

East Asian dust storm in May 2017: observations, modelling and its influence on Asia-Pacific region

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Abstract. A severe dust storm event originated from the Gobi Desert in Central and East Asia during 2-7 May, 2017. Based on moderate resolution imaging spectroradiometer (MODIS) satellite products, hourly environmental monitoring measurements from Chinese cities and East Asian meteorological observation stations, and numerical simulations, we analysed the spatial and temporal characteristics of this dust event as well as its associated impact on the Asia-Pacific region. The maximum observed hourly PM₁₀ (particulate matter with an aerodynamic diameter $\leq 10 \mu\text{m}$) concentration was above 1000 $\mu\text{g m}^{-3}$ in Beijing, Tianjin, Shijiazhuang, Baoding, and Langfang and above 2000 $\mu\text{g m}^{-3}$ in Erdos, Hohhot, Baotou, and Alxa in northern China. This dust event affected over 8.35 million km², or 87% of mainland China, and significantly deteriorated air quality in 316 cities of the 367 cities examined across China. The maximum surface wind speed during the dust storm was 23-24 m s⁻¹ in the Mongolian Gobi Desert and 20-22 m s⁻¹ in central Inner Mongolia, indicating the potential source regions of this dust event. Lidar-derived vertical dust profiles in Beijing, Seoul, and Tokyo indicated dust aerosols were uplifted to an altitude of 1.5-3.5 km whereas simulations by the Weather Research and Forecasting with Chemistry (WRF-Chem) model indicated 20.4 Tg and 5.3 Tg of aeolian dust being deposited respectively across continental Asia and the North Pacific Ocean. According to forward trajectory analysis by the FLEXible PARTicle dispersion (FLEXPART) model, the East Asian dust plume moved across the North Pacific within a week. Dust concentrations decreased from East Asian continent across the Pacific Ocean from a magnitude of 10³ to 10⁻⁵ $\mu\text{g m}^{-3}$, while dust deposition intensity ranged from 10⁴ to 10⁻¹ mg m⁻². This dust event was unusual due to its impact on continental China, Korea, Japan and North Pacific Ocean. Asian dust storms such as observed in early May 2017 may lead to wider climate forcing on a global scale.

Key words: Air quality; Climate change; East Asia; Gobi Desert; Particulate matter

1 Introduction

A major dust storm arose and swept over East Asia on 2-7 May, 2017. This dust storm originated from the deserts of Central and East Asia, namely the Mongolian Gobi Desert, Taklimakan Desert, Hexi Corridor, and Alxa Desert (Fig. 1 and Fig. 2). Visibility was reduced to <100 m as a result of dense dust near Guaizihu (41.37°N, 102.37°E) on the north edge of the Badain
5 Jaran sand desert and Turpan (42.83°N, 89.25°E) on the north edge of Taklimakan Desert. Maximum surface wind speed reached 24 m s⁻¹ in the Mongolian Gobi Desert (43.1°N, 109.2°E) and air quality was consequently very poor during this dust storm. This storm was unusual in that East Asian dust storms typically develop along more south-eastward trajectories (Satake et al., 2004; Nee et al, 2007; Huang et al., 2008). Dust storms develop as a result of passage of synoptic cold fronts (Hsu et al., 2006). Over the past five decades, the frequency of Asian dust events has decreased due to ecological restoration efforts and
10 climate change (Shao et al., 2011a; Lyu et al., 2017a). Strong dust storms have not occurred in the past seven years. Although East Asian dust storms mostly occur during springtime (Zhang et al., 1997; Shao and Dong, 2006; Chen, 2010; Li et al., 2012), it is essential to determine dust sources, emission, transport, and deposition to enhance our understanding of the negative impact of atmospheric dust on global warming (Tegen et al., 1996; Stanhill, 2005; Park et al., 2011; IPCC, 2013; Carslaw et al., 2013; Huang et al., 2014).

15 Dust aerosols can be transported long distances, even on a global scale from Africa to the Americas or from Asia to North America (Merrill et al., 1994; Uno et al., 2009; Shao et al., 2011a). Atmospheric dust has been observed across continents and oceans, giving rise to its importance in both terrestrial and marine ecosystems (Huebert et al, 2003; Mahowald et al., 2009; IPCC, 2013; Kok et al., 2017). Mineral aerosols can influence air quality by reducing visibility and bolstering concentrations of inhalable particulate matter (Sharratt et al., 2006; Huneus et al., 2011; Goudie, 2014). In dust source regions, atmospheric
20 dust concentrations can approach 1-10 mg m⁻³ while dust particles can be uplifted to altitudes of 2-10 km under strong wind shear stress (McTainsh and Strong, 2007; Cottle et al., 2013a; Shao, 2013; Goudie, 2014). Fine particulates reaching high altitudes may be transported by tropospheric winds (Shao, 2000; Eguchi et al., 2009). Trans-Pacific transport of mineral dust from East Asia to North America has been frequently detected during springtime (Merrill et al., 1989; Mahowald et al., 1999; Uno et al., 2001; Zhao et al., 2003; Gong et al., 2006; McKendry et al., 2008; Cottle et al., 2013a). Long-range transport of
25 dust aerosol has been substantiated by ice core samples taken at the North Pole (Jaffe et al., 1999; Mahowald et al., 2017). In addition, oceanic chlorophyll observations have suggested a strong linkage between mineral dust and oceanic primary production after atmospheric dust deposition events (Young et al., 1991; Mahowald et al., 2009). Duce et al. (1991) and Tagliabue et al. (2017) also suggest a possible association between dust storms and enrichment of iron (Fe) and phosphorus (P) in oceans. Mineral dust aerosols are the primary source of Fe in the atmosphere (Mahowald et al., 2017). According to
30 physically-based model estimation, more than 60 Tg Fe and 1 Tg P are deposited into world oceans as a result of fallout of atmospheric dust (Luo et al., 2005; Mahowald et al., 2017). However, uncertainties exist in assessing the global dust cycle due to a lack of understanding in parameterizing dust emission, transport, and deposition (Wang et al., 2000; Ginoux et al., 2001; Gong et al., 2003; Mahowald et al., 2003; Shao and Dong, 2006; Zhao et al., 2010; Huneus et al., 2011; Kok, 2011). Therefore,

the estimation of the impact of dust on the biogeochemical cycle is still uncertain and unclear (Takemura et al., 2002; Mahowald et al., 2005; Mahowald et al., 2009; Field et al., 2010; Huneus et al., 2011; Shao et al., 2013).

Asian dust has long been an environmental concern to China, which notably has affected the formation of the Loess Plateau and historic Chinese civilization (Tsoar and Pye, 1987; An et al., 1991; Zhang et al., 1996; An, 2000; Husar et al., 2001; Chen et al., 2014; Goudie, 2014; Huang et al., 2014). To quantify and assess the impact of dust cycles on the environment, remote sensing (i.e. satellite) and modelling techniques based on physical processes must be used along with environmental monitoring data and surface observations (Shao et al., 2011a). Few studies, however, have combined the use of these techniques and monitoring data to document the fate of dust in the atmosphere and especially the range of transport of dust from its source in East Asia. Trans-Pacific transport not only has the potential to impact the North Pacific marine environment, but also air quality of communities within and downwind of the source region. The purpose of this study was therefore to determine dust emission, transport, and deposition during the May 2017 Asian dust storm using environmental observations and remote sensing data along with simulation techniques.

2 Materials and methods

2.1 Data sources

2.1.1 Air quality data

Air quality data were collected from China and the United States during the May, 2017 dust storm event. In China, hourly PM₁₀ and PM_{2.5} concentration data were collected from 367 environmental monitoring stations (Fig. 2) maintained by the Ministry of Environmental Protection (MEP, 2011). Ambient PM₁₀ and PM_{2.5} concentrations ($\mu\text{g m}^{-3}$) were measured with beta radiation attenuation monitors designed to continuously collect particulate matter and which are widely used in air quality monitoring. The technique relies upon the absorption of beta radiation by solid particles extracted from air flow in determining PM₁₀ and PM_{2.5} concentration (USEPA, 2009). The particulate matter monitors were installed at 1.5 m above the ground. Air quality index (AQI) data were obtained from nationwide air quality monitoring statistics published by the MEP (<http://datacenter.mep.gov.cn>). These AQI data were used to illustrate the influence of airborne dust versus other air pollutants on ambient air quality. In this study, we assessed AQI based upon only particulate matter concentrations. The AQI is dependent on the concentration of a single air pollutant (USEPA, 2006; Wang et al., 2013) and calculated according to:

$$AQI_i = \frac{AQI_u - AQI_L}{C_u - C_L} \times (C_i - C_L) + AQI_L, \quad (1)$$

Where AQI_i is the index for pollutant i (i.e., PM₁₀, PM_{2.5}), AQI_u and AQI_L are the upper and lower limits of the index for a specific category of air quality (i.e. excellent, moderate, slight pollution, moderate pollution, heavy pollution and severe pollution), C_i is the observed concentration of pollutant, and C_u and C_L are the upper and lower concentration limits of the pollutant for a specific category of air quality. Information regarding the determination of the AQI index can be accessed from the MEP (MEP, 2012a, 2012b). Based on the AQI, air quality was classified as: excellent, with AQI ≤ 50; moderate, with AQI

50-100; light pollution, with AQI 100-150; moderate pollution with AQI 150-200; heavy pollution, with AQI 200-300; and severe pollution, with AQI 300-500. Air quality indices associated with particulate matter concentrations are listed in Table 1. In the United States, hourly ambient PM₁₀ concentration data were collected at 12 locations maintained by the Environmental Protection Agency (EPA). Data were obtained from https://aqs.epa.gov/aqsweb/airdata/download_files.html for the time period May 2-15 in an attempt to identify elevated concentrations arising from long-range transport of dust from Asia.

2.1.2 Satellite data

MODIS Terra satellite data were collected from the U.S. National Aeronautics and Space Administration (<https://terra.nasa.gov>). The Terra satellite images the entire Earth's surface every one to two days in 36 discrete spectral bands. MODIS Level 3 Deep-blue products of aerosols optical depth (AOD) were collected for analysing the spatiotemporal distribution of dust aerosols across large spatial scales (Hyer et al., 2011); products collected included comprehensive properties of aerosol optical depth, Ångström exponent, and total column optical extinction of aerosol at a wavelength of 550 nm. Extinction at a wavelength of 550 nm has been used to quantitatively track the evolution of global dust and fine-mode anthropogenic aerosols (Hsu et al., 2006).

The CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) satellite was launched on 28 April, 2006 to study the roles of clouds and aerosols on climate and weather. The satellite carries three instruments: the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP Lidar), the Imaging Infrared Radiometer (IIR), and the Wide Field Camera (WFC). Passive and active remote sensing instruments on the satellite continuously monitor aerosols and clouds at a temporal and spatial resolution of 0.74 seconds and 333 m, respectively. We used CALIPSO aerosol optical depth (AOD) data at 532 nm of Vertical Feature Mask (VFM) level 2 version 4.10 to analyse mineral dust transport across the North Pacific Ocean. The utility of using CALIPSO products (https://eosweb.larc.nasa.gov/project/calipso/cal_lid_l2_vfm-standard-v4-10) allows aerosols to be classified as clean marine, dust, polluted continental, clean continental, polluted dust, and smoke.

2.1.3 Meteorological data

Meteorological data, including synoptic conditions, surface wind speed, and visibility, for more than 2000 meteorological observation stations in East Asia were collected from the China Meteorological Administration. Observations were taken every three hours. Dust conditions at each station were defined by visibility and subjective synoptic reports according to World Meteorological Organization (WMO) protocol. Both "present weather" and "past weather" conditions were recorded by the meteorological observer with descriptions in specified format and codes. Codes were used to designate the intensity and duration of dust periods (<http://www.wmo.int/pages/prog/www/WMOcodes.html>; Shao and Dong, 2006).

2.1.4 Lidar data

Lidar data, which was used to examine the vertical distribution of dust in the atmosphere, were collected from AD-Net (<http://www-lidar.nies.go.jp/AD-Net>) for meteorological stations in Beijing, Seoul, Matsue, Osaka, and Tokyo (Fig. 2 and Table 2). The ground-based Lidars were developed by the Japanese National Institute for Environmental Studies (NIES) and operated as part of the Japanese NIES Lidar network and the Asian dust network (Murayama et al., 2001; Shimizu et al., 2004). Dust particles tend to be highly non-spherical and show a high degree of depolarization (Cottle et al., 2013a), therefore we

used non-spherical data observed by the Lidar network. Depolarization at dual-wavelength channels of 1064 nm and 532 nm was used to identify aerosol types from the Lidar measurements (Sugimoto et al., 2003; Shimizu et al., 2004). The laser beam was vertically oriented toward the sky and collimated with a beam expander. The beam had an output power of 20 mJ/pulse at 1064 nm (30 mJ/pulse at 532 nm) and a pulse repetition rate of 10 Hz (Shimizu et al., 2016). The scattered light was received by a 20 cm Schmidt Cassegrain type telescope which separated the light at 532 nm and 1064 nm (Sugimoto et al., 2008). The measured Lidar signal was collected every 15 minutes with a vertical resolution of 30 m. Detailed information on the calibration method and its accuracy can be found in Shimizu et al. (2004).

2.2 WRF-Chem model

The WRF-Chem model (version 3.7.1 available at <http://ruc.noaa.gov/wrf/WG11>) was used to simulate dust aerosol emission, transport and deposition across the Asia-Pacific region. The model was run using National Center for Atmospheric Research/National Center of Environmental Prediction (NCAR/NCEP) reanalysis meteorological input data (<http://rda.ucar.edu/datasets/ds083.2>) at a horizontal resolution of $1^\circ \times 1^\circ$ and vertical resolution of 26 levels. The WRF-Chem model included the following components: Noah land surface scheme, Yonsei University planetary boundary layer scheme, MM5 similarity surface layer scheme, WRF single-moment 5-class microphysics scheme, and the Grell 3-D cumulus scheme. Simulations were carried out from 25 April to 10 May, 2017 with the first week of simulation (25 April -1 May) being a spin-up period to reduce the impact of initial conditions. Emission of dust particles from the surface is a key component in the surface exchange process (Wesely and Hicks, 2000) and dust emission flux is closely related to the mass of dust deposition (Whicker et al., 2014). Dust emissions is simulated by various modules in the WRF-Chem model, including the Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) (Chin et al., 2000; Ginoux et al., 2001), Model for Simulating Aerosol Interactions and Chemistry (MOSAIC), modified GOCART, Shao (2001) scheme, Shao (2004) scheme, and Shao et al. (2011b) scheme. The size-resolved dust emission scheme of Shao et al. (2011b) was developed based upon implicit physical mechanism following the schemes of Shao (2001) and Shao (2004). The Shao et al. (2011b) scheme has been rigorously examined and validated with field measurements, and found to perform well in simulating dust emission fluxes (Shao et al., 2011b). Therefore, in this study, we selected the dust emission scheme of Shao et al. (2011b) in the WRF-Chem model as this scheme has been widely used and tested in East Asia Gobi Desert region (Kang et al., 2011; Wu and Lin, 2014). The Shao et al. (2011b) dust emission scheme classified particles into four bin sizes: 0-2.5, 2.5-5, 5-10 and 10-20 μm . Dust deposition in the WRF-Chem model was simulated using Wesely's aerodynamic resistance model (Wesely, 1989) which accounts for diffusion of particulates through the air.

2.3 Trajectory model

We used the FLEXPART model (version 9.0.2 available at <http://www.flexpart.eu>) to simulate long-range and mesoscale dispersion of air parcels over the Asia-Pacific region. This model simulates forward in time to trace particles from source areas or backward in time to backtrack particles from given receptors (Brioude et al. 2013). In this study, we simulated 216-hour

forward-trajectories at 00, 12 and 24 UTC each day during the period May 2-10, 2017. The trajectories were simulated starting at the receptor point of potential dust emission sources (discussed in Section 3.2) from 2000 to 3000 m a.s.l (above sea level); this range of altitude was chosen because trans-Pacific dust clouds have been observed at these altitudes (Cottle et al., 2013a; Cottle et al., 2013b). Input data for the FLEXPART model were derived from the NCEP Global Data Assimilation System mesoscale meteorological global model. These data included 6 hour products such as temperature, precipitation, wind speed, relative humidity and geopotential height for 23 levels.

3 Results and discussion

3.1 Pervasive air pollution

Figure 1 shows an overview of the severe dust storm that developed over East Asia on 2-7 May, 2017 using data from the MODIS Terra sensor. The dust storm originated in the Mongolian Gobi Desert, Hexi Corridor, and Taklimakan Desert on 2 May, 2017. Dense dust clouds formed initially over southern Mongolia and western Inner Mongolia on 2-3 May, 2017, then moved quickly across north and northeast China and migrated pervasively into the southeast China coast, Korean peninsula, and Japan. On 4 May, yellow dust clouds masked the North China Plain and northeast China as these regions were not visible from space. The strongest dust plumes were observed over southern Mongolia and west Inner Mongolia on 3 May, 2017. Dust signals were accordingly captured in the Yellow Sea and East China Sea on 4-6 May, and in the north Japan Sea and sea of Okhotsk on 6-7 May. Figure 3 depicts the movement of dust clouds across continental China according to the spatiotemporal variation in hourly average PM₁₀ concentration at 367 Chinese environmental monitoring stations during this dust event. The maximum observed hourly PM₁₀ concentration was above 1000 µg m⁻³ in Beijing, Tianjin, Shijiazhuang, Baoding, Langfang, Xi'an and Lanzhou, and above 2000 µg m⁻³ in Erdos, Hohhot, Baotou, Alxa, Shizuishan, Yan'an, Changchun and Jilin. The highest hourly PM₁₀ dust concentration (4277 µg m⁻³) was observed over Inner Mongolia at Erdos (39.59°N, 109.77°E) at 2 a.m. on 5 May, which was 30 times higher than the concentration observed on 2 May. Figure 3 also indicates that air quality was beginning to deteriorate in northwest China on 2 May as PM₁₀ concentrations were 759 µg m⁻³ at Aksu and 380 µg m⁻³ at Hotan in the Taklimakan Desert. Air quality simultaneously deteriorated along the Hexi Corridor as PM₁₀ concentrations were 1297 µg m⁻³ in Jiuquan, 957 µg m⁻³ in Zhangye, 869 µg m⁻³ in Jiayuguan and 796 µg m⁻³ in Jinchang. It should be noted that major cities in Northeast China Plain such as Beijing, Langfang, Shijiazhuang and Zhengzhou had level 2 or 3 air quality on 2 May due to anthropogenic pollution caused by static stability weather conditions. On 3 May, air pollution became evident in northern China, especially central Inner Mongolia and Northeast China. PM₁₀ concentration rose to 2500 µg m⁻³ in Hohhot, 1540 µg m⁻³ in Baotou, 898 µg m⁻³ in Erdos, 1526 µg m⁻³ in Shizuishan, 2403 µg m⁻³ in Wuhai, 3706 µg m⁻³ in Banyan Nur, 2592 µg m⁻³ in Ulanqab, and 1681 µg m⁻³ in Alax. In addition, PM₁₀ concentrations in Northeast China rose to 1634 µg m⁻³ in Mudanjiang, 1056 µg m⁻³ in Songyuan, and 1249 µg m⁻³ in Suihua. On 4 May, the dust storm severely influenced the North China Plain as PM₁₀ concentrations rose to 1000-2000 µg m⁻³. Beginning at 4 a.m. (CST) on 4 May, air quality deteriorated in Beijing, Tianjing, and Shijiazhuang in the North China Plain as well as in Changchun, Jilin, and Tongliao in the Northeast

China Plain. Ambient PM₁₀ concentration in Beijing increased from 62 µg m⁻³ at 3 a.m. to 491 µg m⁻³ at 4 a.m. and then to 1000 µg m⁻³ at 7 a.m. On 4 May, the maximum ambient PM₁₀ concentration at Tianjin, Shijiazhuang and Zhangjiakou was respectively 1508 µg m⁻³, 1475 µg m⁻³, and 2849 µg m⁻³. Aeolian dust migrated south-eastward to the Central China Plain in the lower reaches of the Yellow River. Dense dust clouds continued to move east to southeast China where high PM₁₀ concentrations were observed on the Shandong Peninsula on 5 May, 2017. On this date, the ambient PM₁₀ concentration in Qingdao rose from 39 µg m⁻³ at 13 p.m. to 831 µg m⁻³ at 17 p.m. The adverse effects of the dust storm subsided on 5 May in Northwest China as PM₁₀ concentrations in Aksu, Hotan, Jiayuguan, Zhangye and Jiuquan decreased respectively to 147 µg m⁻³, 224 µg m⁻³, 64 µg m⁻³, 106 µg m⁻³ and 71 µg m⁻³. The Changjiang River Delta region in east-central China was affected by dust on 6-7 May, 2017. Compared with the excellent air quality (PM₁₀ concentrations ranged from 37-41 µg m⁻³) on 4-5 May, PM₁₀ concentrations in Shanghai and Nanjing increased to 194-282 µg m⁻³ on 6 May. Dust clouds crossed the Changjiang River Delta region and extended to Jiangxi Province in South China. The PM₁₀ concentration in Jiujiang (Jiangxi Province) rose from 56 µg m⁻³ to 225 µg m⁻³ within 24 hours and peaked at 275 µg m⁻³ at 2 a.m. on 7 May. The spatiotemporal variation in PM_{2.5} concentration at the 367 stations is provided in Supplement S1. PM_{2.5} concentrations paralleled PM₁₀ concentrations across the region with PM_{2.5}/PM₁₀ ratios of 0.3 to 0.5 (Supplement S2).

Airborne dust is one of chief pollutants influencing air quality in China (Zhang et al., 2010). Thus, the relative contribution of mineral dust to the AQI was analysed to identify the impact of airborne dust on air quality in major cities of China. We examined the relative contribution of dust to AQI at Alxa, Erdos and Hohhot in the arid region of north China; Beijing, Tianjing, and Shijiazhuang in the North China Plain; Xi'an, Zhengzhou and Qingdao in central China; and Wuhan, Nanjing and Shanghai in southeast China (Fig. 4). The data suggest that atmospheric dust pollution decreased from north to south and from west to east (inland to coast). Degraded air quality would have affected more than 700 million Chinese people living in the path of the dust storm.

MODIS AOD, with a quality assurance confidence (level-2 single pixel measurements) of 3 over land and > 0 over ocean and a maximum retrievable signal of 1.0 (Masuoka et al., 2010), was used to describe the dust load in East Asia. Mahowald et al. (2017) indicated that during dust events, AOD can be used as a reliable tool to represent dust loading in the atmosphere. High AOD values were observed in Mongolian, Inner Mongolia, Hexi Corridor, east Taklimakan Desert and Northwest China Plain (Fig. 5). The MODIS AOD data indicated atmospheric mineral dust reached east Taiwan to the south and crossed the East China Sea toward the North Pacific region. Our comparison of MODIS AOD with WRF-Chem model simulations corroborated the spatiotemporal variation in the dust cloud throughout the Asian region. The pattern of evolution of the severe East Asian dust storm during 2-7 March 2017 was reasonably well reproduced by the WRF-Chem model and showed the ability to capture the major characteristics of dust storm event.

3.2 Distribution of maximum wind speed

Dust storms are typically caused by anticyclone conditions that result in high winds across northwest China (Shao, 2000). The magnitude of wind speed is one of the main factors influencing dust emission, transport and deposition processes (Pye, 1987;

Liu et al., 2005). Dry soil particles were uplifted from the surface by aerodynamic forces under strong winds, generating dust emission. Uplift of particles or initiation of wind erosion generally occurs at wind speeds above 7 m s^{-1} (Saxton et al., 2000; Sharratt et al., 2010; Liu et al., 2015). Figure 6 presented the spatial distribution of maximum wind speed above 7 m s^{-1} under the observed synoptic conditions in East Asia at the meteorological stations during 2-7 May, 2017. The data show winds were sufficient to cause wind erosion in Mongolia, north China, and the Korea peninsula. Maximum surface wind speeds above 17.2 m s^{-1} (categorized meteorologically as a strong wind) were observed in the Gobi Desert of south and southeast Mongolia (e.g., Zamiin Ude, Barum-Urt, and Tsgot-Ovo), and central Inner Mongolia (e.g., Erenhot, Suniteyouqi, Xilinhot, and Hails). Synoptic records indicated that visibility was reduced to $< 100 \text{ m}$ at Guaizihu (41.37°N , 102.37°E) in the Badain Jaran Desert and at Turpan (42.83°N , 89.25°E) in the north edge of Taklimakan Desert. The maximum surface wind speed during the dust storm was $23\text{-}24 \text{ m s}^{-1}$ in the Mongolian Gobi Desert and $20\text{-}22 \text{ m s}^{-1}$ in central Inner Mongolia, indicating these likely potential source regions during the dust event. Under strong northwest and west winds, aeolian sand and dust were blown southeastwards to Asia-Pacific regions. Atmospheric dust was, therefore, observed in over the Korean peninsula and Japan (e.g., Asahikawa, Hakodate, Oshima, Kushiro, and Wakkanai) during 6-7 May, 2017.

3.3 Vertical and horizontal dust dispersion

The observed temporal and vertical dust layering structures and dust mass concentration provide information for validation of dust transport simulation studies. These dust characteristics were identified by Lidar and suggest the transport and dispersion of dust originating in northwest China were influenced by strong atmospheric circulation forcing. Figure 7 illustrates Lidar observations of vertical dust profiles in Beijing, Seoul, Matsue, Osaka and Tokyo from 2 to 10 May, 2017. Airborne dust appeared to be uplifted to altitudes of $1.5\text{-}3.5 \text{ km}$. Dust was clearly visible in Lidar observations beginning on 2 May in Beijing and Seoul and ending in the Korean Peninsula and Japan on 9 May. The detection of dust in Beijing and Seoul on 2 May indicates the rapidity of transport of dust from northwest China. The layering structures from Lidar were identified as dust using the depolarization ratio. Unfortunately, Lidar observations in Beijing were not possible on 6 May due to routine maintenance. In the Lidar measurement for this study, the well-mixed boundary layers in East Asia, prior to the obvious intermingling of subsiding layers from above, show depolarization ratios $150\text{-}250\%$ higher than boundary layers in North America (Cottle et al., 2013a). This indicates that dust clouds moved across the North China Plain at altitudes $< 1500 \text{ m}$. Our Lidar observations of dust being uplifted to altitudes of 3.5 km above Korea and Japan agree closely with those of Murayama et al. (2001) who observed dust being uplifted to altitudes of 3 km over Japan and $4\text{-}5 \text{ km}$ over Korea as a result of a wind erosion event in Northwest China and Mongolia in 1998.

Dust arising from the surface during wind erosion events may be transported along different pathways in the atmosphere due to variations in atmospheric circulation and vertical mixing within the atmosphere across events (Satake et al., 2004). To provide insight to dust flow trajectories and the impact of dust from the potential sources (discussed in Section 3.2) on regions downwind of the source, Figure 8 depicted the 9-day forward trajectories of dust particles from 2 May, 2017 (00:00 UTC) by FLEXPART model. This numerical experiment identified the location of dust emissions according to the ground observations

by WMO. Simulations indicated dust particles were released from source regions with an intensity of 1000 mg m⁻² at 2000 to 3000 m a.s.l. Strong atmospheric circulation resulted in the transport of this emitted dust to the North American continent within a week. The FLEXPART model indicated a high probability that dust particles emitted during the May 2 dust storm event crossed the North Pacific Ocean and reached the coasts of the northwestern U.S. and western Canada.

5 3.4 Atmospheric dust deposition

Long range transport of dust is influenced by dry and wet depositional processes (Shao and Dong, 2006; Tanaka and Chiba, 2006; Zheng et al., 2016). Atmospheric mineral dust and subsequent deposition in the ocean is an important source of iron in high-nutrient-low-chlorophyll (HNLC) oceanic regions (Mahowald et al., 2009). The intensity of dust deposition on land or ocean can exceed 1000 g m⁻² yr⁻¹ (Ginoux et al., 2001; Liu et al., 2004; Zhang et al., 2010). However, the dust deposition rate over Chinese deserts has been reported to be 70 times larger than over the North Pacific Ocean (Shao, 2000). Atmospheric dust concentrations may change rapidly during the early stages of dust transport (Uematsu et al., 1983). Few observations exist of East Asian dust deposition over the Pacific Ocean. Uematsu et al. (1983) estimated that 1.6 Tg of dust aerosols are deposited over the North Pacific Ocean during East Asian dust storm events. The annual average deposition of mineral dust over the North Pacific could be as high as 480 Tg (Uematsu et al., 2003). Figure 9 displays the simulated daily emission, loading and deposition of dust over East Asia and North Pacific regions. As simulated by the WRF-Chem model, approximately 29.7 Tg of dust was emitted from dust sources in Mongolia and China (Fig. 9a and Table 3). Subsequently, 25.7 Tg of dust was deposited over the Asia-Pacific region with 20.4 Tg of dust deposited over land and 5.3 Tg of dust deposited over the North Pacific Ocean (Fig. 9c and Table 3). Simulated results further indicate that 4 Tg of dust were suspended in the atmosphere. The amount of dust deposited over China, Mongolia, Korea peninsula, and Japan was 14.7, 4.5, 0.2 and 0.1 Tg while the dust deposition intensity in the Yellow Sea, East China Sea and Japan Sea were 1.3, 0.2 and 0.6 g m⁻², respectively. The estimated dust deposition over East Asia (20.8 Tg) during 2-7, May 2017 was of the same magnitude as deposition during the 2002 and 2010 Asian dust storms (Shao et al., 2002; Han et al., 2004; Li et al., 2011). In addition, the ratio of dust deposition intensity over the Yellow Sea to East China Sea (6.5) was close to that reported by Tan et al. (2017). Deposition intensity is highly correlated with atmospheric dust concentration (Shao et al., 2013; Zhang et al., 2017), thus we assume that areas with high deposition also had high atmospheric concentration. We estimated that 0.9 Tg of dust was deposited over North America. Iron deposition over the North Pacific Ocean was estimated by ourselves to be 0.19 Tg assuming the dust contained 3.5% iron (Luo et al., 2005; Mahowald et al., 2017).

Transport of dust emitted from East Asian desert sources is highly dependent on atmospheric circulation (Zhang et al., 1997). The Eurasian atmospheric circulation greatly influences weather of East Asia and is primarily driven by the strength of Asian Monsoon and the Siberian High (Park et al., 2011; Shao et al., 2013). Strong winds associated with those atmospheric circulations cause large amounts of mineral dust to be emitted into the atmosphere, and then redeposited after long-ranged transport through wet scavenging and dry settling. According the WRF-Chem model, dust emitted from East Asian Gobi

Desert sources on 2 May took 3, 3.5, and 7 d to reach the Korean peninsula, Japan, and the western coast of the United State and Canada, respectively.

Gobi and sand deserts in East Asia are important sources of global atmospheric mineral dust (Ginoux et al., 2001; Shao et al., 2013; Chen et al., 2017a). Atmospheric deposition of mixed Asian dust pollutants can result in the deposition of many compounds (e.g., sulphate, nitrate, ammonium, base cations, and heavy metals) in remote areas (Carrico et al., 2003; Li et al., 2012). Figure 10 displayed the vertical profile variations over North Pacific Ocean on 7-8 May, 2017. The profiles show atmospheric mineral dust at latitudes of 35°N-50°N on May 7 and 30°N-45°N on May 8 in the North Pacific Ocean. Dust deposition in the planetary boundary layer was also detected in the western North Pacific Ocean, which is near the source of East Asian dust (Fig. 10a). The westerly winds aloft can carry dust raised from the surface rapidly out over the Pacific Ocean in spring which is then transported eastward. The long-range transport of atmospheric constituents from East Asia not only delivers mineral dust aerosols but also carries mixed anthropogenic pollutants and nutrients to remote continents and oceans (Li et al., 2012; Lyu et al., 2017b). As indicated from Figure 10b, 10c and 10f, anthropogenic pollution was detected in dust at an altitude of 3-8 km. This observation is consistent with the previous studies for the trans-Pacific dust transport as reported by Huebert et al. (2003), Uno et al. (2009) and Mahowald et al. (2009).

Based upon WRF-Chem simulations, dust was emitted from localized sources in North America during 2-10 May, 2017. Tanaka and Chiba (2006) and Wu et al. (2018) also suggest that dust is emitted from localized sources in North America. There was 0.7 Tg of dust emitted across Arizona, Nevada, and the Mexican Desert during 2-10 May, 2017 according to WRF-Chem simulations. Approximately 0.7 Tg of dust was deposited in across the U.S. To visualize the influence of the North American dust sources on atmospheric dust loading, supplementary materials S3 displays the hourly PM₁₀ concentration for locations in California, Arizona, Nevada and Washington during 2-15 May, 2017. These results indicate dust emitted from the Mexican Desert and drylands in Arizona and Nevada significantly influenced the atmospheric environment in the southwest U.S.

3.5 Influence on Asia-Pacific region

Long-range transport of mineral dust aerosols occur with high temporal and spatial variability (Mahowald et al., 2017). In addition, dust deposition rates are highly variable as deposition during singular dust storms can account for over 3% of the annual dust deposition flux (Liu et al., 2004; Zhang et al., 2010). For marine ecosystems, long-range transport and subsequent deposition of mineral dust can result in an influx of nutrients and thereby stimulate growth of aquatic organisms. For example, aeolian dust contains Fe which is essential to the growth of aquatic organisms such as phytoplankton (Zhuang et al., 1992; Luo et al., 2005; Mahowald et al., 2009; Mahowald et al., 2017; Tagliabue et al., 2017). Zhuang et al.(1992) proposed that Fe contained in dust may couple with anthropogenic S in the atmosphere and ocean, thereby enhancing solubility and subsequent availability to aquatic organisms. Thus, an influx of nutrients to the ocean during the May 2017 dust event would significantly influence aquatic primary productivity.

Cottle et al. (2013a) and Hu et al. (2016) reported long-range transport of Asian dust can impact the Pacific region. Indeed, high latitude dust clouds from the May 2017 event were observed crossing toward North America as evidenced by CALIPSO retrieval signals in Figure 10. Dust was observed at approximately 2-8 km height over North America on 9-10 May (Supplement S4b and S4e), a week after initiation of the East Asian dust storm. The source of high altitude dust over North America may not be entirely from Asia, but could also be attributed to dust emissions from the southwestern U.S. and northern Mexico. Indeed, the WRF-Chem model predicted 0.7 Tg of dust emitted from these regions of North America during 2-10 May 2017 (Fig. 9a and Table 3). While we are unable to conclusively determine the source of high altitude dust over North America, we believe the likely source was Asian dust due to zonal transport of high altitude dust from Asia as well as seemingly little dust remaining in the atmosphere after accounting for deposition (dust emissions and deposition were equal as indicated in Table 3) over the southwestern U.S. and northern Mexico. Strong signals of dust aerosols were also observed at mid-latitude in the east North Pacific (Supplement Fig.S4a and S4e).

Asian dust can be transported further north to the Arctic at altitudes of 3-7 km as a result of either a blocking high pressure system in the northwest Pacific Ocean or a trough-ridge configuration between East Asia and the North Pacific Ocean (Di Pierro et al., 2011). Mineral dust was observed throughout the vertical profile over high latitudes near the North Pole on 9 May as indicated by CALIPSO satellite data (Supplement Fig. S4a). The zonal-transported dust may mix with ice nuclei at high latitudes through microphysical nucleation process and result in cloud formation (Liu et al., 2012; Yu et al., 2012; Sand et al., 2017). Our simulations showed by the time the dust had been transported across the Pacific Ocean that >4 Tg of fine dust aerosols remained in suspension in the atmosphere (Fig. 9b and Fig. 9c). This suspended dust likely influenced the atmospheric chemical composition as well as optical properties. These anomalies of fast-rising atmospheric aerosol concentration could directly or indirectly influence the climate of temperature-sensitive regions like the Arctic (Di Pierro et al., 2011; Carslaw et al., 2013; Sand et al., 2017).

During intercontinental transport, particulate matter more likely remained at low altitudes due to less uplift by thermal eddies and precipitation. Long-range transport of dust aerosols in the troposphere has been detected from satellite and Lidar observations. Our results suggest a threefold increase in dust deposition over the Pacific Ocean during dust events, emphasizing the importance of dust emission sources from East Asian lands to current ambient particulate matter levels in the environment. In general, long-range transport Asian dust originated from the Gobi Desert or other sources can significantly elevate ambient particulate matter concentration and affect air quality in major cities of China, Mongolia, Korea, Japan, and far beyond (Uno et al., 2006; Huang et al., 2008; Mahowald et al., 2009; Chen et al., 2017b; Huang et al., 2017; Mahowald et al., 2017).

4 Conclusions

The atmospheric environment of East Asia is severely affected by dust emitted from arid and semiarid regions. This study was undertaken to quantify ambient PM₁₀ concentration and dust deposition in East Asia as well as its impact on the Asia-Pacific region. Based upon wind field patterns, Alxa Desert in western Inner Mongolia and the Gobi Desert of Mongolia were found

to be main dust sources during the May 2017 dust storm event. This event resulted in an estimated dust emission of 29.7 Tg. Two thirds of the emitted dust was deposited over East Asia while one sixth of the emitted dust was deposited into the North Pacific Ocean. This dust event dominated the atmospheric environment in East Asia. Data collected at environmental monitoring stations suggested aeolian dust was a major pollutant in East Asia affecting regional air quality and a significant contributor to the global dust budget. This dust storm impacted a wide area of China and other Asian nations and reached North America within one week. The spatial distribution and temporal variability in ambient PM₁₀ concentration showed significant decreases along the transport trajectory and persistence on a regional scale. Dust from other sources such as the Sahara, Middle-East and central Asia may also affect the Asia-Pacific region, therefore additional observations would be necessary to clarify the contributions from other potential dust source regions on dust transport and deposition in East Asia and North Pacific Ocean. A combination of satellite and surface observations and numerical simulation presented in this study would reduce the uncertainties in quantitative estimations of Asian dust impact.

Competing interests. The authors declare that they have no conflict of interest.

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Tables

Table 1. Ambient particulate matter concentration related to air pollution levels in China.

Levels	Air Quality Index (AQI)	PM ₁₀ concentration (µg m ⁻³)	PM _{2.5} concentration (µg m ⁻³)	Air quality rating
1	0-50	0-50	0-35	Excellent
2	51-100	50-150	35-75	Moderate
3	101-150	150-250	75-115	Lightly pollution
4	151-200	250-350	115-150	Moderate pollution
5	201-300	350-420	150-250	Heavy pollution
6	301-500	>420	>250	Severe pollution

Table 2. List of Lidar observation stations in this study.

No.	Station	Latitude	Longitude	Location
1	Beijing	39.97° N	116.37° E	Institute of Atmospheric Physics, CAS
2	Seoul	37.46° N	126.95° E	Seoul National University
3	Matsue	35.48° N	133.01° E	Shimane Prefecture
4	Osaka	34.65° N	135.59° E	Kinki University
5	Tokyo	35.69° N	139.71° E	Shinjuku

Table 3. Estimates of atmospheric dust emission and deposition over the Asian-Pacific region during 2-10 May, 2017.

Earth surface	Region	Emission (Tg)	Deposition (Tg)
Continent	Mongolia	13.3	4.5
	China	16.4	14.7
	Korea peninsula	-	0.2
	Japan	-	0.1
	Canada	-	0.2
	United States	0.7	0.7
Ocean	Yellow Sea	-	0.5
	East China Sea	-	0.1
	Japan Sea	-	0.7
	North Pacific	-	5.3
Total		30.4	25.7

Figures

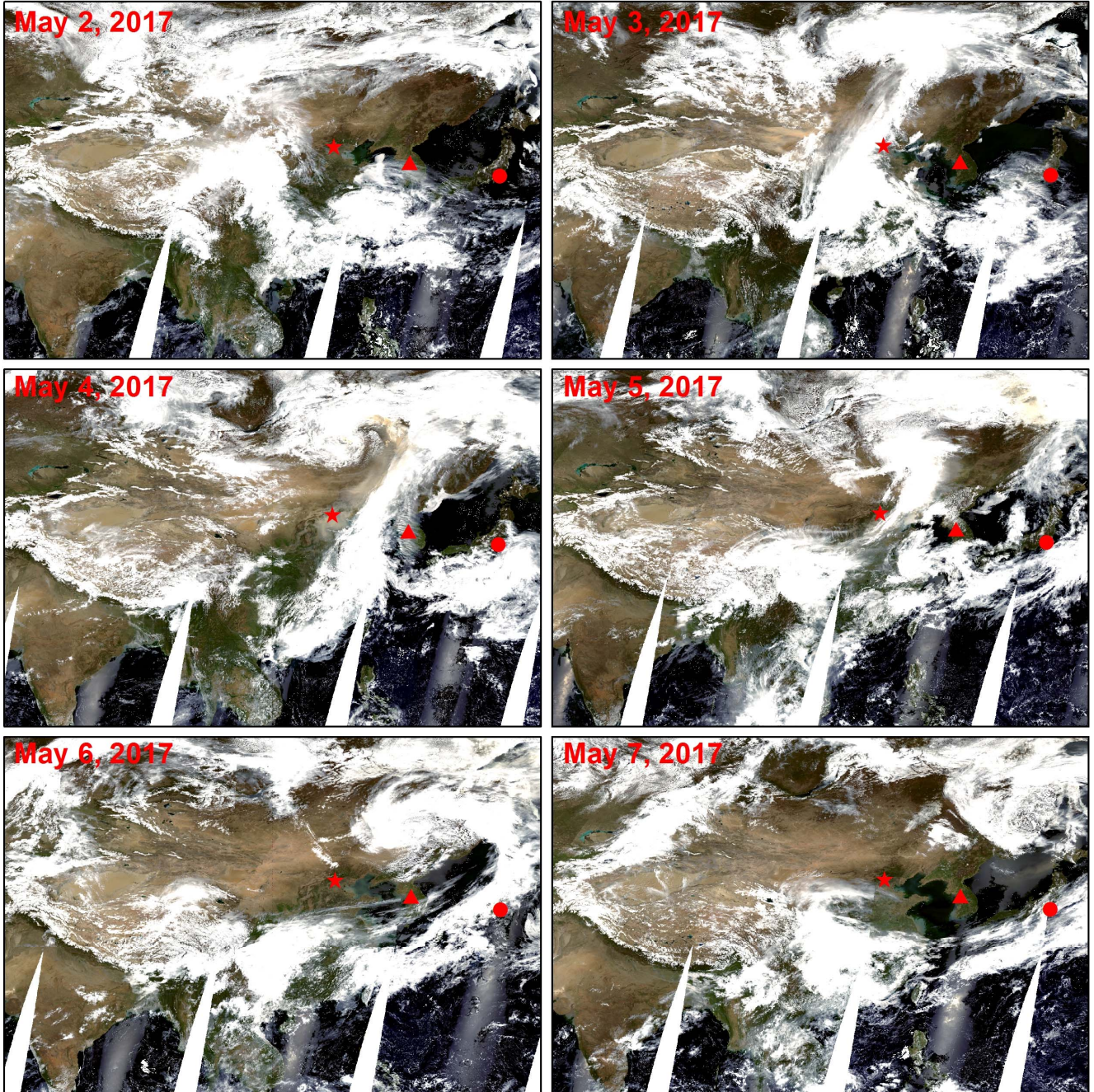


Figure 1. Terra-MODIS images showing dust outbreak across East Asia from 2 to 7 May, 2017. Red star, rectangle and circle indicate Beijing, Seoul, and Tokyo, respectively.

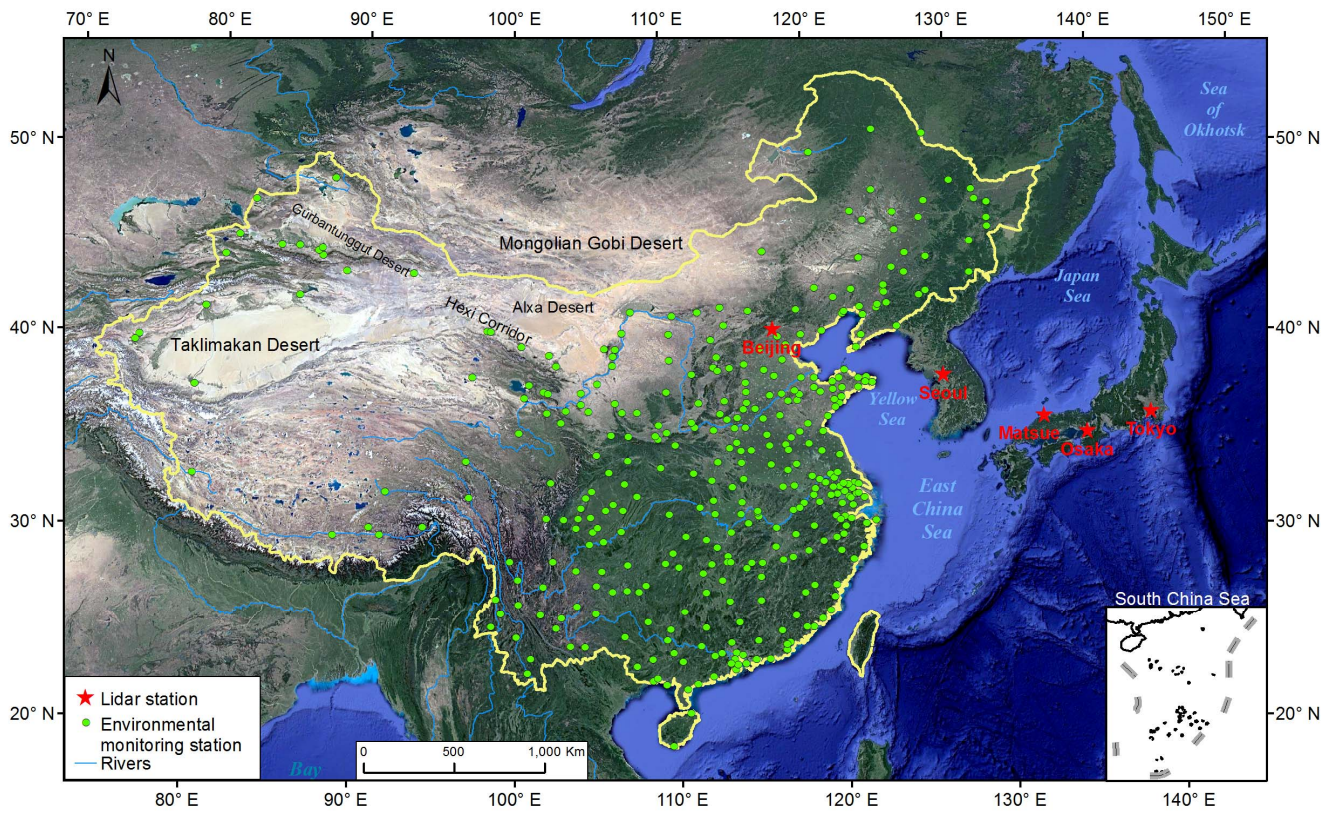


Figure 2. Location of environmental monitoring stations in China and Lidar monitoring stations in east Asia.

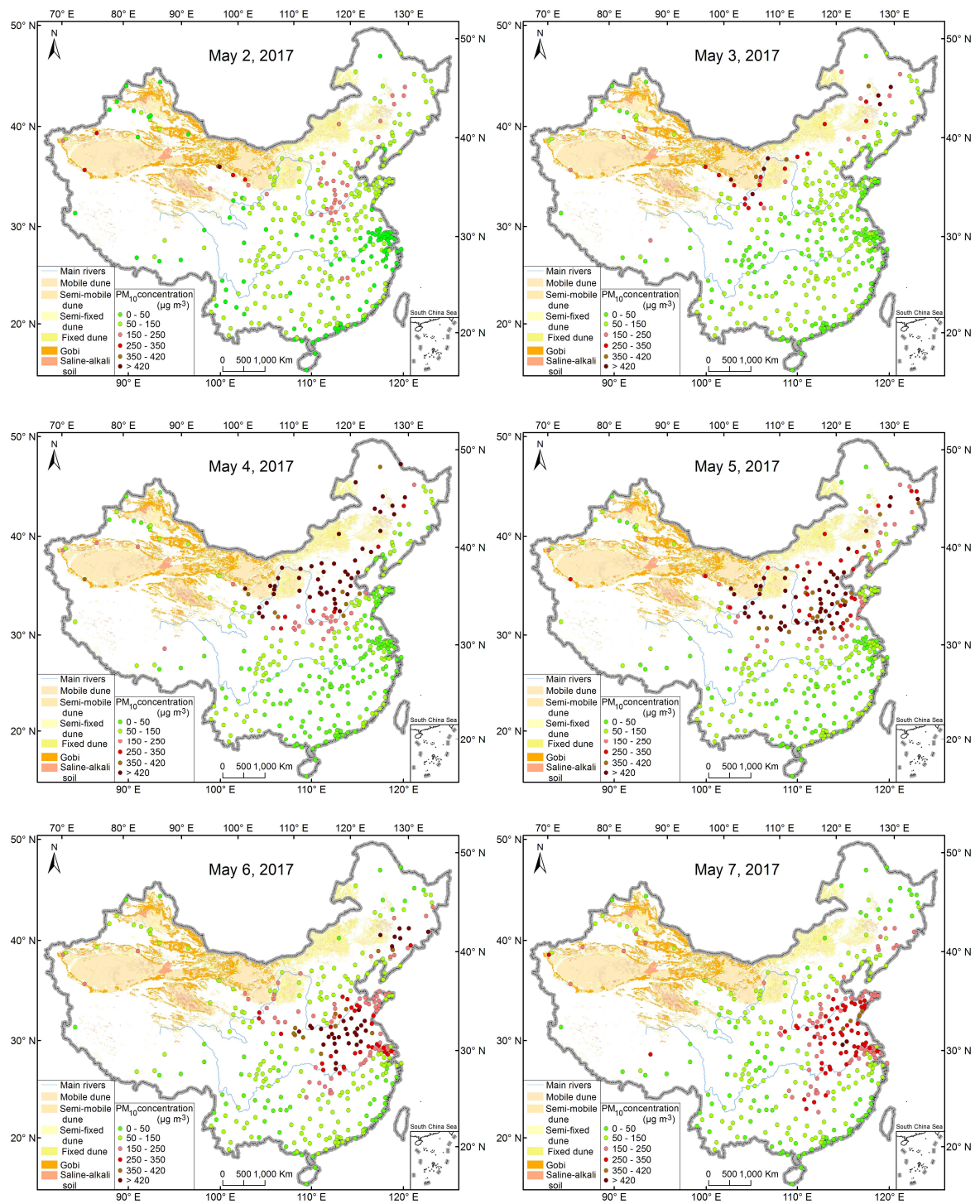


Figure 3. Observations of PM₁₀ concentrations across China during 2-7 May, 2017. PM₁₀ concentrations are reported as average hourly based on 24 observations during the day. Land use types are identified across the China according to Wang et al., 2005.

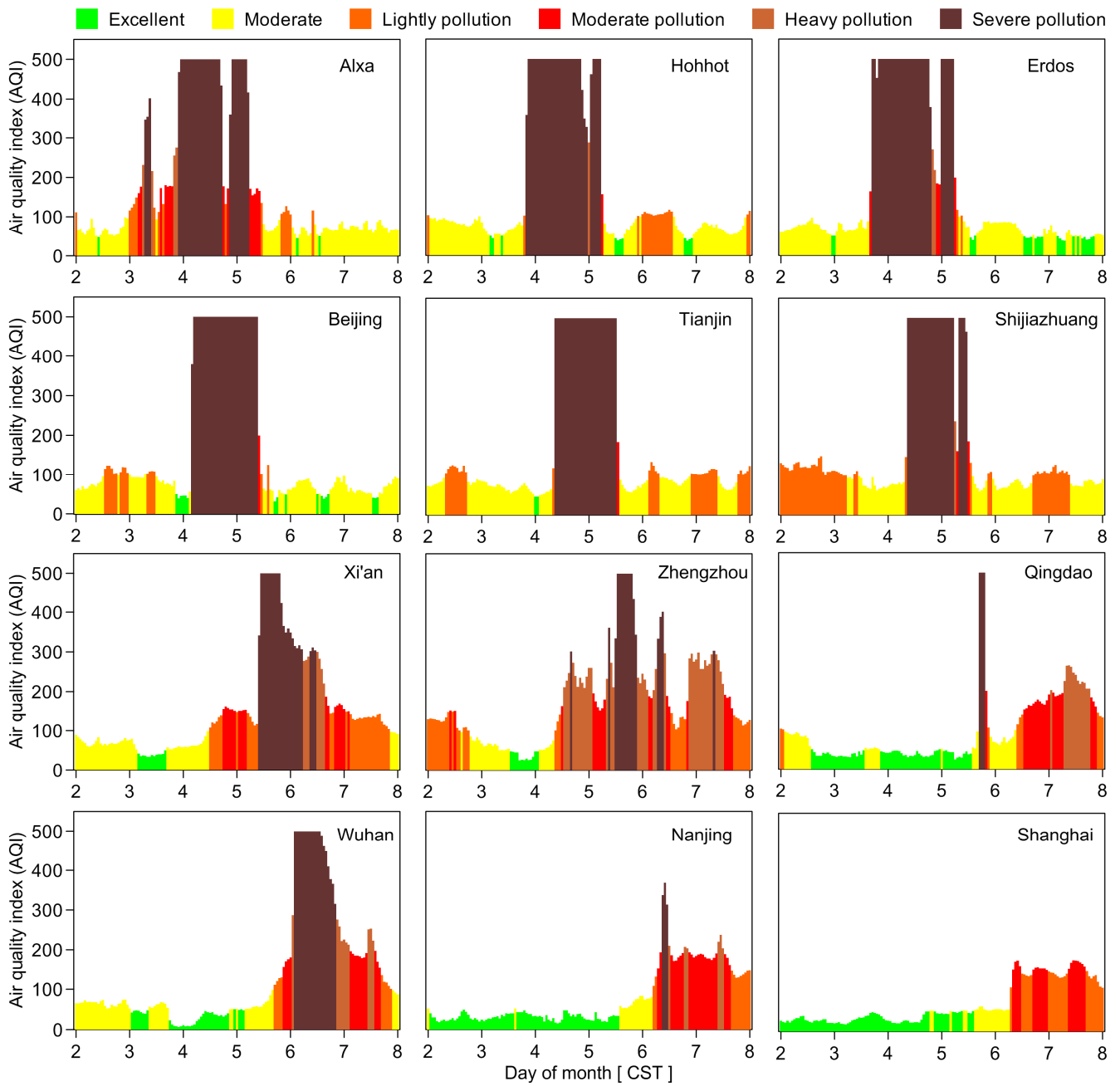


Figure 4. Hourly air quality index as observed for major stations in China during 2-7 May, 2017. The PM_{10} pollutant contributing to the hourly AQI is identified for each station.

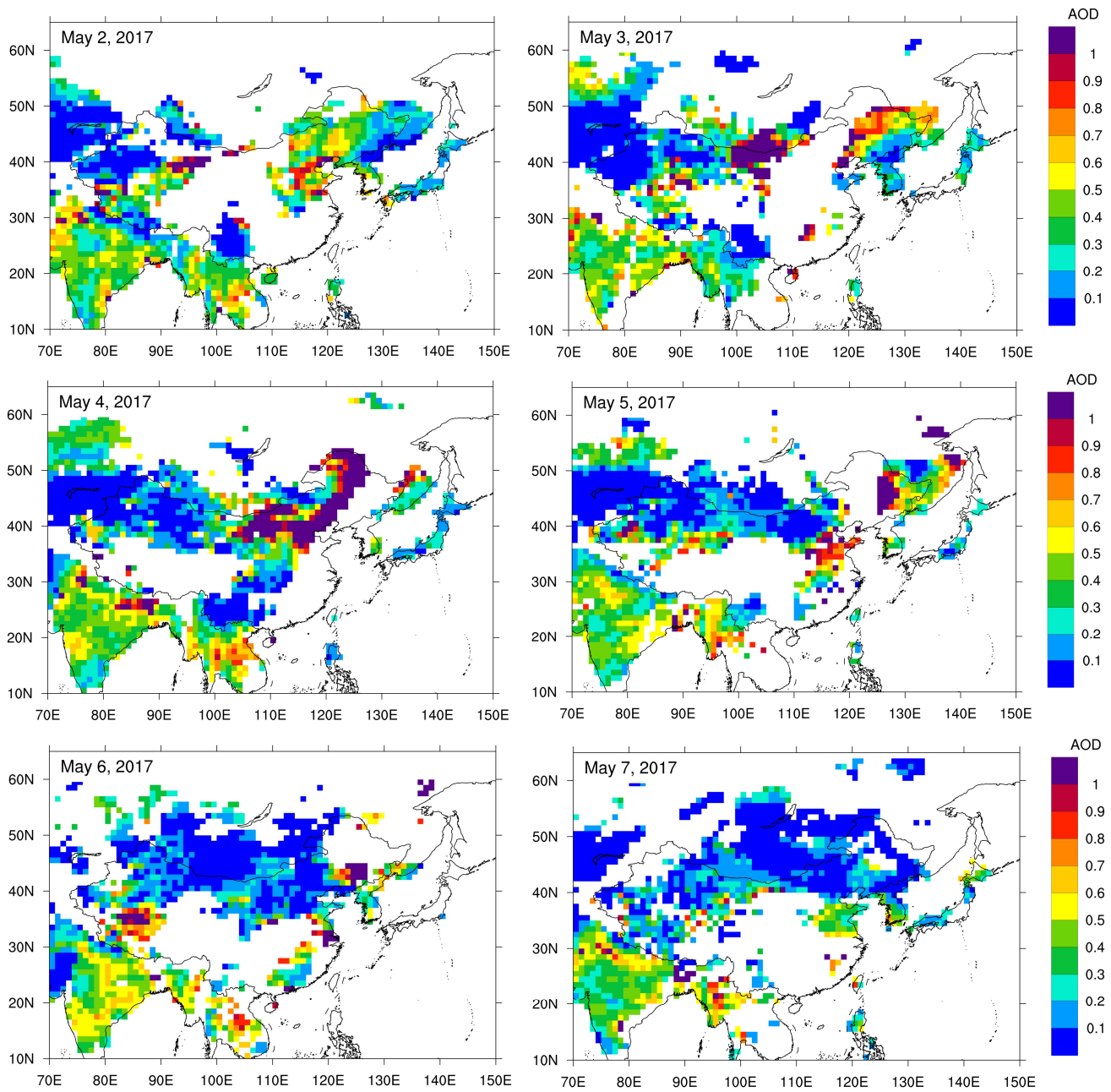


Figure 5. Distribution of mean aerosol optical depth (AOD) at 550 nm derived from MODIS Terra Deep-blue product in East Asia during 2-7 May, 2017.

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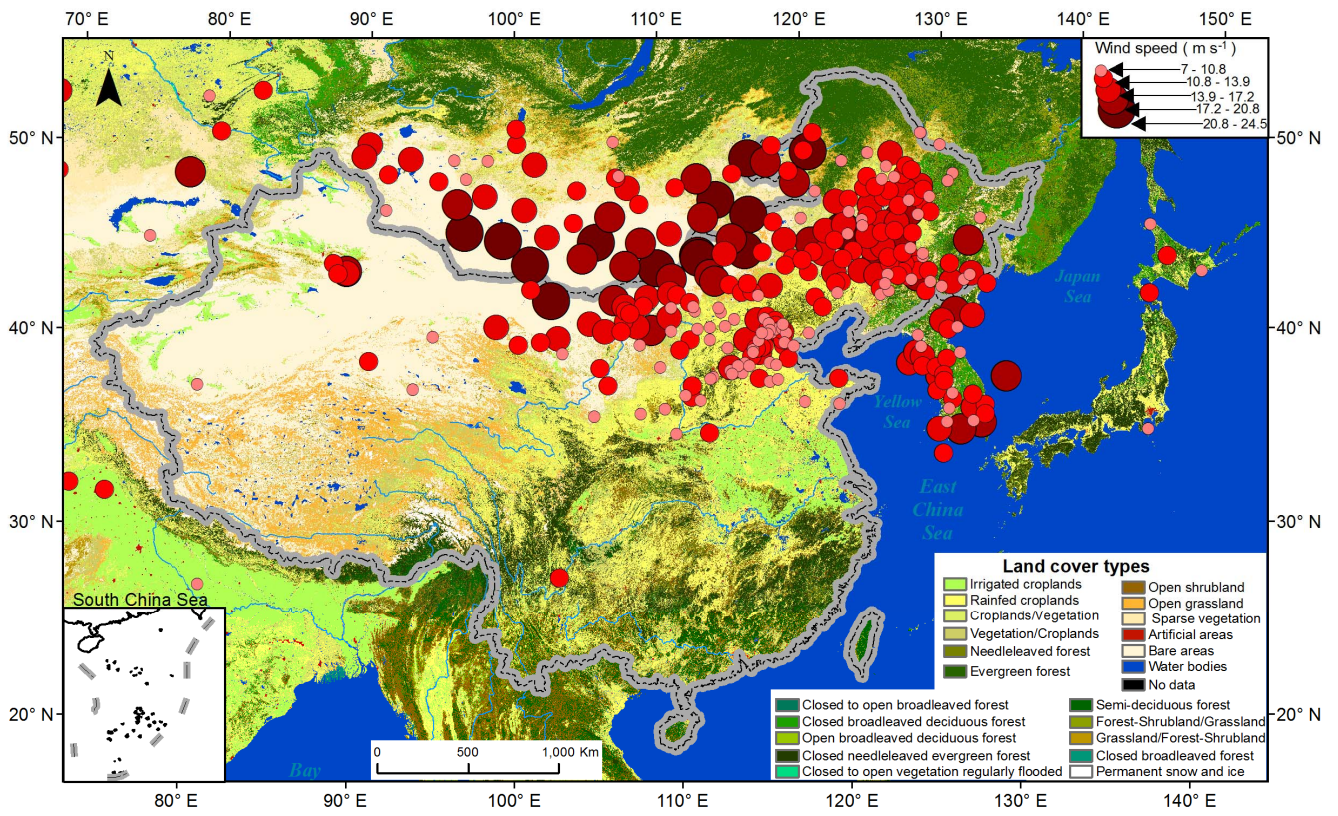


Figure 6. Maximum wind speed across East Asia during 2-7 May, 2017. Land cover types in East Asia are derived from global land cover products published by European Space Agency (ESA).

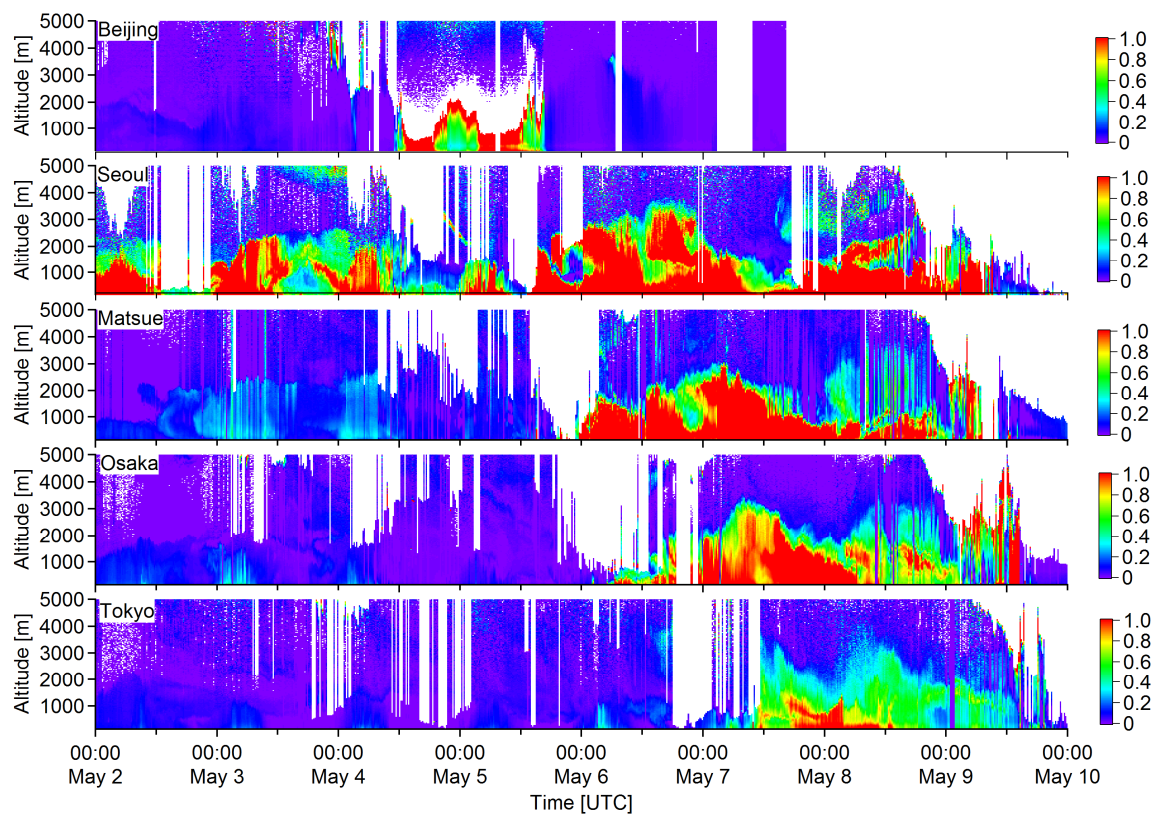


Figure 7. Lidar profile of dust vertical distribution in Beijing, Seoul, Matsue, Osaka and Tokyo during 2-10 May, 2017. Colors indicate depolarization ratio observed in ground Lidar.

5

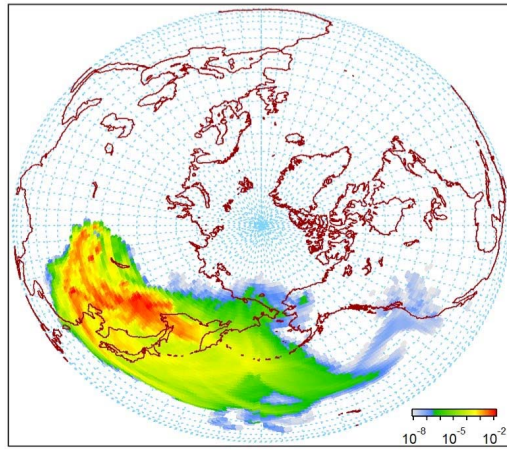


Figure 8. Forward trajectory analysis on dust transport (units: $\mu\text{g m}^{-3}$) in free atmosphere by FLEXPART model in 216 hours from 2-10 May, 2017.

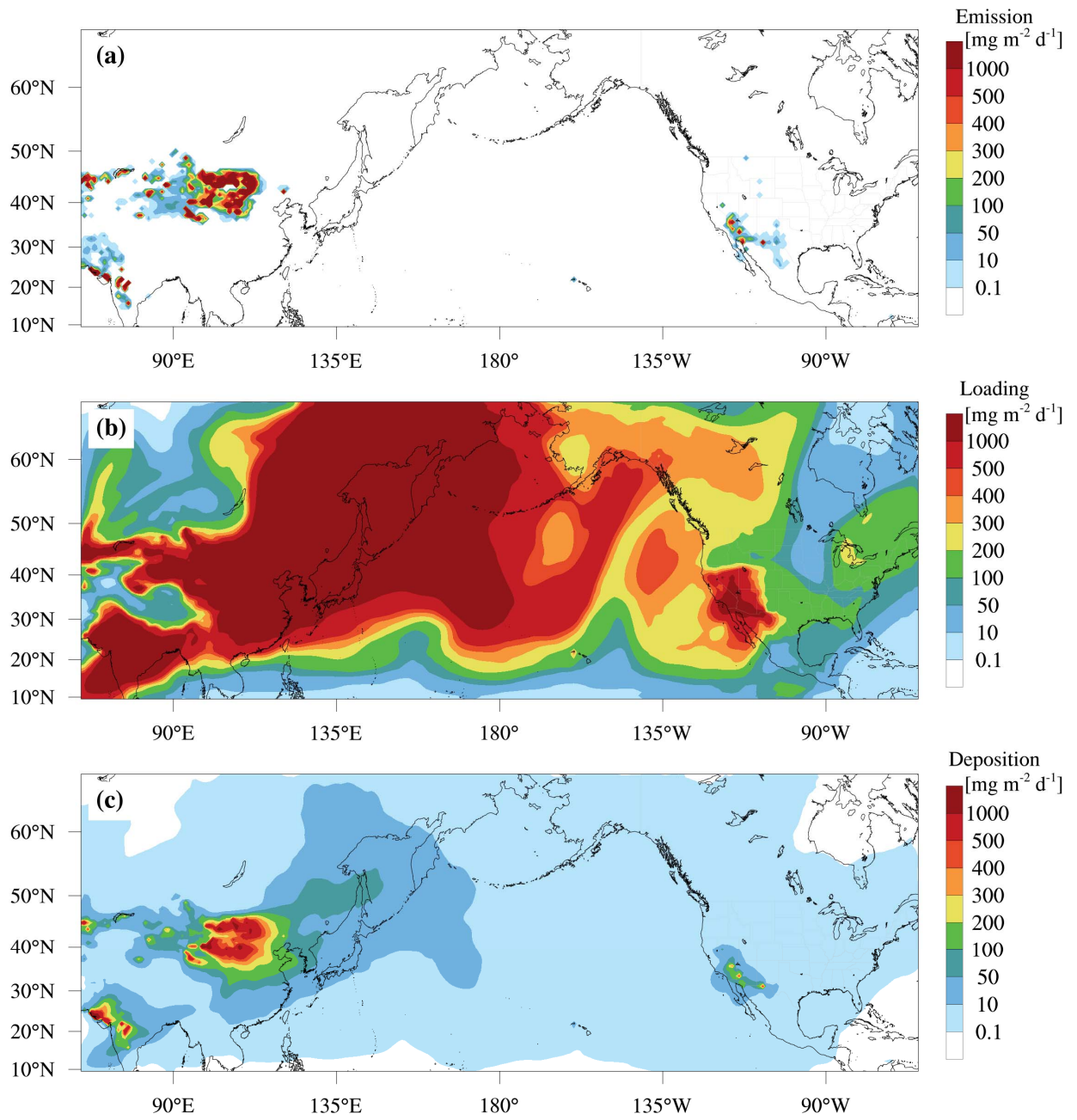


Figure 9. Estimation of daily dust emission (a), dust loading (b) and dust deposition (c) over Asia-Pacific region during 2-10 May, 2017.

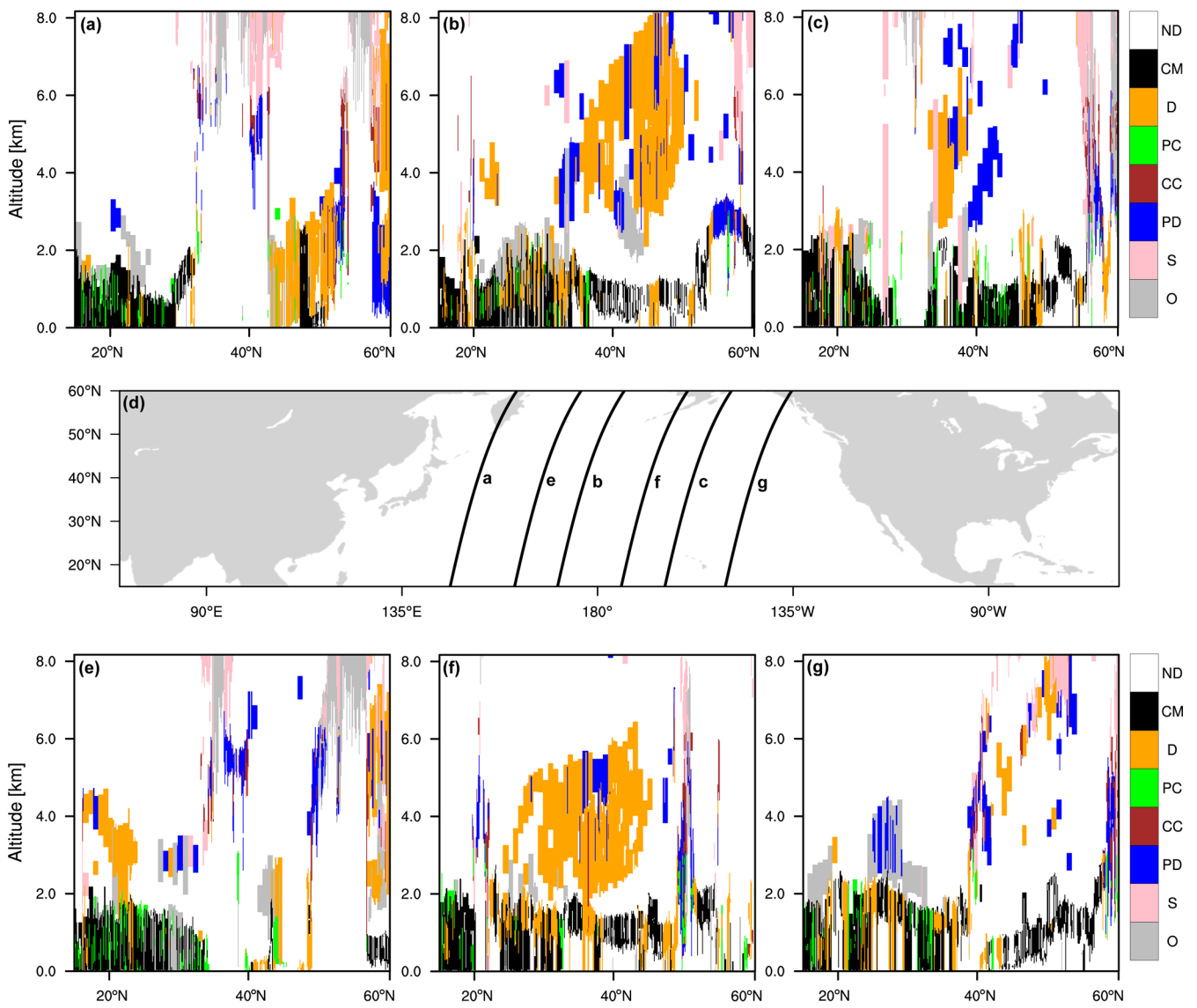


Figure 10. Vertical profiles of atmospheric features derived from CALIPSO satellite VFM data on 7 May (Fig.10a, 10b and 10c) and 8 May (Fig.10e, 10f, and 10g), 2017. (ND=Not determined, CM=Clean marine, D=Dust, PC=Polluted continental, CC=Clean continental, PD=Polluted dust, S=Smoke, O=Other). Each Satellite trajectories of vertical profiles were presented in Fig. 10d.