulting in positive or negative forcing (Rosenfeld et al., 2001; Tegen, 2003). Dust is also involved in cloud formation and precipitation processes

and can alter the albedo of snow and ice surfaces, thereby causing indirect effects on the Earth's energy budget (Rodríguez et al., 2012; Rosenfeld et al., 2001; Bangert et al., 2012).

Due to the long-distance transport of dust plumes (Zhu et al., 2007), dust particles can alter the atmospheric conditions in ~~source regions and affect the~~ regional ~~and even~~ global ~~scale climate~~ (Goudie, 2009). ~~It has been suggested that the~~ The dust aerosols from the Taklimakan and Gobi Deserts can travel thousands of miles, thereby affecting large areas of China (Wang et al., 2013; Lee et al., 2010; Chen et al., 2015; Tan et al., 2012), South Korean and Japan (Mikami et al., 2006), and even the Northern Pacific Ocean and North America (Fairlie et al., 2007; Creamean and Prather, 2013; Guo et al., 2017). Dust storms can cause poor air quality and low visibility ~~over both origin regions and transport regions~~ and have severe effects on the human health and environment (Goudie, 2009; Lee et al., 2010). Desert dust is the main contributor to aerosol loading and particulate matter PM ~~(PMparticulate matter)~~ mass concentrations in China during the spring season (Wang et al., 2013). During heavy dust outbreaks, PM₁₀ (PM less than 10 ~~mm~~ µm in aerodynamic diameter) mass concentrations can even reach 20 exceedances of the internationally recommended limit ~~values~~ value in northern China. Moreover, dust particles can interact with anthropogenic pollution and smoke, causing air conditions with greater complexity (Dall'Osto et al., 2010).

Many ~~studies~~ literatures have ~~been carried out to study different aspects of~~ studied desert dust plumes from ~~deserts~~ different perspectives using different satellite data, ground-based observations and model simulations (Badarinath et al., 2010; Wang et al., 2013; Teixeira et al., 2016). ~~On~~ For example, some analysed the ~~one hand, many studies analyse the dust~~ chemical composition and ~~source of dust and~~ investigate the dust radiative effects ~~of dust. These studies focus on the contributions of desert, i.e., dust~~ to aerosol optical and micro-physical properties ~~to obtain a better understanding~~ (Alam et al., 2014; Basha et al., 2015; Srivastava et al., 2014). ~~On the~~ The other ~~hand, some studies are concerned with~~ focused on the long-distance transport of dust plumes using satellite observations and/or model simulations (Huang et al., 2008; Guo et al., 2017; Athanasopoulou et al., 2016) ~~based on the combined use of different data sources to analyse dust formation and transport in depth.~~ However, few studies have been carried out to fully examine the source, distribution, transport, optical properties of the dust storm. This is possibly because each observation system can only characterize one or several aspects of them.

Recently,

This study tried to picture a comprehensive view of dust event using different satellite and ground

measurements with a recent heavy dust storm ~~swept through~~ northern China and southern Mongolia from 3 to 8 May 2017. ~~Influenced by the wind, the~~ as an example. The dust storm spread with wind across south-eastern Russia and even reached the Bering Sea on 7-8 May 2017. ~~This dust event exerted a large-scale influence and caused severe air quality problems, especially in northern China. Based on multi-satellite~~ Satellite time series observations ~~and ground-based measurements, the dynamics and the effects of this severe dust storm on the local aerosol properties were deeply investigated. Satellite observations~~ (the Himawari-8 satellite Advanced Himawari Imager (AHI) true-colour images and the Ozone Monitoring Instrument (OMI) aerosol index (AI) images) were used to capture the dust transport ~~of dust~~. The ~~Ozone Monitoring Instrument (OMI) aerosol index (AI)~~ was also used to provide ~~comprehensive~~ information about the absorbing aerosol distribution. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data were used ~~as an ancillary data source~~ to monitor the dust aerosol type ~~as well as the and~~ vertical distribution ~~of the dust particles~~. The Air Resources Laboratory's HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used to generate back trajectories to identify the dust ~~sources~~ sources. Ground-based measurements from both Aerosol Robotic Network (AERONET) and air quality stations ~~measurements were collected as a complement to characterize the dust-affected areas and used to~~ analyse the variations in aerosol properties caused by the dust storm. ~~This study aims to present a large-scale investigation~~ The connections and comprehensive insight into the long-distance transport of the dust event correspondences among different observations are briefly analysed.

2. Data and methods

2.1 General description of the study area

Fig. 1 shows the topography of the study area. The deserts in China and Mongolia, where an abundance of dust events occur, constitute the second-largest dust source in the world. During the spring, the Gobi region is affected by the Mongolian cyclones, which is the main factor to the severe Asian dust storms (Shao et al., 2011).

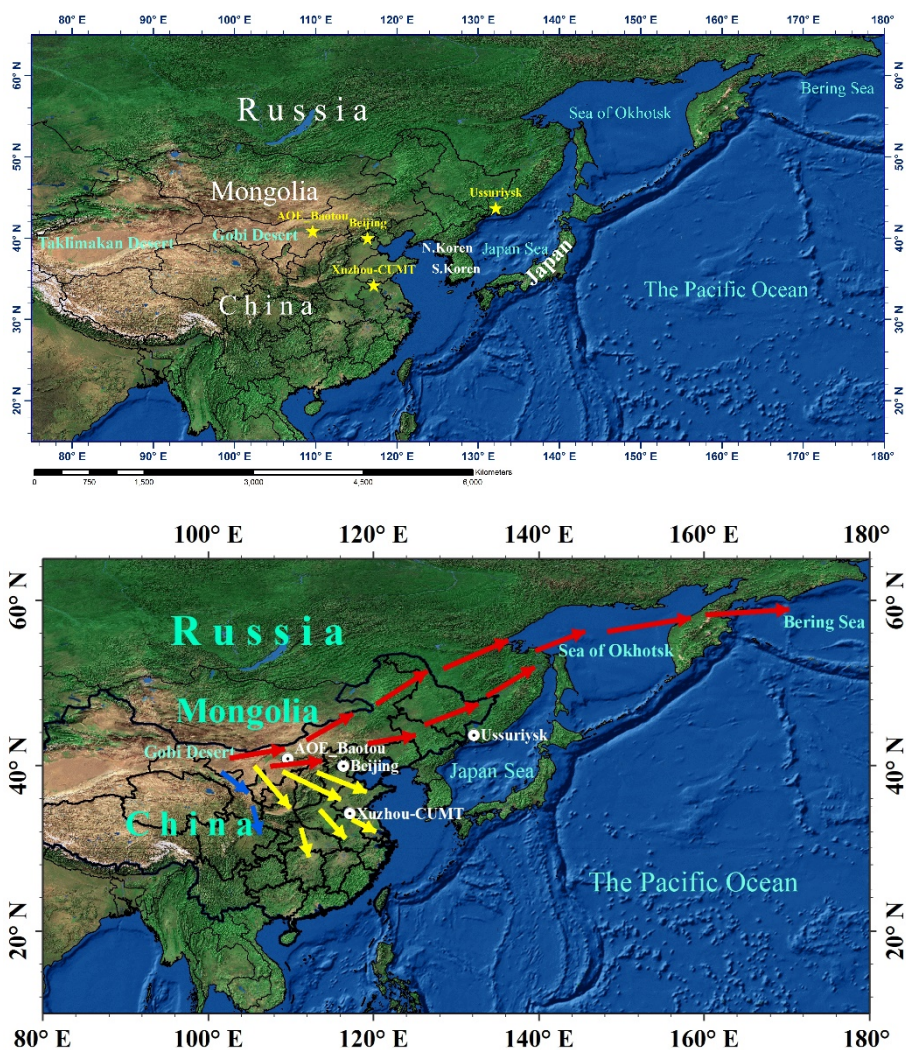


Fig. 1. Study area of this analysis of dust events. The yellow-white circles with black point stars represent four AERONET stations and the arrows show the dust transport directions.

2.2 AHI/Himawari-8 data

The Himawari-8 (H8) satellite was launched on 7 October 2014 by the Japan Meteorological Agency (JMA). It started operation on 7 July 2015. The Advanced Himawari Imager (AHI) onboard H8 can provide multi-spectral observations with a high spatial resolution and high temporal frequency. It has 16 channels with a spatial resolution of 0.5-2 km. The AHI level 2 calibrated data provided by JMA have a spatial coverage of 120° by 120° centred at 0° N, 140° E, and the observation area includes most of eastern Asia, Australia and the Pacific Ocean. In addition, the AHI provides full-disk observations every 10 minutes; this provides us with wide swath, high frequency observations to characterize the dust transport. Here, AHI level 2 calibrated data provided by the JMA and downloaded from the Japan Aerospace Exploration Agency (JAXA) Earth Observation Research Center (EORC) were used

(~~downloaded from~~ <http://www.eorc.jaxa.jp/ptree/terms.html>).

2.3 OMI/Aura

The OMI sensor aboard the Aura satellite measures the Earth in the ultraviolet (UV) and visible spectra (270-550 nm) with a wide swath. ~~The observations of the UV spectra make the OMI data suitable for studying aerosol absorption in the UV spectrum.~~ The OMI provides a parameter called the UV aerosol index (UV-AI), which is a qualitative parameter that detects UV-absorbing aerosols. The UV-AI is sensitive to absorbing aerosols, including mineral dust, black carbon, and biomass burning aerosols (Eck et al., 2001). Therefore, the UV-AI can be used to identify aerosol types through positive values for dust and biomass burning particles and near-zero or small positive values for clouds and weakly absorbing aerosols (Torres et al., 2007). In addition, the UV-AI can be obtained under both cloudy and cloudless conditions; ~~the~~ The surface reflectance also has no impact on the UV-AI, which ~~can detect~~ makes it capable of detecting absorption by aerosols over highly reflective surfaces (Torres et al., 2007). Since this dust event occurred in May, a high UV-AI can be a good indicator of high dust aerosol loading when combined with CALIPSO observations, as Aura and CALIPSO have similar equatorial crossing times. Here, level 3 OMI UV-AI data were used, ~~which have with a $0.125^\circ \times \pm 0.125^\circ$ spatial resolution of $0.125^\circ \times 0.125^\circ$.~~

2.4 CALIOP/CALIPSO

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument on board the CALIPSO satellite provides vertical profiles of the elastic backscatter at two wavelengths (532 nm and 1064 nm) during both day and night. The CALIOP payload also provides linear depolarization at 532 nm that can be used to identify dust aerosols since dust aerosols have a high linear depolarization ratio due to their non-sphericity. Aerosol types are also provided in the CALIPSO aerosol product. The CALIPSO algorithm defines six aerosol types, including smoke, dust, polluted dust, clean continental, polluted continental, and marine (Omar et al., 2009; Omar et al., 2013). It has been ~~suggested~~ evaluated that the CALIPSO aerosol classification works well in most cases (Wu et al., 2014). It should ~~also be considered~~ noted that the accuracy of aerosol detection is decreased over highly reflected land surfaces such as deserts and snow-covered regions, ~~and there is no aerosol information from passive sensors (e.g., OMI) during the night time.~~ Here, CALIPSO level 2 vertical feature mask (VFM) aerosol layer products

were used to provide independent information about dust aerosols, especially for the night-time, as the signal-to-noise ratio during the night-time is better than that during the daytime for CALIPSO (Liu et al., 2009). The VFM products have a vertical resolution of 30 m below 8.2 km, 60 m for 8.2-20.2 km, and 180 m for 20.2-30.1 km (Winker et al., 2007). The dust ~~information, especially regarding the~~ vertical distribution and dust layer height, were analysed using CALIPSO VFM data.

2.5 AERONET data

The ~~Aerosol Robotic Network (AERONET)~~ is a ground-based remote sensing aerosol network (Holben et al., 1998) that provides spectral aerosol optical depth (AOD) and inversion products derived from direct and diffuse radiation measurements by Cimel sun/sky-radiometers (Dubovik et al., 2006). The inversion products ~~includes~~include both microphysical parameters (e.g., the size distribution and complex refractive index) and radiative properties (e.g., the single-scattering albedo and phase function) (Dubovik et al., 2006).

In this study, Level 1.5 cloud screened data including both sun direct data (Version 2 and Version 3) and Inversion data (Version 2) from four AERONET sites in the study area were used to analyse the temporal variations in aerosol properties, including the AOD, the extinction Ångström exponent (EAE), volume size distribution (VSD), and single-scattering albedo (SSA). Fig. 1 shows the locations of the four sites (~~yellow-white circles~~stars), namely, AOE_Baotou, Beijing, Xuzhou-CUMT, and Ussuriysk.

2.6 PM measurements

There are thousands of air quality stations over China that can provide hourly PM measurements during both ~~the daytime, day-time~~ and ~~the~~ night-time. In addition, the measurements are free from the influences of clouds, making it a perfect complement to AERONET observations and satellite observations, ~~as few AERONET stations provided useful observations over China during May 2017.~~ Ground-based measurements of the PM mass concentration over the Chinese mainland were collected to ~~illustrate~~evaluate the dust-affected areas and to further analyse the transport of the dust plume. Furthermore, the temporal variations in the PM concentrations at 14 typical stations were analysed in detail to examine the propagation of dust particles in different directions. Detailed information about these 14 air quality stations is given in Table 1.

Table 1. The cities and locations of the 14 air quality stations to examine the propagation of dust particles

<u>City (Site)</u>	<u>Longitude</u> <u>(°)</u>	<u>Latitude</u> <u>(°)</u>	<u>City (Site)</u>	<u>Longitude</u> <u>(°)</u>	<u>Latitude</u> <u>(°)</u>
<u>Bayannao'er (BYN)</u>	<u>107.5936</u>	<u>40.916</u>	<u>Shanghai (SHS)</u>	<u>121.536</u>	<u>31.2659</u>
<u>Changsha (CSS)</u>	<u>112.9958</u>	<u>28.3586</u>	<u>Taiyuan (TYS)</u>	<u>112.5583</u>	<u>37.7394</u>
<u>Chengde (CDS)</u>	<u>117.9664</u>	<u>40.9161</u>	<u>Tianshui (TSS)</u>	<u>105.7281</u>	<u>34.5814</u>
<u>Guangyuan (GYS)</u>	<u>105.8153</u>	<u>32.4246</u>	<u>Tongliao (TLS)</u>	<u>122.2603</u>	<u>43.6267</u>
<u>Heihe (HHS)</u>	<u>127.4961</u>	<u>50.2486</u>	<u>Weihai (WHS)</u>	<u>122.0508</u>	<u>37.5325</u>
<u>Huhhot (HHT)</u>	<u>111.7277</u>	<u>40.8062</u>	<u>Zhengzhou (ZZS)</u>	<u>113.6113</u>	<u>34.9162</u>
<u>Jiangchang (JCS)</u>	<u>102.1878</u>	<u>38.5247</u>	<u>Zhongwei (ZWS)</u>	<u>105.18</u>	<u>37.0172</u>

2.82.7 HYSPLIT trajectories and meteorological data

The NOAA HYSPLIT model developed by NOAA's Air Resources Laboratory was employed (Draxler and Rolph, 2013). It is widely used for computing air mass forward/backward trajectories to analyse the transport of air/pollution parcels. The start/end point as well as the time of the HYSPLIT computation can be ~~set depending on your interest customized~~. Here, HYSPLIT was used to generate air mass backward trajectories to trace the air movement. The data from Global Data Assimilation System (GDAS) with a spatial resolution of 0.5 degree were used as meteorology input. The backward trajectories ending at 9 selected points were calculated for determining the dust source. The meteorological data including wind vectors and geopotential height (GH) from ECMWF ERA Interim reanalysis dataset were also used (<http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=pl/>). The distribution of the wind direction, wind speed and GH with a spatial resolution of 1 degree during 3-8 May 2017 were analysed to understand the origin and transport of the dust storm.

Table 1. The cities and locations of the 14 air quality stations ~~to examine the propagation of dust particles~~

<u>City (Site)</u>	<u>Longitude</u> <u>(°)</u>	<u>Latitude</u> <u>(°)</u>	<u>City (Site)</u>	<u>Longitude</u> <u>(°)</u>	<u>Latitude</u> <u>(°)</u>
<u>Bayannao'er (BYN)</u>	<u>107.5936</u>	<u>40.916</u>	<u>Shanghai (SHS)</u>	<u>121.536</u>	<u>31.2659</u>
<u>Changsha (CSS)</u>	<u>112.9958</u>	<u>28.3586</u>	<u>Taiyuan (TYS)</u>	<u>112.5583</u>	<u>37.7394</u>

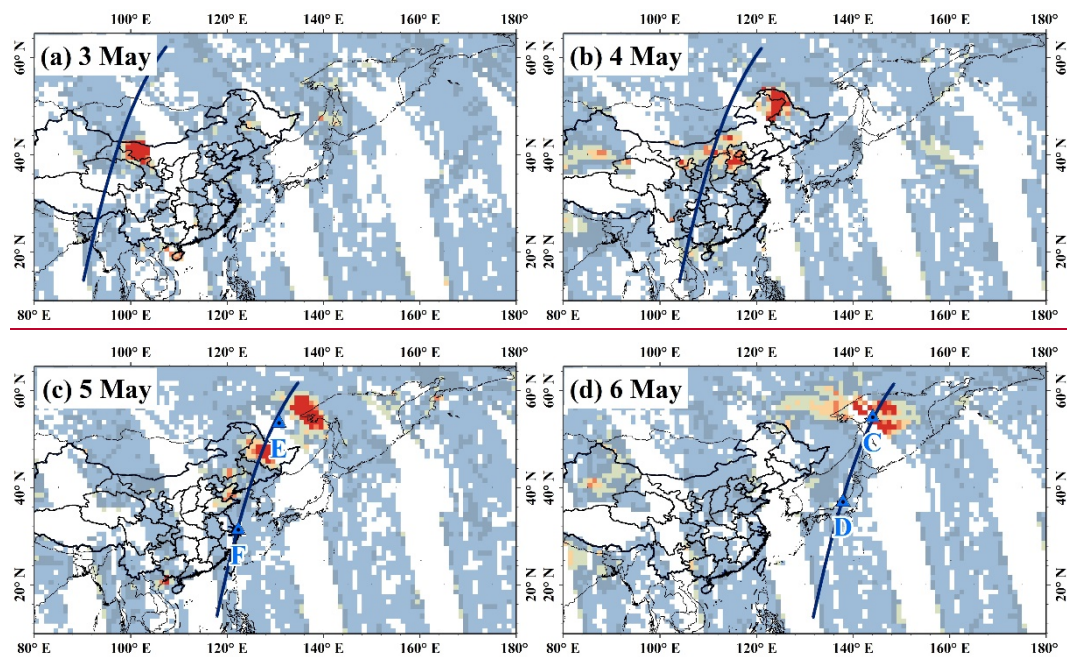
Chengde (CDS)	417.9664	40.9161	Tianshui (TSS)	405.7281	34.5814
Guangyuan (GYS)	405.8153	32.4246	Tongliao (TLS)	422.2603	43.6267
Heihe (HHS)	427.4961	50.2486	Weihai (WHS)	422.0508	37.5325
Huhot (HHT)	411.7277	40.8062	Zhengzhou (ZXS)	413.6113	34.9162
Jiangchang (JCS)	402.1878	38.5247	Zhongwei (ZWS)	405.18	37.0172

3. Results

3.1 ~~OriginSource~~ and transport of the dust event

Fig. 2 shows the spatial distribution of the UV-AI over East Asia from 3 to 8 May 2017 obtained from the OMI-Aura observations. High AI values (>2.0) can be observed over northern China, especially over Inner Mongolia on 3 May, north eastern China on 4-5 May, and south eastern Russia on 5-6 May. The maximum OMI-AI values even exceed 3, indicating time series revealed one of the existence of a large area with a high loading long-distance transport path of the strong absorbing aerosols. From multi-day images, temporal variations in the AI distribution were clearly observed, and that originated from the regions with high AI values were moved Gobi Desert, i.e., moving towards the east and then northeast (hereafter referred to as northeast direction for simplicity). This can be explained by the strong west and southwest wind evident in Fig. 3, which showing the spatial distribution of the wind vectors and geopotential height field at 500-pha level at 06:00 UTC during 3-8 May. The dust storm was initially developed over western Inner Mongolia ($\sim 40^\circ$ N, 100° E) on 3 May 2017 (see Fig. 2a) and then swept through the North China plain on 4 May 2017 due to a strong easterly wind, and the dust storm and reached north eastern China ($\sim 50^\circ$ N, 125° E) within one day on 4 May 2017 due to a strong west wind (Fig. 2b and Fig. 3). On 5 May, the dust plume was transported to the western Sea of Okhotsk ($\sim 56^\circ$ N, 140° E). For the next two days, the elevated dust plume travelled across the Sea of Okhotsk and finally reached the Bering Sea on 7-8 May (see Fig. 2e-f). The OMI-AI effectively revealed the long-distance transport of the strong absorbing aerosols that originated from the Gobi Desert (see Fig. 2e-f). Furthermore, there is a small portion of the high AI values in the Japan Sea on 7 May (Fig. 2e) indicating that there is a second dust transport path of all the way east and the Korean Peninsula and Japan were affected. This is because the wind field diverged to two directions at North China plain, i.e., towards northeast and towards east (Fig. 3).

To ~~be sure~~confirm that the high AI values were caused by dust aerosols, CALIPSO observations that passed through the ~~dusty~~high AI value regions during the night-time were employed to provide aerosol type and vertical distribution information ~~of the dust plume.~~ Fig. 3 shows the overpass trajectory of the CALIPSO observations employed in this study during 3–8 May. Fig. 4 depicts the vertical distributions of the aerosol types ~~and their corresponding~~ for six overpass trajectories. As ~~shown in Fig.2 (the deep blue lines)~~. The dust aerosol (yellow) in Fig. 4b illustrated, large numbers of elevated dust aerosols were distributed over Inner Mongolia and Shanxi Province (from $\sim 40^{\circ}\text{N}$ $\sim 32^{\circ}\text{N}$) on 4 May. As the dust plume travelled eastward and northeastward, a dominant, thick dust layer was observed over the southeastern Russia, northeastern China and Yellow Sea regions on 5 May (corresponded well to the high AI value region in Fig. 4c). Especially over southeastern Russia². Furthermore, the dust layer was thick and distributed from the surface to a 10 km height of 10 km. In the following several days, the elevated dust particles were transported northeasterly and proceeded to the Sea of Okhotsk (Fig. 4d) and Russia's remote Kamchatka Peninsula (Fig. 4e) before finally reaching the Bering Sea (Fig. 4f). Moreover, a part of the aerosol layer was marked as ~~at~~the polluted dust subtype by the VFM product over ~~the~~ Central China on 4 May and over the ~~region of~~ northern China on 6 May. This may be explained by the mixture of dust and anthropogenic pollution.



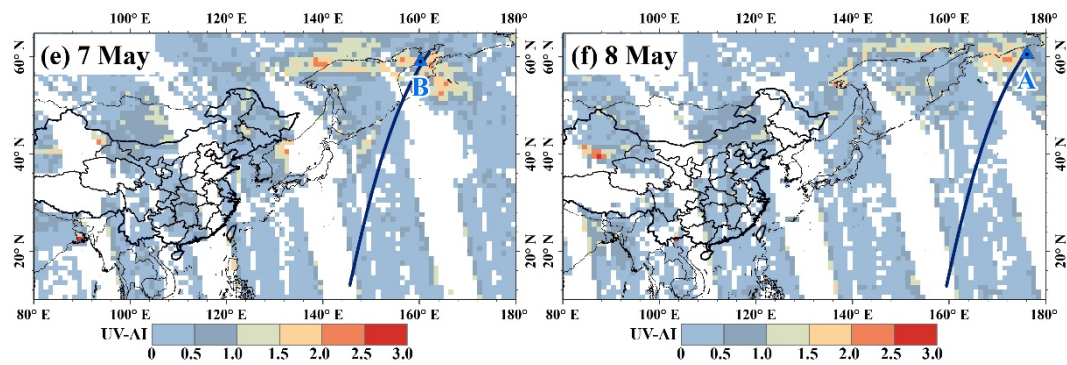


Fig. 4d2. —during the movement of the dust-plume. In addition, dust-marine-aerosol layers over the ocean were also detected on 6–8 May (Fig. 4d2. a–f).

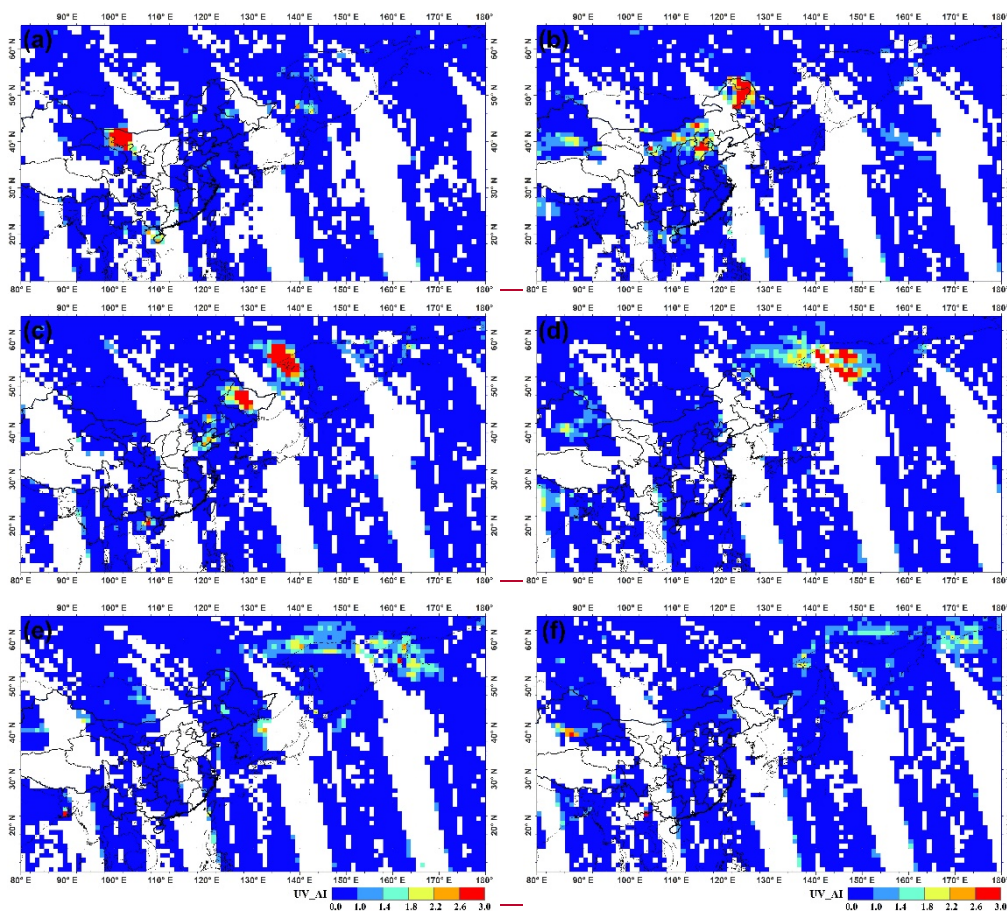


Fig. 2(a–f). Spatial distributions of the OMI UV aerosol-index AI from 3 to 8 May 2017.

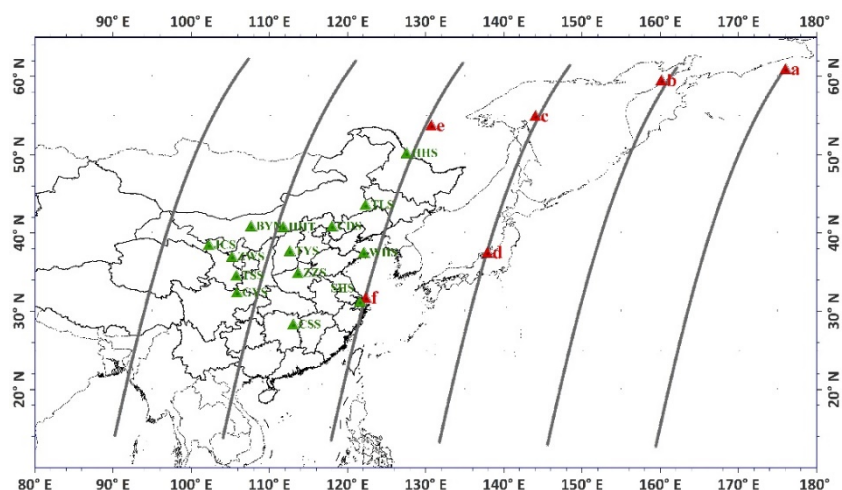
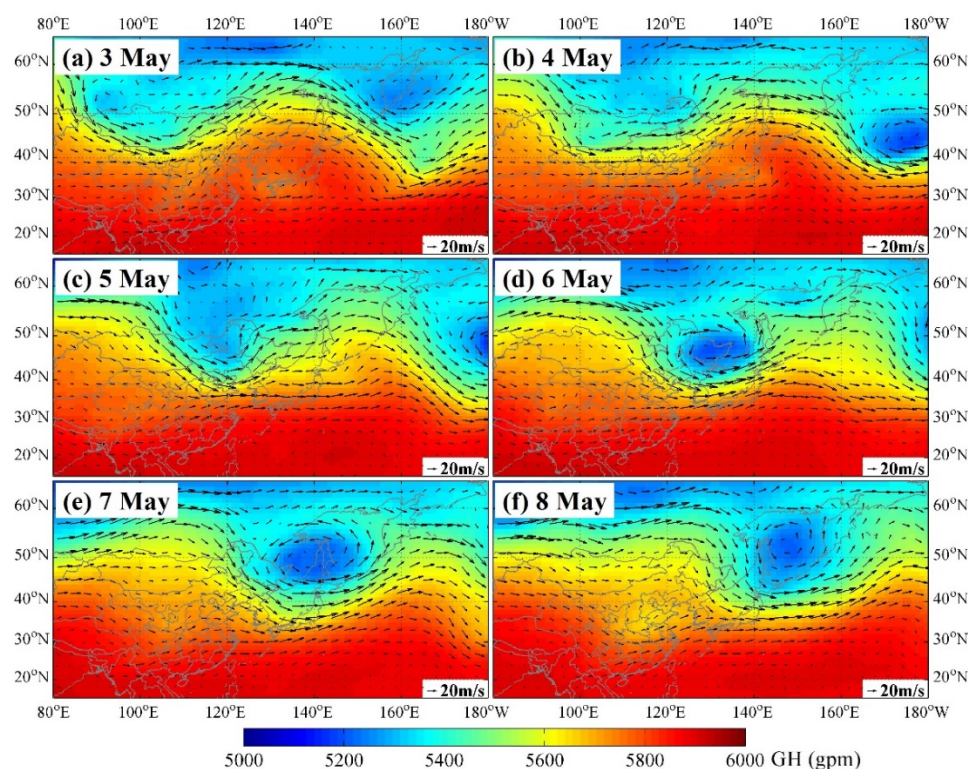
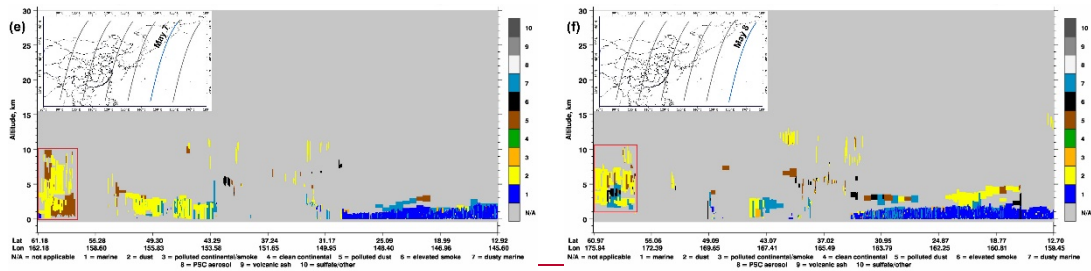
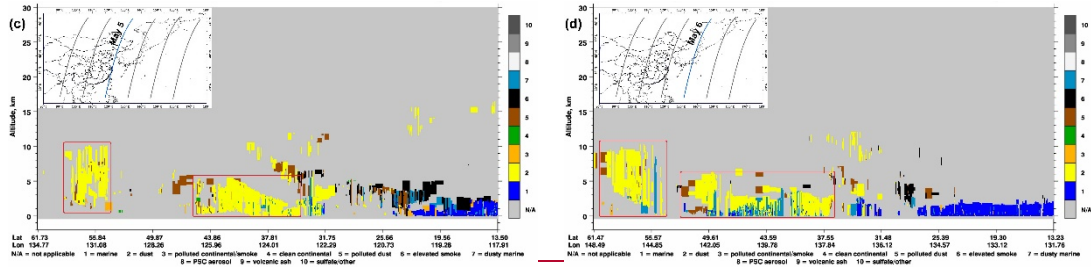
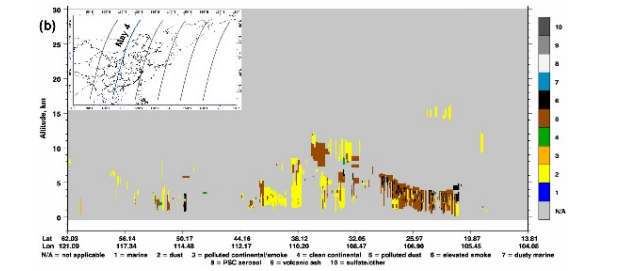
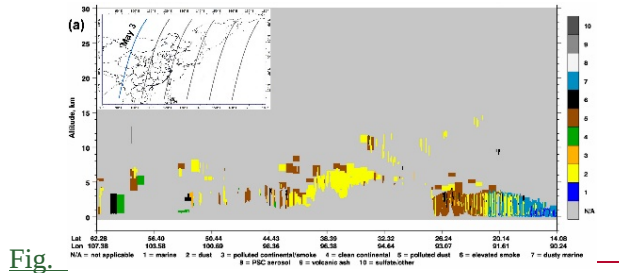


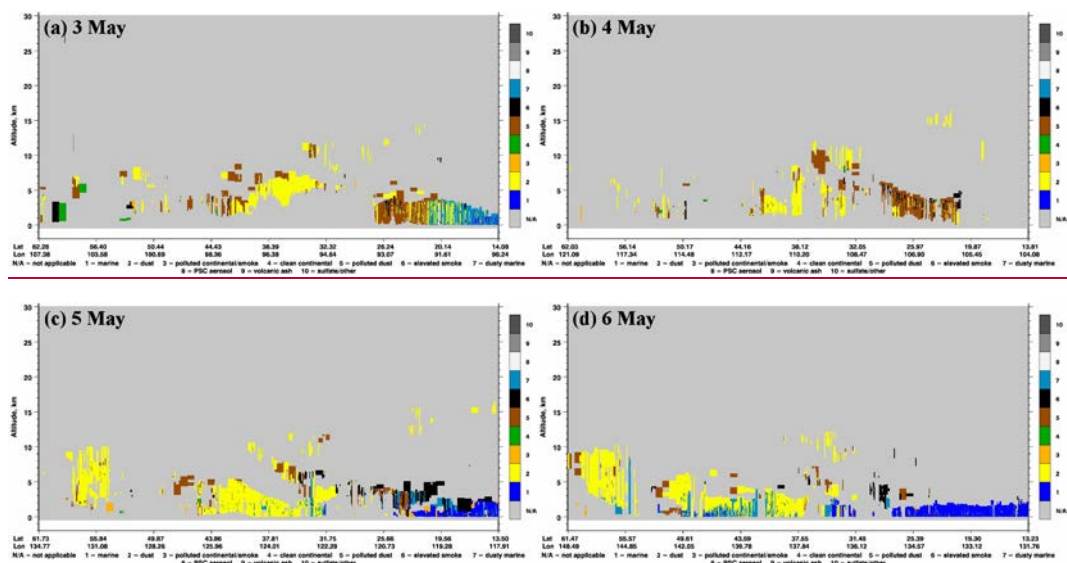
Fig. 3. The deep blue lines are the overpass trajectories of the used CALIPSO observations (grey lines) during 3-8 May, the locations of the air quality stations (green on that day. The blue triangles), and are the end points of the HYSPLIT computation (red triangles).

Fig. 5 shows the backward trajectories at different sources (the blue triangles in Fig. 2) during 5-8 May 2017. The trajectories are computed at three different altitudes (1000 m, 2000 m, and 3000 m). The HYSPLIT backward trajectory analysis revealed that the air masses that reached the Bering Sea (Fig. 5a), the Kamchatka Peninsula (Fig. 5b), the Sea of Okhotsk (Fig. 5c), and the Japan Sea (Fig. 5d) originated from the Gobi Desert. This result is consistent with that from the OMI-AI and CALIPSO aerosol type information.





3. a-f. Spatial distribution of wind vectors and geopotential height (GH) at 500-hPa level at 06:00 UTC during 3-8 May. The GH and wind vectors were derived from ECMWF ERA Interim reanalysis dataset.



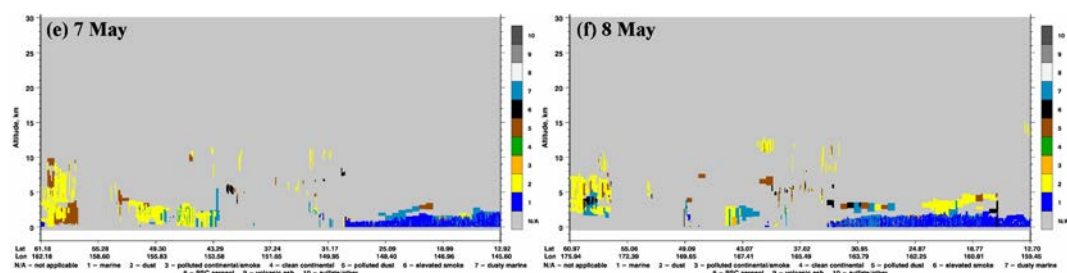


Fig. 4. a-f. CALIPSO aerosol subtypes on 3-8 May 2017. The grey and blue lines in the map represent the orbit tracks used in this work, while the blue line is the corresponding to the overpass trajectory of the trajectories shown in Fig. 2. The dust aerosol subtype is shown in yellow.

Fig. 5 shows the backward trajectories at different sources (the red blue triangles in Fig. 3) within the dusty regions (the red square in Fig. 4c-f) during 5-8 May 2017. The trajectories are computed at three different altitudes (1000 m, 2000 m, and 3000 m). The HYSPLIT backward trajectory analysis revealed that the air masses that reached the Bering Sea (Fig. 5a), the Kamchatka Peninsula (Fig. 5b), and the Sea of Okhotsk (Fig. 5c) in addition to southeastern Russia, and the Japan Sea (Fig. 5e) and eastern China (Fig. 5f) were derived originated from the Gobi Desert. This result is consistent with that from the OMI AI and CALIPSO aerosol type information, providing clearer insight into the sources as well as the movements of the dust particles.

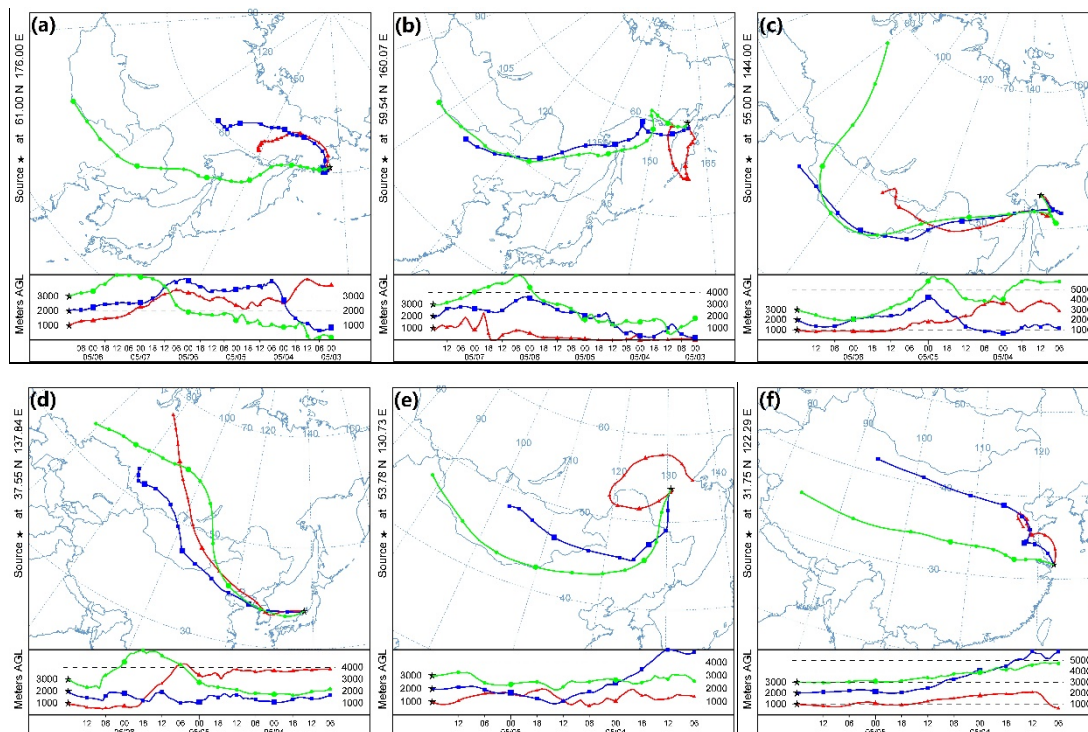
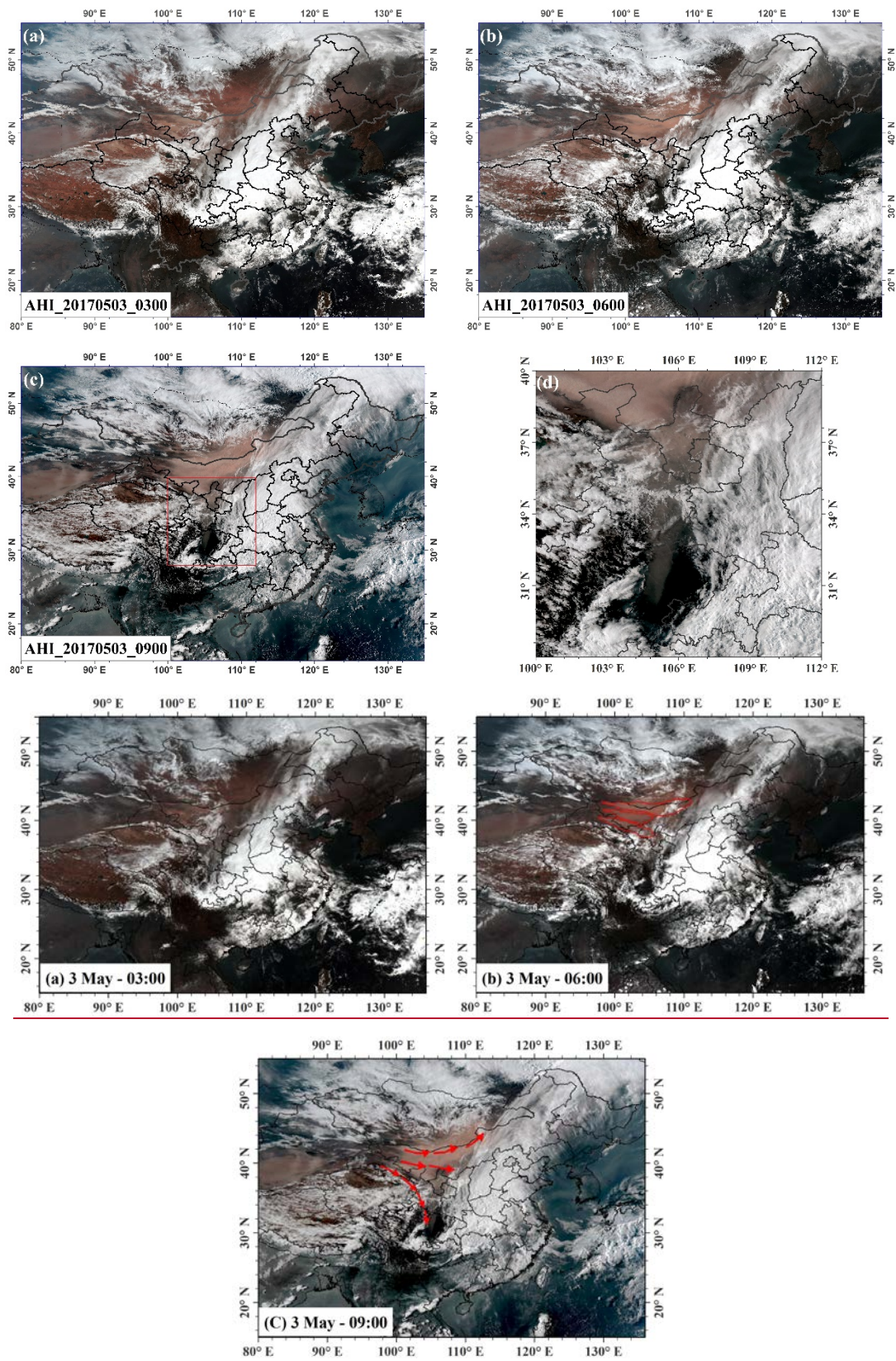


Fig. 5. Backward trajectories derived from the HYSPLIT model at different locations during 5-8 May 2017: (a) 132-h back trajectories ending at the Bering Sea on 8 May, (b) 108-h back trajectories ending at the Kamchatka Peninsula on 7 May, (c-d) 84-h back trajectories ending at the Sea of Okhotsk and the Sea of

Japan on 6 May, respectively, and (e-f) 60-h back trajectories ending at southeastern Russia and the Yangtze River estuary region on 5 May, respectively.

As dust plumes usually move fast with a high temporal variation, polar-orbiting satellites can typically provide only one or two observations per day. Therefore, it is potentially impossible to detect the rapid movements of dust events using polar orbiting observations, as some dust activity would be missed due to the limited pass time and dust deposition. Geostationary satellites can provide high frequency observations over large areas and have unique advantages for obtaining the comprehensive spatial-temporal variations of dust events. For a better view of the transport of the dust plume transport, the high-temporal-resolution observations from the Himawari-8/AHI were used. A time series of true-colour composite images on 3 May (Fig. 6) and 4 May were analysed for more detailed information about the dust evolution. Fig. 6 shows the composite images over a 3-h interval from 03:00 to 09:00 UTC on 3 May (Fig. 7) were shown. The results in Fig. 6 suggest that the strong dust storm was originated from the western part of the Gobi Desert and was formed by several distinct dust clusters (Fig. 6b). In the morning on 3 May, only a small area was covered by a dust plume in the Gobi Desert (Fig. 6a), as the dust storm was continuously increasing and quickly moving. On the one hand, moved. Part of the dust plume over south-western Inner Mongolia moved along the edge of the Qinghai-Tibet Plateau and then finally reached the northern Sichuan basin (Fig. 6c), revealing the third path of the dust transport. This path of the dust transport is not revealed in the OMI AI time series maps possibly because the dust in this path is not very severe. On the other hand, massive dust storm plume travelled along the China-Mongolia border with a continually increasing dust intensity and moved quickly towards the northeast and east. The dust plume moved northeastward reached the border of China, Mongolia and Russian on the afternoon of 3 May. As the dust plume moved eastward, it arrived in the North China Plain and northeastern China on the morning of 4 May (Fig. 7), causing more than 10 provinces in northern China to be covered by a dust plume. In addition, in the late afternoon of 4 May 2017, (Fig. 7), another thick dust storm plume was found that originated from northern Inner Mongolia (Fig. 7e-f7c) that was quickly transported eastward due to strong westerly winds. High-frequency observations from the AHI presented more information about this severe dust event storm, revealing a continuous dust storm multi-plumes propagation and several different transport directions, including south-eastward, eastward and north-eastward. The longest-distance transport occurred in the north-eastward direction, as OMI-AI and CALIPSO-VFM illustrated in the previous section, and the dust

317 finally arrived at the Bering Sea.



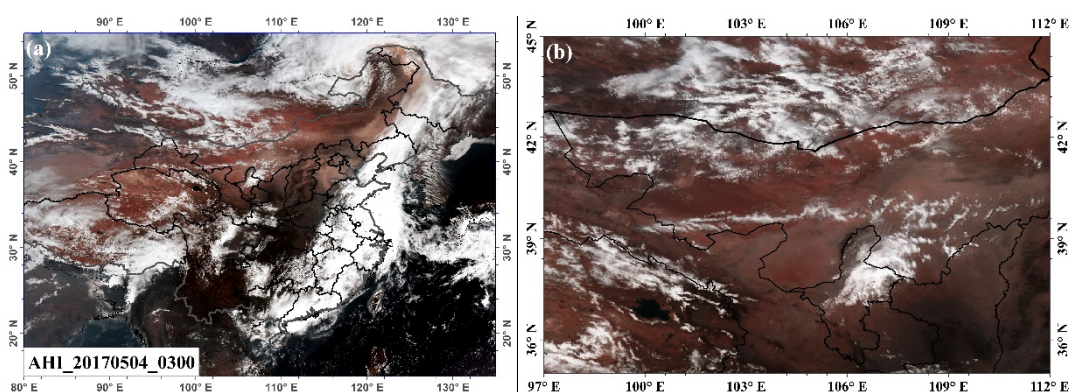
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320 Fig. 6. True-colour composite images of mainland China (a-c) from AHI data over a 3-h interval on 3 May
321 2017. (a) 03:00, (b) 06:00, (c) 09:00, and (d) the area of the red square frame in (c). The red polygons in (b)
322 are dust clusters. The arrows in (c) represents the dust transport directions.

3.2 PM characterization in China during the dust event

In this section, the temporal variations in the $PM_{2.5}$ ($PM < 2.5 \mu m$ in aerodynamic diameter) and PM_{10} mass concentrations over mainland China were analysed and the third path of the dust transport, i.e., towards southeast, is obvious. Fig. 8 depicts the hourly PM_{10} concentration distribution over mainland China over a 12-h interval from 06:00 a.m. on 5 May to 06:00 p.m. on 7 May (Beijing time) using a total of 1350 stations, the PM values are real-time measurements per hour. The PM concentration value less than 200 were shown in grey. Interestingly, south eastward transport was revealed through the intensive PM concentration measurements, which was almost missed by most of the satellite observations because the central and eastern China were covered by cloud during 5-7 May. The high PM_{10} concentration was mostly distributed over $35-40^\circ N$ at 06:00 on 5 May (Fig. 8a). After 12 hours, the dust plume moved to Shandong Peninsula (eastern China close to the Yellow Sea) and further affected Central China on 6 May (Figs. 8 c-d). On May 7 the dust events were found in most stations of eastern and central China (Figs. 8 e-f). The southward propagation of the dust plume caused a high PM_{10} concentration (>500) in south-central China ($\sim 28^\circ N$, $118^\circ E$) as well as the eastern coastal areas including the Shandong Peninsula (eastern China close to the Yellow Sea), and the Yangtze River Delta.



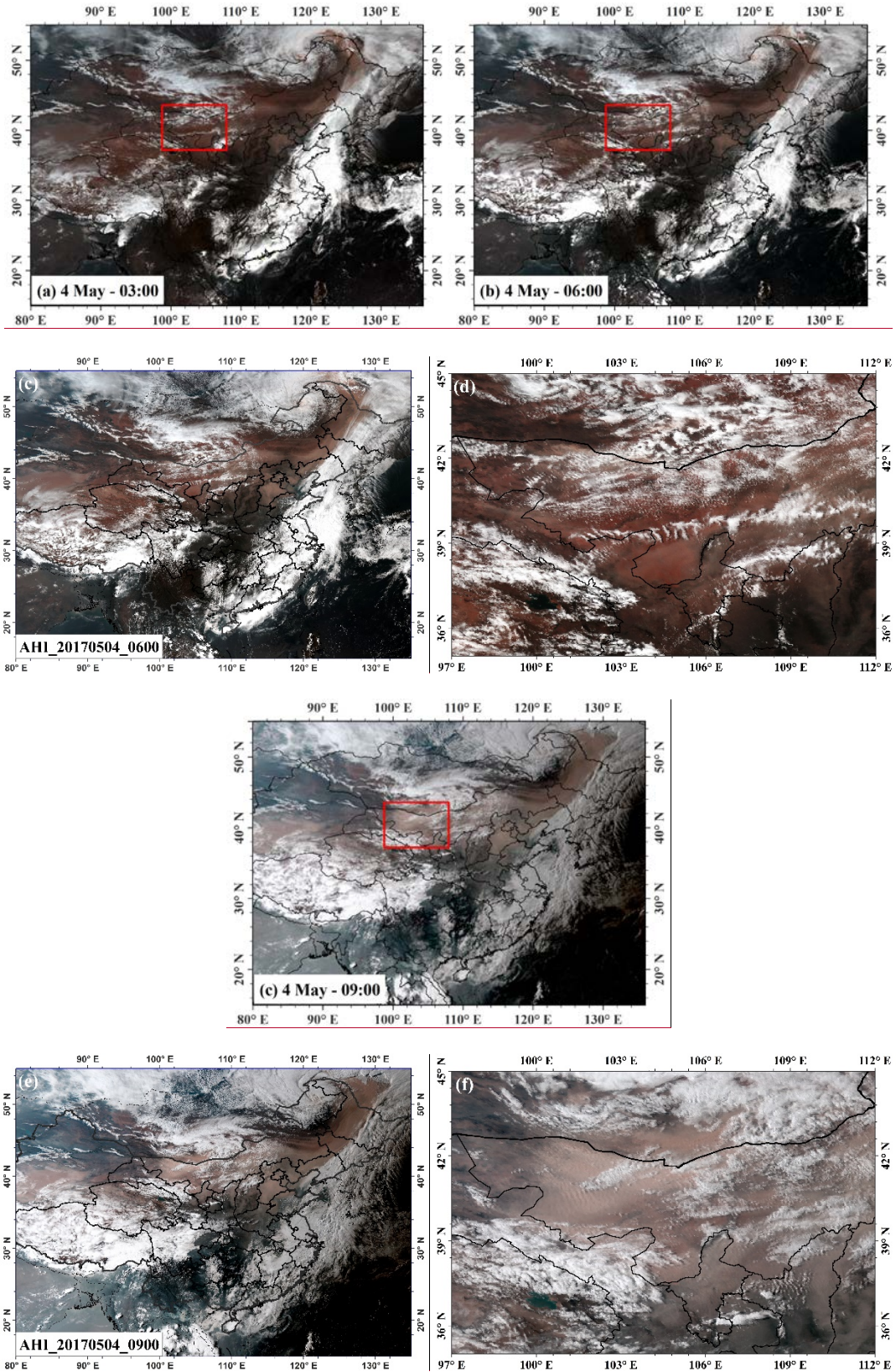
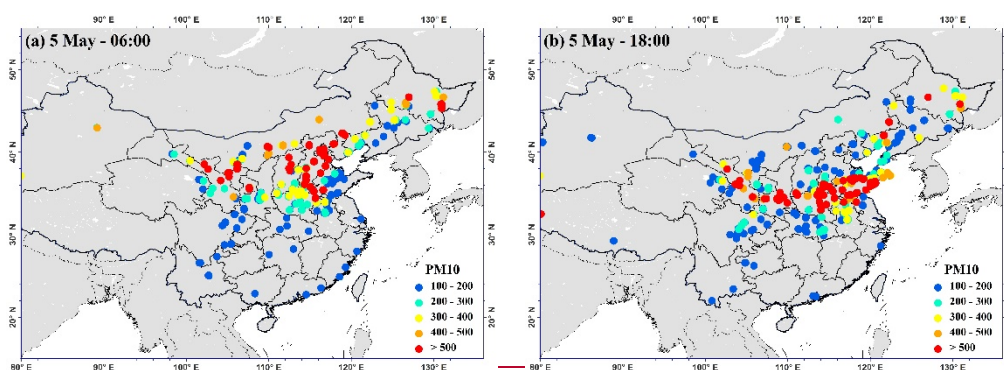


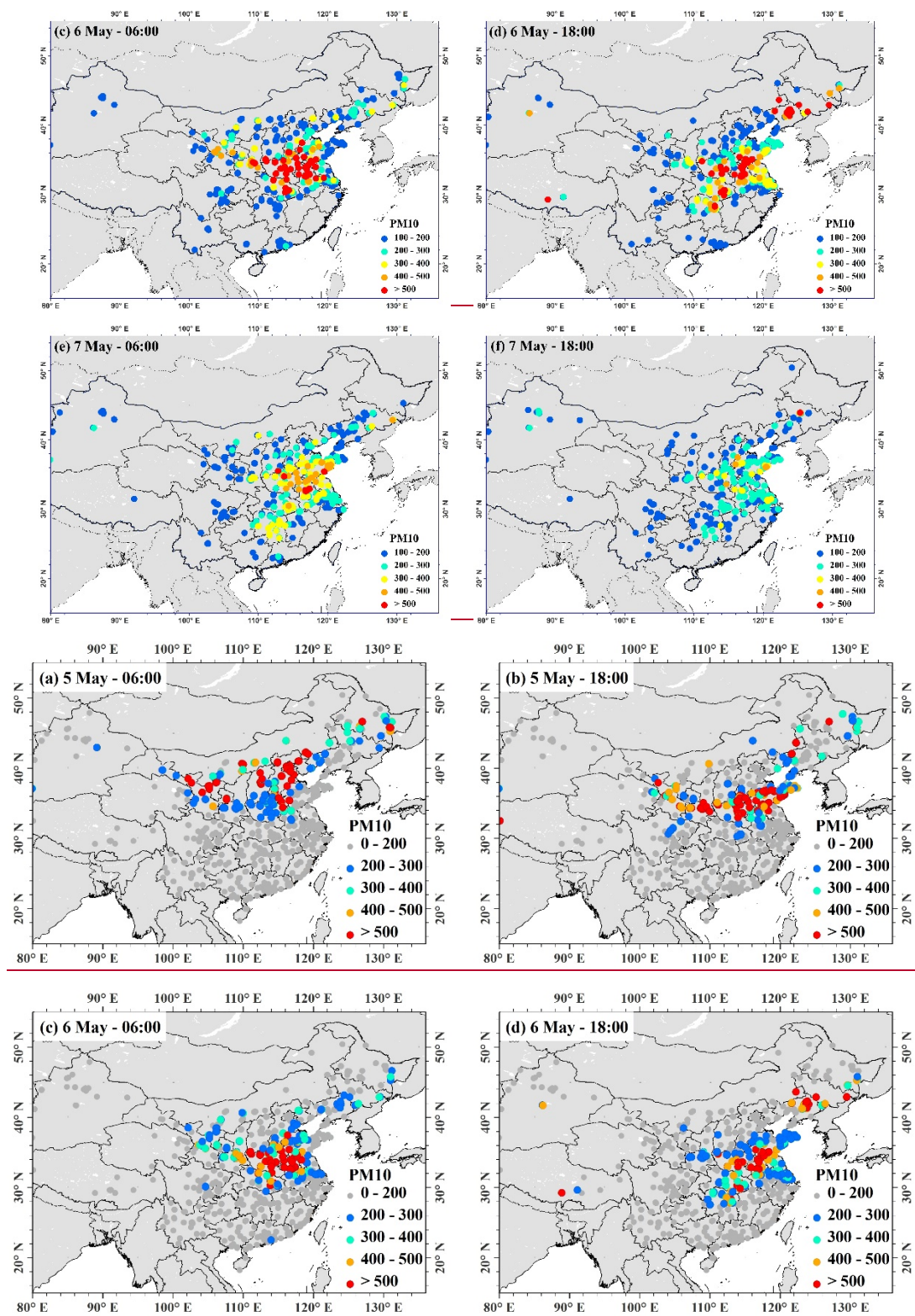
Fig. 7. True-colour composite images of mainland China (a, c, and e) and western Inner Mongolia and the surrounding areas (b, d, and f) from AHI data over a 3-h interval from 03:00 UTC to 09:00 UTC on 4 May 2017. (a) 03:00, (b) 06:00, (c) 09:00. (a) and (b) are at 03:00, (c) and (d) are at 06:00, and (e) and (f) are at

09:00. The red rectangles marked the area where another dust plumes originated from in the afternoon of 4 May.

3.2 PM characterization in China during the dust event

In this section, the temporal variations in the $PM_{2.5}$ ($PM < 2.5 \mu m$ in aerodynamic diameter) and PM_{10} mass concentrations over mainland China were deeply analysed. The and the third path of the dust plume often caused a high aerosol loading and high PM concentration, especially PM_{10} transport, i.e., towards southeast, is obvious. Fig. 8 depicts the hourly PM_{10} concentration distribution over mainland China over a 12 h interval from 06:00 a.m. on 5 May to 06:00 p.m. on 7 May (Beijing time.) using a total of 1350 stations, the PM values are real time measurements per hour. The PM concentration value less than 200 were shown in grey. Interestingly, southeastward transport was revealed through the intensive PM concentration measurements, while it which was almost missed by most of the satellite observations because the central and eastern China were covered by a huge cloud during 5-7 May. The high PM_{10} concentration was mostly distributed over $35-40^\circ N$ at 06:00 on 5 May (Fig. 8a); meanwhile, after). After 12 hours, the dust plume moved to Shandong Peninsula and Henan Province (eastern China close to the Yellow Sea) and further affected Central China on 6 May; two days later, (Figs. 8 c-d). On May 7 the dust events were found in most stations of eastern and central China (Fig. 8 e-f). The southward propagation of this dust event plume caused a high PM_{10} concentration (>500) in south-central China (e.g., Hunan Province ($\sim 28^\circ N, 118^\circ E$)) as well as the eastern coastal areas including the Shandong Peninsula, Jiangsu Province (eastern China close to the Yellow Sea), and the Yangtze River Delta.





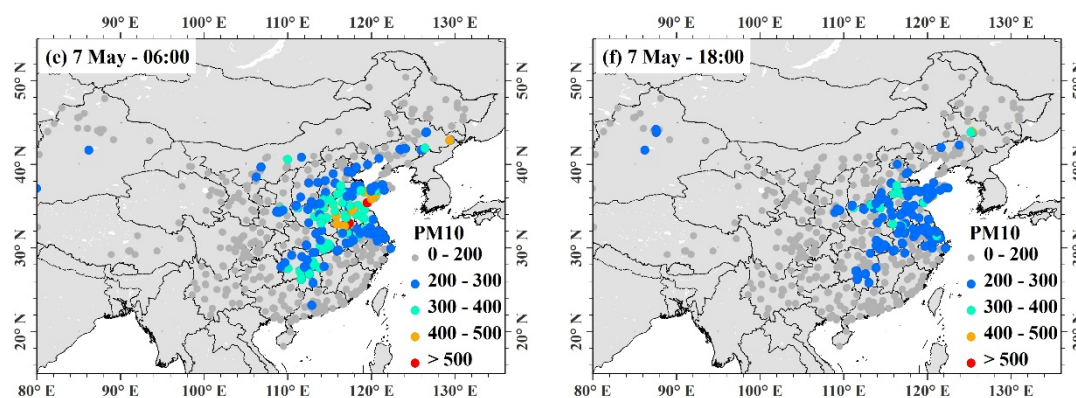


Fig. 8. PM₁₀ mass concentrations measured by ground-based air quality stations in mainland China over a 12-h interval from 06:00 on May 5 to 18:00 on May 7.

To obtain better insight into the dust evolution, measurements from 14 typical air quality stations (the colour circles in Fig. 9) situated within the source and transport areas of the dust were analysed in detail. As the PM concentration was measured during both the day-time and night-time, the data can provide much more information about this continuous dust plume. Fig. 10 shows the PM temporal variations along three different dust transport directions during 2 to 7 May, including the northeastward propagation (a), southward propagation (b) and southeastward propagation (c). It is clearly observed that both the PM_{2.5} and the PM₁₀ increased dramatically, and the PM₁₀ showed much larger increments than the PM_{2.5} during this dust event from all three figures.

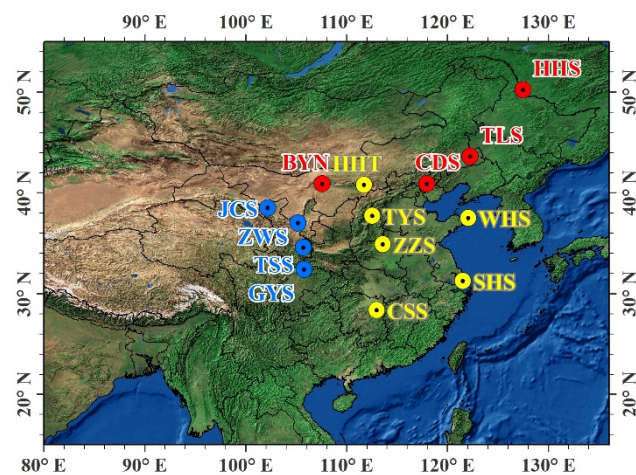


Fig. 9. The locations of the 14 air quality stations. Different color represent different dust transport directions names by sequencing site names in the time order when the dust passes: the northeast direction of BYN-CDS-TLS-HHS, and the two south directions of JCS-ZWS-TSS-GYS and HHT-TYS-ZYS-CSS. Note the east direction travelling to the Japan Sea is not shown as most of its path is over sea without air quality stations.

To obtain better insight into the dust evolution, measurements from 14 typical air quality stations (the green trianglescolor circles in Fig. 39) situated within the originsource and transport areas of the dust were analysed in detail. As the PM concentration was measured during both the daytimeday time and the

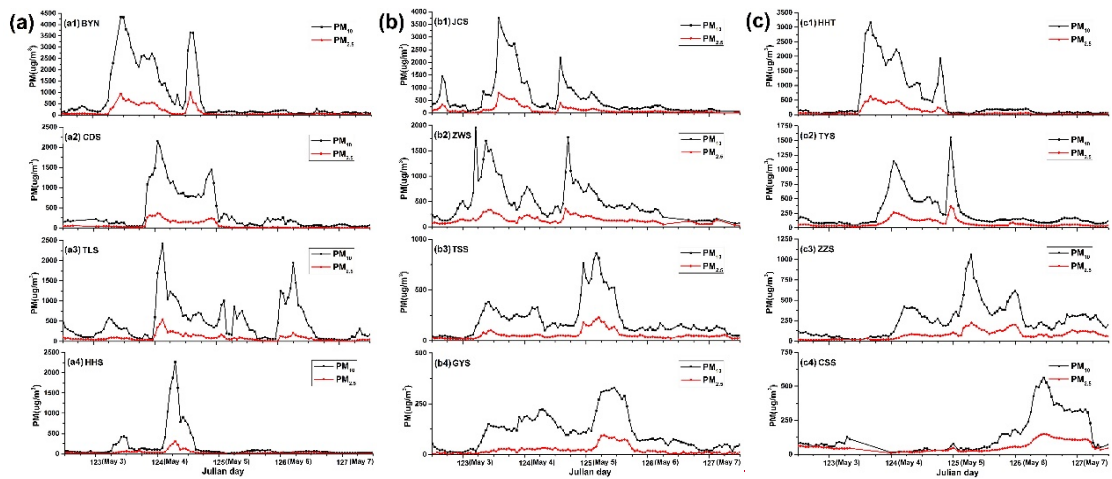
night time, the data can provide much more information about this continuous dust plume. Fig. 910 shows the PM temporal variations along three different dust transport directions during 2 to 7 May, including the northeastward propagation (a), southward propagation (b) and southeastward propagation (c). It is clearly observed that both the PM_{2.5} and the PM₁₀ were increasingincreased dramatically, and the PM₁₀ showed much larger increments than the PM_{2.5} during this dust event from all three figures.

As Fig. 9a10a illustrates, the sharp increase in the PM mass concentration was first observed at BYN station BYN on the morning onof 3 May, followed by the stations at CDS (23:00 UTC on 3 May) and TLS (8:00 UTC on 4 May), and reached the northeastern-most city, namely, Heihe (HHS) (06:00 UTC on 4 May). The maximum value of PM₁₀ concentration at BYN reached 4333 µg/m³ on 4 May. And continuing sharp increase in the PM₁₀ concentration were observed at those sites, indicating continuous outbreak of dust storms. Cities in northeastern China were deeply affected by the transported heavy dust storms, highHigh PM₁₀ concentrations occurred successively at those sites. These drastic changes in the PM₁₀ are in agreement with the dust movements revealed from the satellite observations.

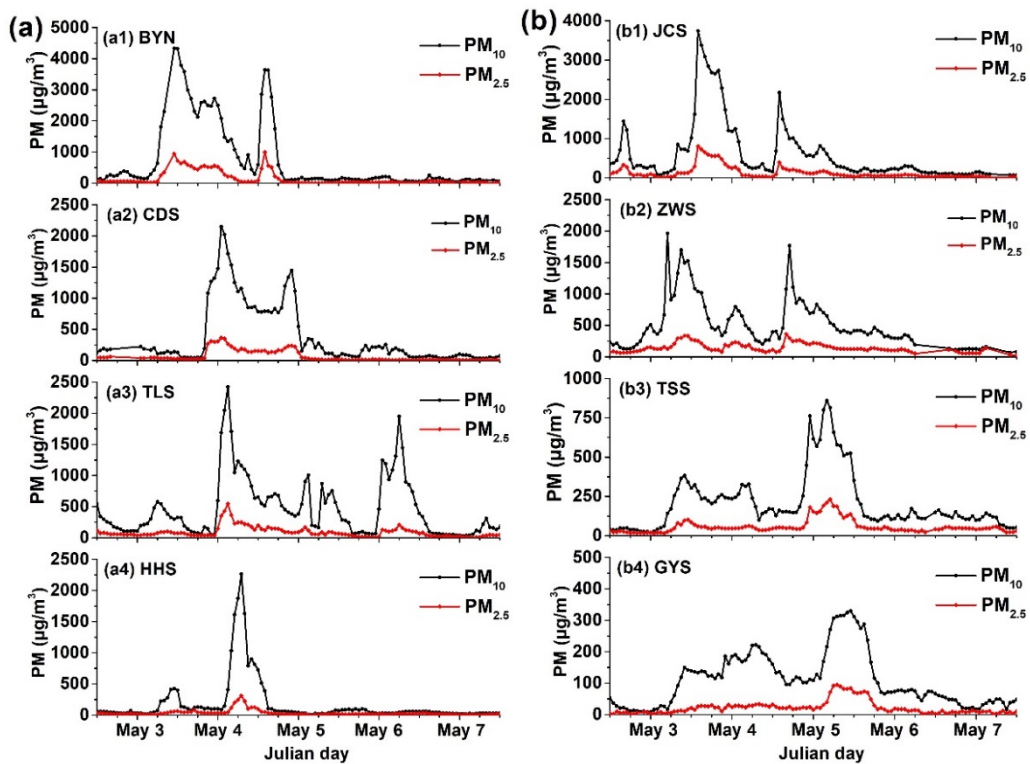
PM measurements at 4 stations distributed along the eastern edge of the Qinghai-Tibet Plateau, including JCS, ZWS, TSS and GYS, are shown in Fig. 9b10b. Within one day, the dust plume was transported across Gansu and reached GYS, which is located in the Sichuan Basin. This transport was also revealed by the high-frequency AHI observations (Fig. 6c-and-d), although it is not as noticeable.

Fig. 9e10c displays the PM concentration variations over the cities located in Central China, including Taiyuan (TYS), Zhengzhou (ZZS), and Changsha (CSS). The sharp increase in the PM₁₀ concentration with a very slight rise in the PM_{2.5} concentration indicates that the dust plume travelled to southern Central China and caused a bad air quality there. In addition, high PM concentrationconcentrations were observed in the coastal areas of eastern China, as shown in Fig. 10-shows11. Note that the increases of PM₁₀ are much larger than the increments of PM_{2.5} in those these stations, suggesting that the dust particles were transported to southern and eastern China.

To confirm this southward propagation of dust, the backward trajectories ending at GYS, CSS, and SHS were analysed by HYSPLIT, as shown in Fig. 1112. The trajectories are computed at three different altitudes (500 m, 1000 m, and 1500 m). As the trajectories illustrate, theThe northwestern air masses at all three locations originated from sources in the Gobi Desert. Thus, dust could be the main reason for the sudden jumpincrease in the PM concentrations. The back trajectories at the three sites computed from HYSPLIT are consistent with our analysis based on PM measurements.



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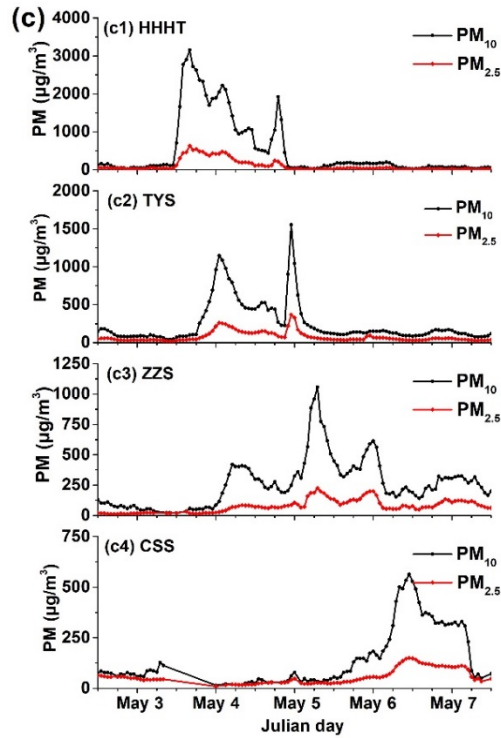


Fig. 910. Time series of the $PM_{2.5}$ (red curves) and PM_{10} concentrations (black curves) during 2-7 May at 14 air quality stations in three directions: (a) northeastward propagation, including (a1) BYN, (a2) CDS, (a3) TLS and (a4) HHS, (b) southward propagation, including (b1) JCS, (b2) BYS, (b3) TSS and (b4) GYS, and (c) southeastward propagation, including (c1) HHT, (c2) TYS, (c3) ZZS and (c4) CSS.

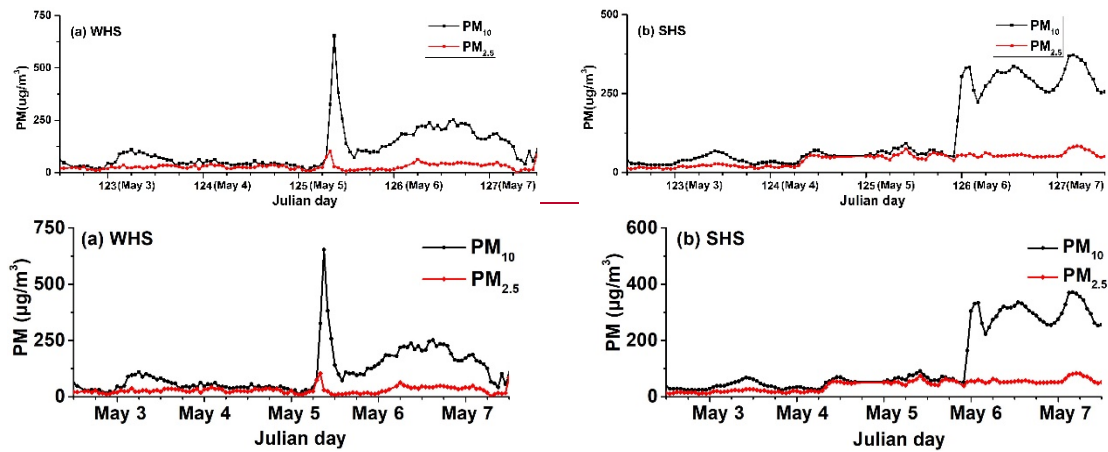


Fig. 1011. Time series of the $PM_{2.5}$ (red curves) and PM_{10} concentrations (black curves) during 2-7 May at (a) WHS and (b) SHS.

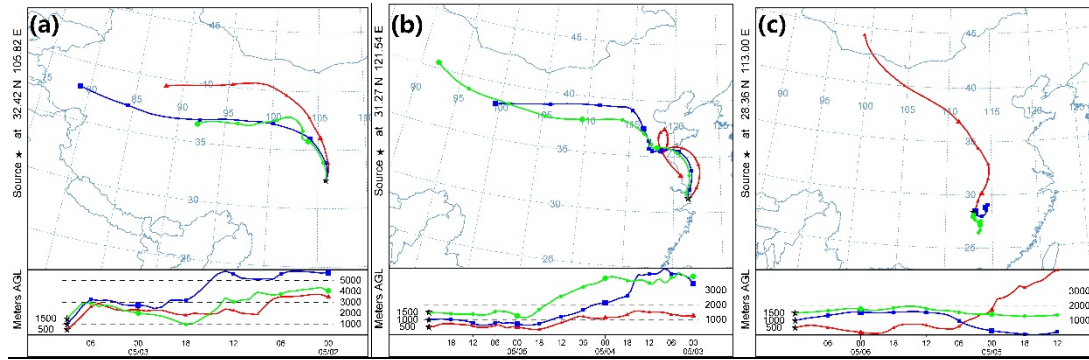


Fig. 12. Backward trajectories derived from the HYSPLIT model at different altitude levels (500 m, 1000 m, and 1500 m) at (a) GYS on 3 May, (b) SHS on 6 May, and (c) CSS on 6 May 2017.

3.3 Aerosol property variations during the dust event

In order to understand the effects of dust storm on aerosol properties, the changes in the aerosol properties at four typical AERONET stations located in the study area were investigated. ~~These four sites are located in different environments; the~~ The longitudes of AOE_Baotou, Beijing, and Ussuriysk increase from west to east, and the latitudes of AOE_Baotou, Beijing, and Xuzhou-CUMT decrease from north to south. ~~This can help to illustrate the temporal variations in the aerosol characteristics due to the movement of the dust plume. Several key parameters (Fig. 1).~~ Several key aerosol properties, including the AOD, EAE, SSA, and aerosol ~~volume size distribution (VSD)~~ VSD, were analysed in detail.

The temporal variations in the daily AOD and EAE at the four AERONET sites during dusty and non-dusty days are plotted in Fig. ~~1213-a-d~~. The maximum AODs at 440 nm caused by the dust storm were 2.96, 2.13, 2.87, and 0.65 at AOE_Baotou, Beijing, Xuzhou-CUMT, and Ussuriysk, respectively. The maximum AOD at Baotou (the westernmost station) was recorded on 2 May 2017 and became lower afterwards ~~with a low EAE value of 0.15. Another increase in the AOD as well as a drop in the EAE occurred on 4 May, and the dust continued for several days.~~ Then, the dust storm moved eastward, and the highest AOD value of 2.13 was observed over Beijing on 4 May 2017. As the dust storm travelled northeastward, ~~the~~ Ussuriysk, located in southern Russia, was affected with a slight increase in the AOD (from ~0.25 to ~0.65) and a sharp decrease in the EAE (from ~1 to ~0.1) on 5 May 2017. Xuzhou-CUMT, which is located in southern Central China, was also severely affected by the strong dust on 4-5 May. The maximum AODs occurred at different times at the four sites due to the movement of the dust storm. In addition, there are obvious negative correlations between the AOD and EAE during the dust event. The dust storm brought numerous large particles, causing the low EAE and high extinction properties.

As one of the most important properties affecting aerosol radiative forcing, aerosol absorption also exhibits huge variations. The SSA is strongly related to absorption/scattering characteristics. Fig. 1314 shows the variability of the spectral SSA before, during and after this dust event, and it is compared with the monthly average as a benchmark. The SSA at longer wavelengths (e.g., 675, 870, and 1020 nm) at AOE_Baotou varied from ~0.8 to ~0.9 during non-dusty days (1 May and 62 May), and the monthly average of SSA_{675nm} (SSA at 675 nm) was approximately 0.9, while, In contrast the SSA_{675nm} increased to 0.97-0.98 during dust days (2 and 4 May). In addition, the spectral behaviour of the SSA showed significant differences. The SSA increased with the wavelength on 2 May and 4 May. Especially on 4 May, the SSA largely increased from 440 nm to 675 nm (from 0.93 to 0.98), and the dSSA ($dSSA = SSA_{870nm} - SSA_{440nm}$) also increased to 0.07. According to Dubovik et al. (2002), mineral dust aerosols tend toward a dSSA value greater than 0.05. In contrast, the monthly average of the spectral SSA as well as the spectral SSA during non-dusty days obviously decreased with the an-increase in the wavelength. The high SSA and increasing spectral behaviour indicates that aerosol particles are dominated by large particles with strong scattering. However, it was noticed that the SSA_{440nm} on 2 May was high with low absorption. This could be explained by the mixture of dust aerosols with large amounts of anthropogenic aerosols from industrial emissions, which are more absorbent.

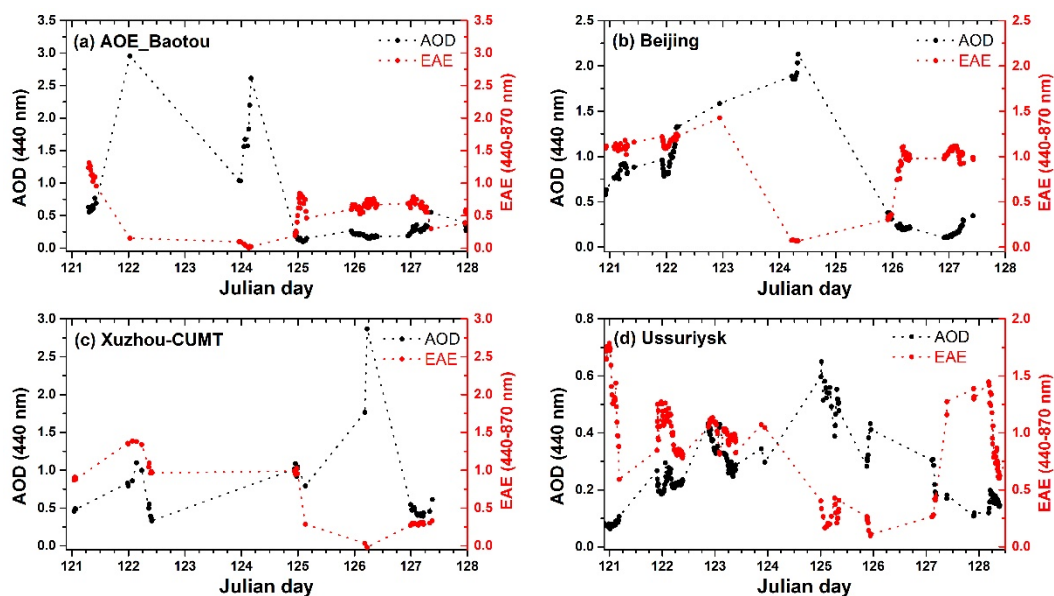


Fig. 1213. Variations in the AOD (440 nm) and Ångström exponent (440-870 nm) at (a) AOE_Baotou, (b) Beijing, (c) Xuzhou-CUMT, and (d) Ussuriysk during 1-8 May 2017.

Similar properties can be observed over Beijing, as the dusts over both Baotou and Beijing have similar sources. However, there are still a few differences. The monthly average of the spectral SSA in

Beijing was lower than that in AOE_Baotou, and an opposite spectral dependence was observed between these two sites. Baotou was affected by a greater quantity of industry emissions than Beijing, as it is a heavy industry city. ~~In addition, it also suffered from additional dust due to its geographical location.~~ The VSD variation showed a more obvious distinction between dusty and non-dusty days. As Fig. 1314 illustrates, the particle volumes of fine-mode aerosols are comparable with those of coarse-mode aerosols in Beijing and Baotou during non-dusty days. The strong dust storm caused a dramatic increase in coarse-mode particles ~~compared with non-dusty days.~~ The volume median radius also showed differences between dusty and non-dusty days; ~~the~~ The VSD peaks ~~increased with the AOD due to the dust storms,~~ ~~and the peak~~ occurred at radii of $\sim 2 \mu\text{m}$ with peak values of 1.05 and 1.8 on 4 May at Baotou and Beijing, respectively. Meanwhile, no significant variation was observed for fine-mode particles. It is observed that the volumes of both fine- and coarse-mode particles were large at AOE_Baotou on 2 May due to the combination of fine-mode aerosols with dust particles. This also explains the spectral SSA behaviour on that day.

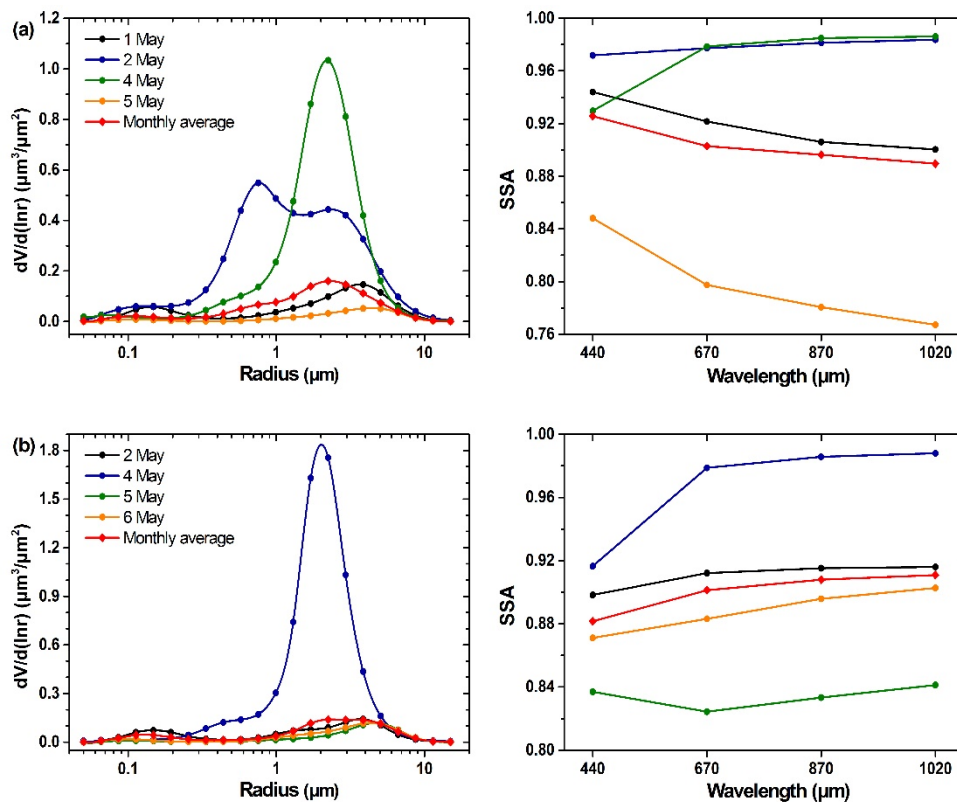


Fig. 1314. Variations in the daily aerosol volume size distribution and spectral SSA during the dust event at (a) AOE_Baotou and (b) Beijing. Different colours represent different days, and the red curves represent the average VSD and SSA in May 2017. There was no VSD and SSA inversion product for Xuzhou-CUMT and Ussuriysk sites during May 3-8 2017.

4. Conclusions

In this study, we described a strong dust storm that occurred in northern China and Mongolia in early May 2017. The ~~origin~~source and transport were investigated using multi-satellite data (including OMI, CALIPSO, and AHI), ground-based measurements (including PM measurements and AERONET observations), and HYSPLIT model computations. Benefiting from the high frequency of geostationary satellite observations, the rapid spatial-temporal variations in the dust plume were captured, including the continuous dust storms originating from the Gobi Desert region and different transport directions over China region. The ~~OMI-AI and~~ OMI-AI and CALIPSO observations during the night-time provided more comprehensive information with larger coverage for the large-scale transport and vertical distribution of the dust plume. Intensive measurements (in both time and space) of the PM mass concentration revealed additional details when the region was covered by thick clouds and CALIPSO covered limited observation areas. The backward trajectories computed from the HYSPLIT model also confirmed the ~~directions of~~ dust transport directions. From the combined observations, this severe dust storm was ~~suggested found~~ to ~~have originated~~originate from the Gobi Desert, ~~due to the strong winds, the continuous dust storms travelled and~~ travel to three different directions ~~and affected~~affecting large areas of China, including northern China, southeast China, and even Central China due to the strong winds. In addition, southern and eastern Russia and the Bering Sea were influenced by the long-distance transport of the strong dust plume. The aerosol properties (EA_E, SSA, and VSD) have changed greatly during the dusty days; as numerous large particles contributed to strong scattering and extinction. Overall, the combined observations of satellite- and ground-based data contributed to the comprehensive monitoring of the ~~origin~~source and long-distance transport of the dust storms, providing complete information on the spatial-temporal distribution.

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