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Identifying sources of dust based on CALIPSO, MODIS satellite data and backward trajectory model

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ABSTRACT

The total suspended particulate matter, total dust and PM_{10} mass concentrations and visibility data were measured using large flow total suspended particle (inhalable particles) sampler (KC–1000), dust storm sampler (SC–1) and visibility meter in Lanzhou, China. Furthermore, the dust origins of the event occurred during 9–14 March 2013 were accurately identified in this study using HYSPLIT (Hybrid–Single Particle Lagrangian Integrated Trajectory) trajectory model and multiple satellite data, including AOD (Aerosol Optical Depth) data from MODIS (Moderate Resolution Imaging Spectroradiometer), and vertical profiles of atmospheric aerosol properties from CALIPSO (Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations). It is found that the total suspended particulate matter mass concentration larger than 8 000 $\mu g\ m^{-3}$ on 9 March was the highest among seven dust days with the visibility lower than 500 m. The dust at low levels (500 and 1 000 m AGL) mainly originated from the Hexi (River West) Corridor and Western and Central Inner Mongolia Plateau, which moved very slowly and circulated around the desert regions in Western and Central Inner Mongolia before arriving at Lanzhou. While the air masses at higher altitudes (2 000 and 3 000 m AGL) were transported from the Taklamakan Desert and the Qaidam basin, and arrived at Lanzhou. Most interesting, the air masses from Badain Jaran and Tengger Deserts and their outer edges brought dust particles on the transport pathways into atmosphere led to increase of particle pollutant concentrations due to tightly adherent ground movement of air masses.

Keywords: *Sources, dust, CALIPSO, MODIS, backward trajectory*

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1. Introduction

Dust aerosols are major component of natural aerosols in the atmosphere. Once in the atmosphere, mineral dust plumes can affect global climate by altering the radiative balance of the atmosphere (Tegen et al., 1996; Kim, 2006) or serve as CCN (cloud condensation nuclei) or IN (ice nuclei), which would alter cloud formation, microphysical properties and lifetimes (Kim, 2006). Dust also has a potential influence on human health (Perez et al., 2008) and regional air quality by impairing visibility (Prospero, 1999). Arid and semiarid regions of the world, covering about one–third of the Earth's land surface, are major sources of mineral dust. Most dust storms affecting China originate from one of the three geographic areas, i.e. the Hexi (River West) Corridor and western Inner Mongolia Plateau, the Taklamakan Desert, and the central Inner Mongolia Plateau (Wang et al., 2004). Dust plumes, originated from these desert regions and their outer edges could be transported thousands of kilometers downwind over the Asian continent and Pacific Ocean, and on occasions reach the North America (Duce et al., 1980; Uematsu et al., 2002; Huang et al., 2008). Reid et al. (2008) indicated that characteristics of dust particles such as size, chemistry and morphology were fairly static from individual sources, as dust particles in the size range 0.8–10 µm are more impacted by soil properties than wind speed and transport processes. Additionally, some studies in the Taklamakan Desert and the Central Inner Mongolia Plateau found that sands in Badain Jaran Desert were coarser than those in the Taklamakan Desert and the Tengger Desert (Wang et al., 2005; Zhang, 2008; Qian et al., 2011). As it can be seen from the above analyses, accurately determining dust sources is essential to assess the effects of dust particles on human health, atmospheric environment and global and regional climate.

Lanzhou (36.05°N, 103.88°E), located in Northwestern China, is the capital of the Gansu province and the geographical center of China. Figure 1 shows the geographical location of Lanzhou, together with the desert and desertified land in China. Located in the transport pathway of Asian dust storms, Lanzhou is easily attacked by dust storms. Several studies about dust aerosol particles have been conducted in Lanzhou (Liu et al., 2004; Ta et al., 2004; Wang et al., 2006; Tao et al., 2007; Huang et al., 2008; Wang et al., 2009; Qu et al., 2010; Zhang et al., 2010; Feng et al., 2011; Liu et al., 2012; Zhang and Li, 2012). Chu et al. (2008) showed that the concentration of the total suspended particles (TSP) in Lanzhou was 2–10 times higher than the third–level air quality criterion (severe pollution) during winter and spring, partly due to dust events. Moreover, most of the "high PM_{10} episodes" (maximum 1 h concentration >1 000 $\mu g\ m^{-3}$) were attributed to desert dust intrusions (Ta et al., 2004). Wang et al. (2006) investigated the impacts of three kinds of dust events (floating dust, dust storm, and blowing dust) on PM_{10} pollution in Beijing, Hohhot, Xi'an and Lanzhou, and indicated that in Lanzhou, the contribution degree of the three dust events to PM_{10} was: floating dust > dust storm> blowing dust. However, most of previous studies on identification of dust sources were mainly focused on horizontal motion of dust plumes (Israelevich et al., 2002; Zhang et al., 2003; Zhang et al., 2009) with little or no studies on vertical distributions of Asian dust plumes using the latest satellite data such as CALIPSO (Huang et al., 2008; Chen et al., 2010). Additionally, the cloud–resolving models may be used to calculate different component of aerosols and dynamical characteristics of dust because the models take into account some important parameters related to dust (Curic and Janc, 2012; Spiridonov and Curic, 2013). The severe regional dust event, occurred during 9–14 March 2013, provided a good opportunity to accurately identify dust source regions using backward trajectory and multiple satellite data.

2. Data and Methods

In situ total suspended particulate matter, total dust and PM_{10} mass concentrations and visibility data measured using large flow total suspended particle (inhalable particles) sampler (KC–1000), dust storm sampler (SC–1) and visibility meter were used in this study together with data from several satellite sensors, including Aerosol Optical Depth (AOD) data from MODIS, and vertical profiles of atmospheric aerosol properties from CALIPSO. All satellite data used in this study were obtained from the Atmospheric Data Center of the NASA (National Aeronautics and Space Administration) Langley Research Center (LARC) (http://eosweb.larc.nasa.gov/). In addition, NCEP (National Centers for Environmental Prediction)/NCAR (National Center for Atmospheric Research) reanalysis data available at 2.5°×2.5° in longitude andlatitude every sixhourswere used to understand synoptic situations related to the dust event.

2.1. Sampling site

Lanzhou (36.05°N, 103.88°E) is located at the intersection of Qinghai–Tibet Plateau, the Inner Mongolian Plateau and the Loess Plateau, and has an average elevation of 1 520 meters. The total area of Lanzhou is 13 000 km^2 and the urban population is 2.58 million in 2010. The area has a continental semi–dry climate, with an annual average temperature of 8.9 °C, and an annual average precipitation of 331 mm. Figure 1 shows the geographical location of Lanzhou and the sampling site, with the distribution of desert and desertified land in China. Lanzhou is located downstream of several dust source regions. The sampling site is on the roof of a 20–m high research building of the Eco–environment monitoring and supervision administration, located in the central part of the Lanzhou urban area, high enough to avoid the effect of re–suspended dust due to human activities. There are no large stationary pollution sources in its surroundings in spring and summer, and the main activities are residential and commercial.

2.2. Satellite data

CALIPSO data. The Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), part of the NASA Afternoon Constellation (A–Train), has a 98°–inclination orbit and is placed in a 705 km sun–synchronous polar orbit, which provides global coverage between 82°N and 82°S with a local afternoon equatorial crossing time of about 1:30 p.m. (ascending node). The CALIPSO Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument measures vertical profiles of elastic backscatter at 532 and 1 064 nm near nadir. The CALIPSO level 1 major data products (version 3.01) have a set of profiles of the total attenuated backscatter at 532 and 1 064 nm and the perpendicular component at 532 nm. The CALIPSO level 2 data products (version 3.01) have vertical feature mask, which can be used to identify thelocation and the type of aerosols. The mean attenuated backscatter, total backscatter color ratio (ratio of the total attenuated backscatter at 1 064 nm to that at 532 nm), and volume depolarization ratio (VDR) (ratio of the perpendicular to parallel components of received lidar signals at 532 nm) of each layer were calculated using the CALIPSO level 1B data. The depolarization ratio and color ratio of dust aerosols are high due to the non–sphericity and the relatively large particle size, respectively, and are normally used as indicators to separate dust from other aerosol types.

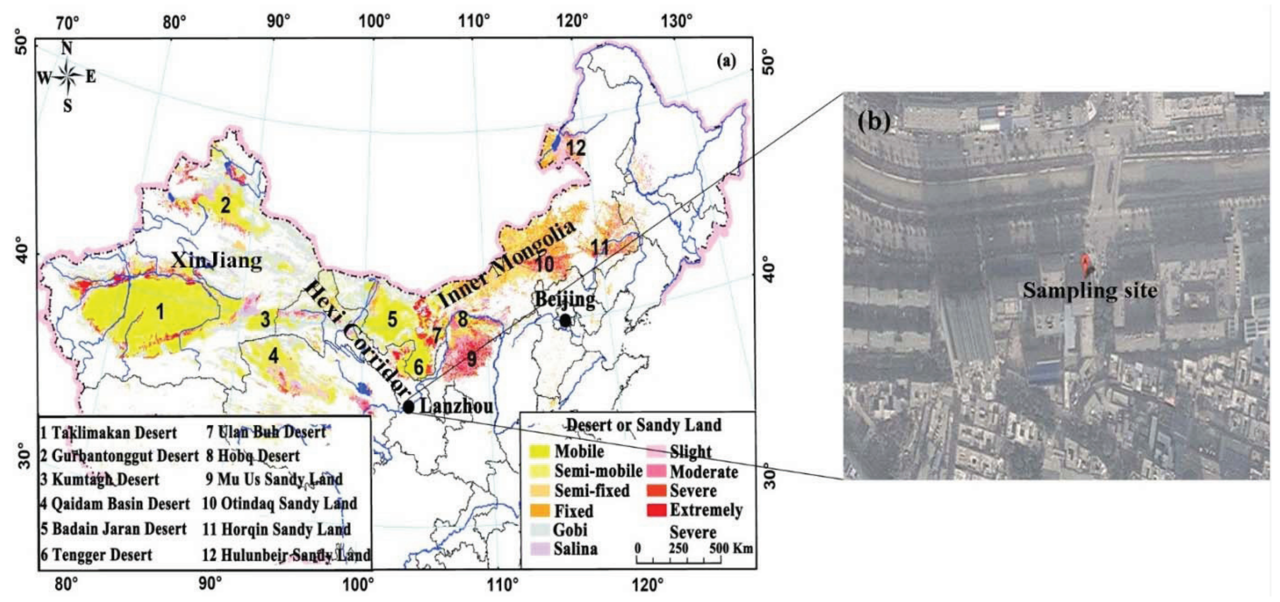

Figure 1. ***(a)*** *Distribution of Chinese desert and desertified land, and* ***(b)*** *geographical location of sampling site.*

MODIS data. The Moderate Resolution Imaging Spectroradiometer (MODIS) is a sensor on board the Terra and Aqua satellites (Parkinson, 2003). Terra passes from north to south in the morning (~10:30 a.m. local time at equator) and Aqua passes from south to north in the afternoon (~1:30 p.m. local time at equator) (Barnes et al., 1998). The MODIS atmospheric products are available at two processing levels, level–2 and 3 with spatial resolution of about 10 km and 1 degree, respectively. Furthermore, Level–2 products contain orbital swath data, whereas level–3 products contain global data that are averaged over time (daily, eight–day, monthly) over small equal angle grids (1 degree resolution) called the Climate Modeling Grid (CMD). Aerosol properties are retrieved using seven spectral channels (0.47–2.1 μm). The instruments aboard the Terra and Aqua satellites provide aerosol related parameters for the entire globe from 2000 and 2002, respectively. The MODIS operational AOD retrieval algorithm from Terra and Aqua is derived only over dark surface. Additionally, the deep–blue algorithm from Aqua developed by Hsu et al. (2004) can be used to derive aerosol optical properties over bright surfaces such as deserts. Therefore, we use the Deep Blue product over the desert region rather than the standard AOD (Aerosol Optical Depth) product, which cannot provide aerosol retrievals over deserts. The uncertainties of the deep blue product were reported to be around 25–30% (Hsu et al., 2006). In this study, the MYD08 Aqua daily deep blue AOD data (level 3, collection 5) at 1 degree spatial resolution during the dust event are utilized due to large scale geographical distribution for dust plume. These data will improve our understanding of horizontal motion of dust.

2.3. Backward trajectory calculation

Backward trajectory analyses were frequently used to estimate the most likely path over geographical areas that air masses were delivered to a receptor at a given time. The method essentially follows a parcel of air backward in hourly time steps for a specified length of time. The Hybrid–Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler et al., 2009) developed by the National Oceanic and Atmospheric Administration's (NOAA) Air Resources Laboratory (ARL) was used in this study to locate the source region of the dust and capture the vertical movement of the air masses from its source to the Lanzhou (36.05°N, 103.88°E) at different heights. The HYSPLIT is a hybrid Lagrangian and Eulerian dispersion model. Advection and dispersion of air masses are processed using Lagrangian approach, while concentrations of pollutants are calculated with Eulerian approach. The model uses internal terrain following sigma coordinate, and the horizontal grids are identical to input meteorological data. The vertical direction is divided into 28 layers and meteorological elements fields are linearly interpolated to corresponding sigma coordinates. Formula for computing air mass locations is given as follows:

$$\begin{aligned} P(t+\Delta t_h) &= P(t) + 0.5[V(P,t) + V(P,t+\Delta t_h)]\Delta t_h \\ P'(t+\Delta t_k) &= P(t) + V(P,t)\Delta t_k \end{aligned} \qquad (1)$$

where, Δt_h and Δt_k are variable time steps, $V(P,t)$ is movement speed of air masses at location P and time t.

Three–day backward trajectories at 500 m, 1 000 m, 2 000 m and 3 000 m above ground level (AGL) were calculated during the dust event using 1°×1° Global Data Assimilation System (GDAS) data from National Centers for Environmental Prediction (NCEP). In the study, the backward trajectories were initialized at the hour of day with the highest total dust concentrations during the dust period. The latitudes, longitudes, altitudes and pressure of air masses were simulated during dust transport process. The time step was computed each hour according to the maximum wind speed, meteorological and concentration grid spacing, and the fraction of a grid cell that a trajectory is permitted to transit in one advection time step. The trajectory end–point positions will be written to the output file each hour. In addition, the top of model was set to 10 000 m above ground level (AGL).

3. Results and Discussion

3.1. Case selection

Several dust storms and floating dust were observed in Lanzhou and other Northern China during March 2009 to May 2013. To identify of different sources of dust using satellite data and backward trajectory model, the severe regional dust storms occurred during 9 to 14 March 2013 were investigated in this study. Figure 2 shows that evolutions of visibility, total suspended particulate matter, PM_{10} and total dust concentrations in Lanzhou during 7 to 15 March 2013. As it can be seen from Figure 2, the total suspended particulate matter mass concentration and the visibility on 9 March were larger than 8 000 μg m^{-3} and lower than 500 m, respectively, which were the highest and lowest among nine days (7 to 15 March), indicating the significant effect of dust particles on Lanzhou urban air quality. After the day, the particulate pollutant concentrations and visibilities fluctuated narrowly during the dust period, and they were higher than 1 000 μg m^{-3} and smaller than 2 500 m, respectively. In addition, the particulate pollutant concentrations showed the opposite trends with visibilities during dust period, indicating effect of dust storms on regional air quality by impairing visibility.

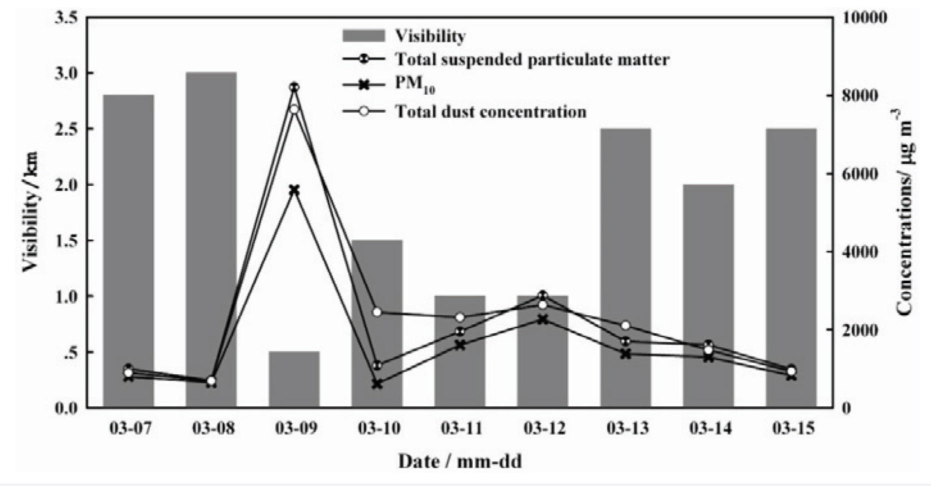

Figure 2. *Evolutions of visibility, total suspended particulate matter, PM_{10} and total dust concentrations in Lanzhou during 7 to 15 March 2013.*

3.2. The identification of dust sources

In order to obtain information on sources of dust during the dust event, the MODIS AOD, vertical profiles of dust layers from CALIPSO, including profiles of total attenuated backscatter at 532 nm, vertical feature mask, total color ratio and the volume depolarization ratio, and the HYSPLIT model were used. In addition, the synoptic situations during 8–11 March 2013 from NCEP/NCAR reanalysis data were analyzed to better understand transport of dust plumes and the geographic areas affected by dust.

The occurrence of regional dust events often goes with the invasion of cold air masses in Northern China. The cold air process occurred during 8–11 March triggered off the most extensive and the strongest dust event in China in 2013. At 500 hPa, there were intense cold advections near the Caspian Sea and the Lake Baikal at 12:00 UTC 8 March due to nearly verticalities between the isotherms and the isohypse contours (Figure 3). Low level cold advections enhance the atmospheric instability of within the boundary layer, which are advantageous to the downward transport of momentum and enhancements of surface wind velocity and dust plumes. In addition, the instability stratification also helped mixture of dust within the boundary layer, and then dust was long–range transported to downstream areas (Zhang and Sun, 2013).

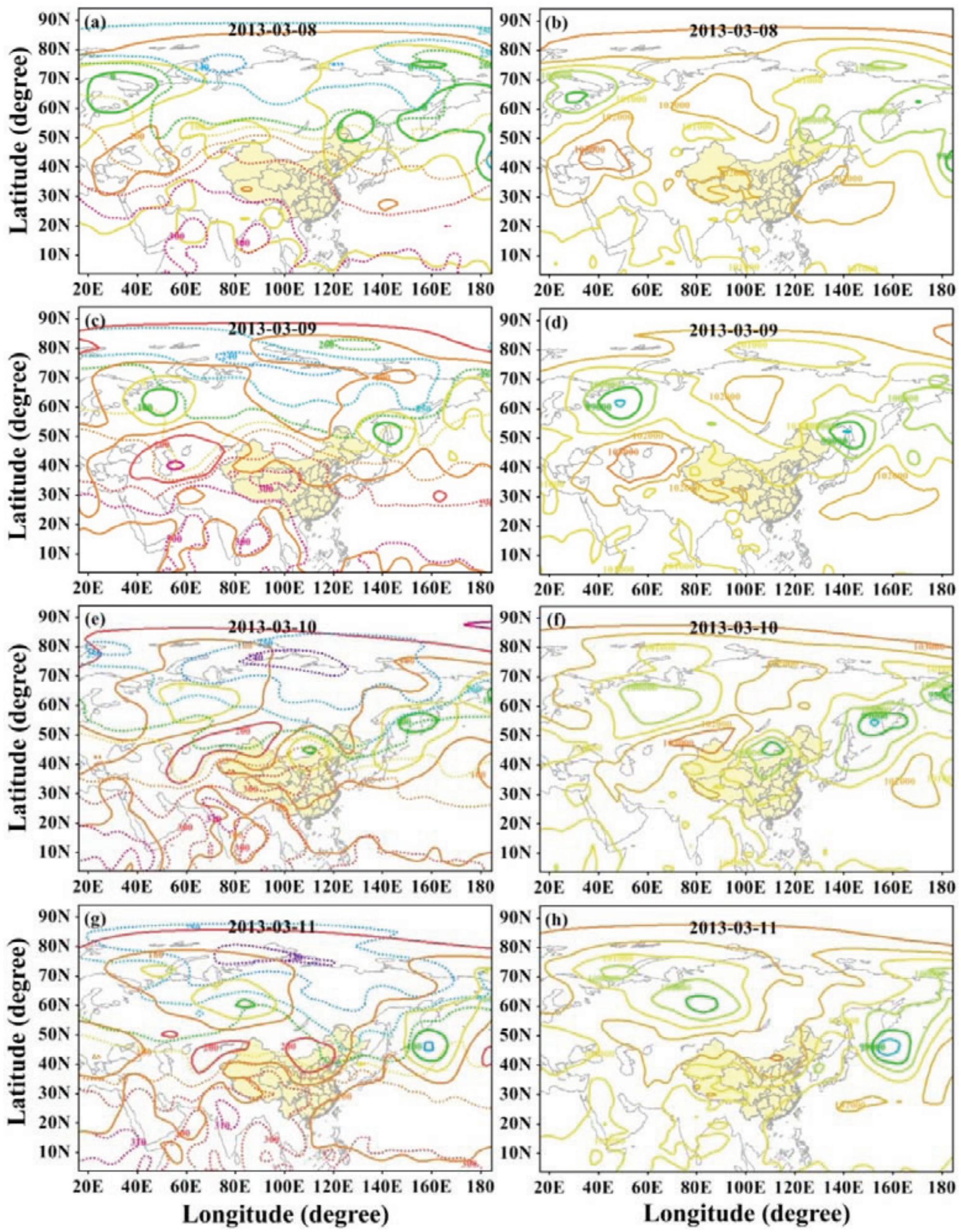

Figure 3. *850 hPa geopotential heights (solid lines, unit: dagpm) and temperature (dashed lines, unit: K)* ***(a), (c), (e), (g)*** *and the sea level pressure (unit: Pa)* ***(b), (d), (f), (h)*** *at 12:00 UTC 8* ***(a–b)****, 9* ***(c–d)****, 10* ***(e–f)*** *and 11* ***(g–h)*** *March 2013.*

The three–day backward trajectories were initialized at 03:00 UTC 9 March, 10:00 UTC 10 March, 06:00 UTC 11 March, 07:00 UTC 12 March, 07:00 UTC 13 March and 07:00 UTC 14 March at Lanzhou, respectively (Figure 5), and the sub–panels of Figure 5 represented height of trajectories initialized at corresponding hour. The back trajectory analysis for paths at low levels (500 and 1 000 m AGL) initialized at 06:00 UTC 11 and 07:00 UTC 12 March suggested that air masses moved very slowly and circulated around the desert regions in western and central Inner Mongolia before arriving at Lanzhou as the regions located in the southwest of surface high pressure on 11 March, which maybe brought dust particles on the transportation pathways into the atmosphere (see Figure 3). While the back trajectories at low levels initialized at 03:00 UTC 9 March moved much faster and traveled all the way from the Gobi Desert in Northeastern Xinjiang/Northwestern Gansu, and arrived at Lanzhou by passing through the desert regions in Western Inner Mongolia, which could be because intense cold advection appeared in Xinjiang province and Hexi Corridor as surface cold high–pressure moved eastwards, which was favorable to dust emissions. Nevertheless, for the other days during dust period, air masses at all heights were transported from the Taklamakan Desert and arrived at Lanzhou by passing through Qaidam basin.

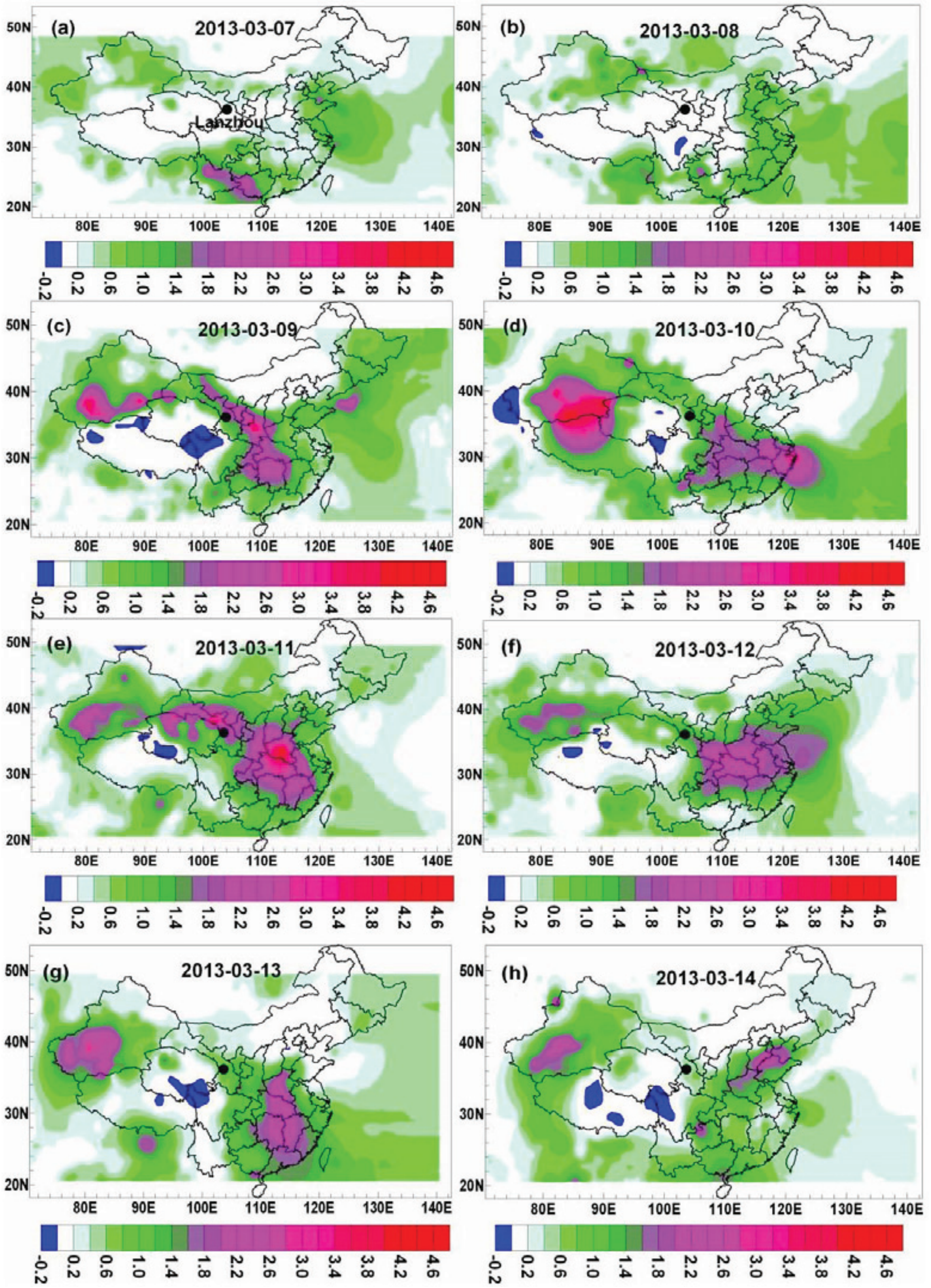

Figure 4. *Spatial distributions of daily mean MODIS Aerosol Optical Depth (AOD) on eight successive days around the dust event.*

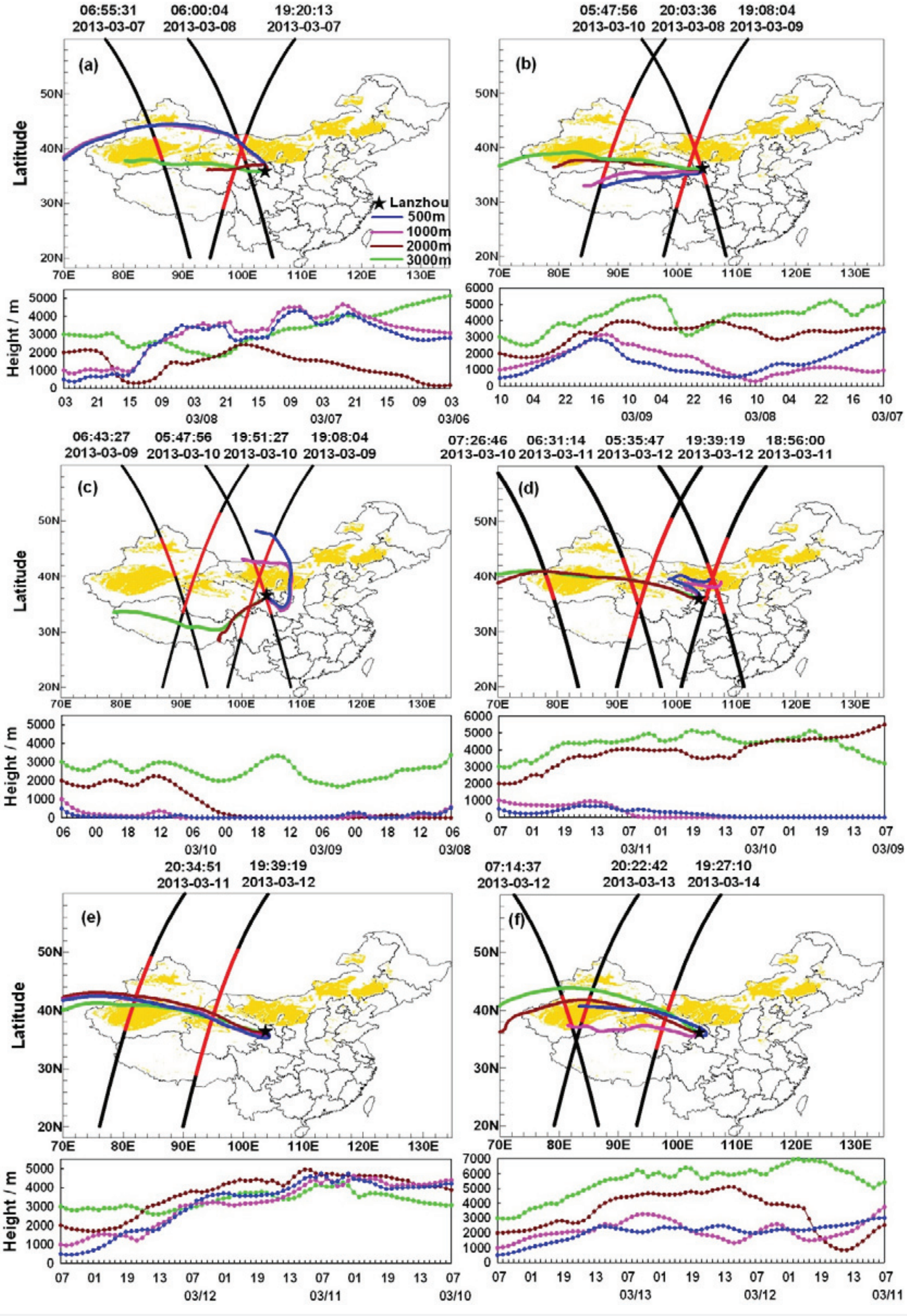

Figure 5. *Three–day (72h) backward trajectories initialized at* ***(a)*** *03:00 UTC 9 March,* ***(b)*** *10:00 UTC 10 March,* ***(c)*** *06:00 UTC 11 March,* ***(d)*** *07:00 UTC 12 March,* ***(e)*** *07:00 UTC 13 March and* ***(f)*** *07:00 UTC 14 March at 500 m, 1000 m, 2000 m and 3000 m AGL. The thick black lines indicate the CALIPSO nadir track, and the red part of the thick black lines indicate the existent of dust aerosols suggested by vertical feature mask. The sub–panels represent height of trajectories initialized at corresponding hour.*

The above back trajectory analyses indicated that dust were from Chinese three source regions, i.e. the Hexi (River West) Corridor and Western Inner Mongolia Plateau, the Taklamakan Desert, and the Central Inner Mongolia Plateau (Wang et al., 2004) where dust aerosols were identified in CALIPSO measurement (indicated by the red part of the track in Figure 5). It is also observed that the AOD values were high at these source regions during the dust event, and the areas with high AOD values moved eastwards and affected Lanzhou as high and low levels systems moved from northwest to southeast (Figures 3 and 4). In addition, the altitudes of air masses originated from western and central Inner Mongolia Plateau were even lower than those from the Hexi (River West) Corridor and Taklimakan Desert, and the movement speeds of dust from Western and Central Inner Mongolia Plateau were much slower due to tightly adherent ground movement of air masses (Figure 5). Therefore, the air masses from western and central Inner Mongolia Plateau brought dust particles on the transportation pathways into atmosphere led to increases of particle pollutant concentrations, which can be also seen from Figure 2 and Figure 4.

Dust aerosols are generally irregularly shaped and have relatively large size. Studies by Liu et al. (2008) and Shen et al. (2010) indicated that, compared with other aerosol types, dust aerosols had large color ratios, peaking at ~0.8, and the depolarization ratio for dust aerosols was generally larger than 0.06 and smaller than 0.35. Figure 6 shows the frequency distributions of the depolarization ratio and color ratio as a function of altitude AGL during 10–12 March 2013. It can be seen from Figure 6, dust aerosol layers originated from Taklamakan Desert were between 2 and 6 km at 07:26 10 March, 06:31 11 March and 19:39 12 March 2013, and the altitudes of dust layers gradually increased as the air masses moved eastwards. While the presence of dust aerosols from western and central Inner Mongolia Plateau was in the lower layers within 2 km at 18:56 11 March and 05:35 12 March 2013, which were consistent to the above results. The evolutions of the color ratio during 10–12 March 2013 presented similar information as the depolarization ratio.

The CALIPSO aerosol sub–type, 532–nm total attenuated backscatter, attenuated depolarization ratio and backscatter color ratio over the dust transport track for 10 and 12 March 2013 were shown in Figure 7. The presence of dust aerosols was in the layer of 1–4 km near the Badain Jaran and Tengger Deserts on 12 March 2013, and within the layer of 1.5–6 km over the Taklamakan Desert on 10 March 2013, which confirmed the dust source regions inferred from back trajectory analyses. On 7 and 8 March 2013, CALIPSO measurements indicated layers with dust aerosols were between 1 and 6 km near Hexi (River West) Corridor and western Inner Mongolia Plateau, (figures not shown). The above results indicated that the dust aerosols affecting Lanzhou during the long–term dust event were from Chinese three desert regions on different days, i.e., the Hexi (River West) Corridor and Western and Central Inner Mongolia and Taklamakan Desert. Furthermore, the air masses from Badain Jaran and Tengger Deserts and their outer edges maybe brought dust particles on the transportation pathways into atmosphere led to increase of particle pollutant concentrations (see also Figures 5–6). Although strong winds were needed for resuspending particles from the ground, these information was important because size characteristics of the dust released during a dust event were most dependent on source regions rather than other external factors such as wind speed and remains nearly unchanged after 1–2 days of transport in the atmosphere (Reid et al., 2008; Sow et al., 2009; Kok, 2011), which meant that the size distribution of mineral dust would not changed during long–range transport except wet deposition or cloud processing.

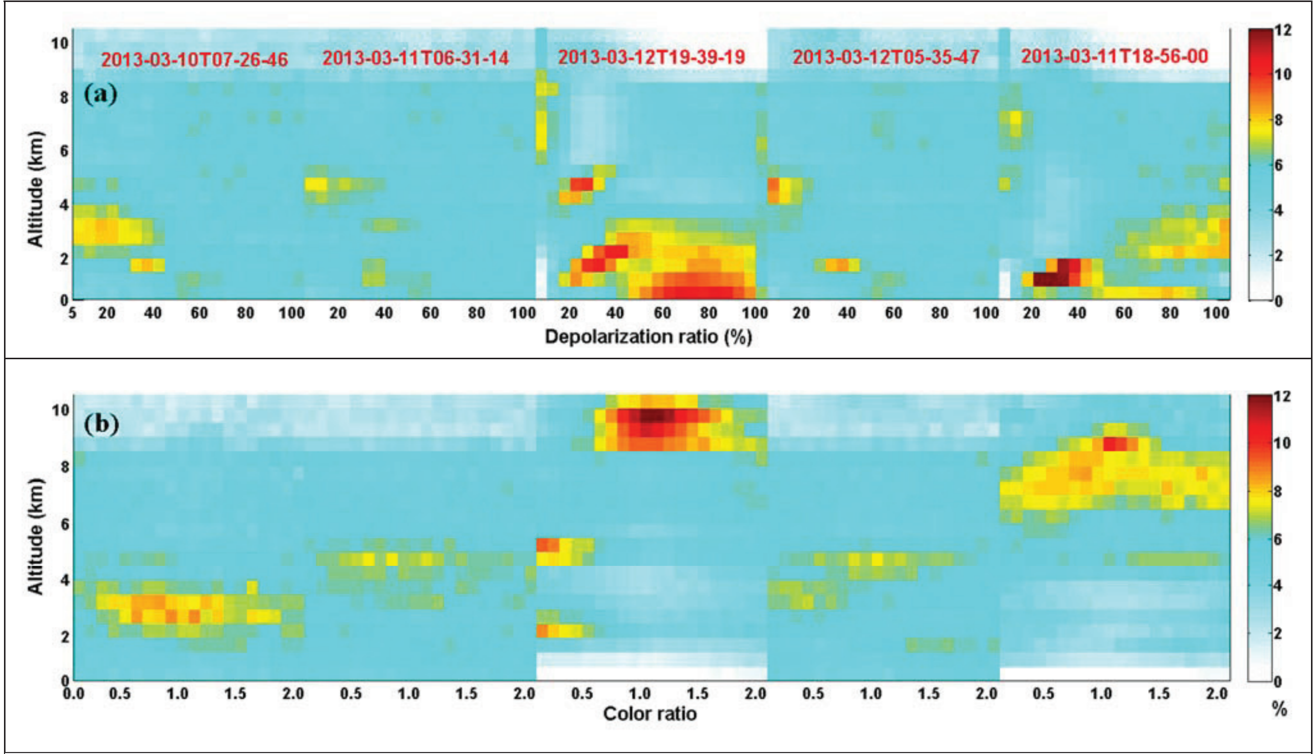

Figure 6. *Frequency distributions of **(a)** the volume depolarization ratio and **(b)** the backscatter color ratio as a function of altitude AGL on 10–12 March 2013.*

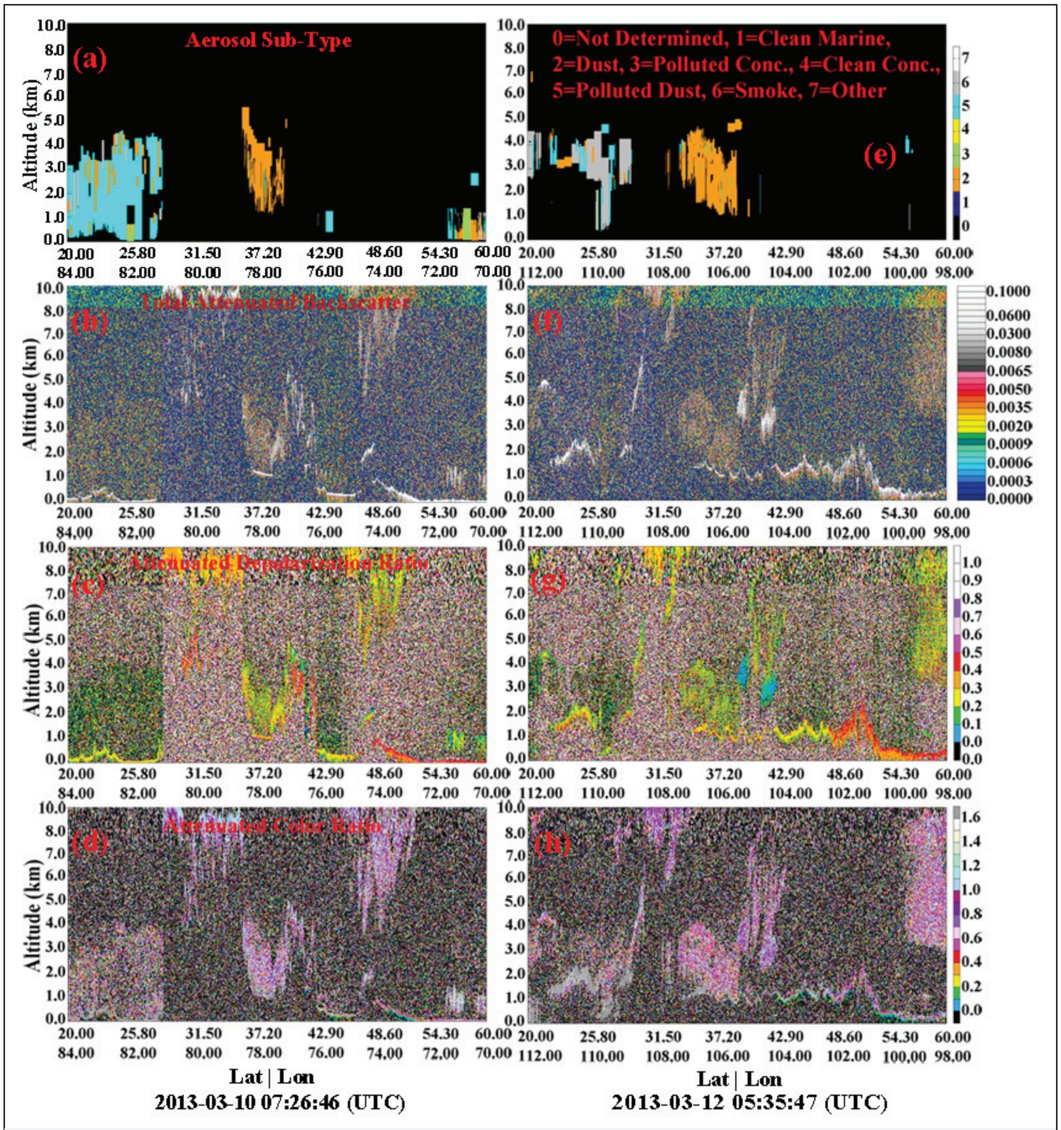

Figure 7. *CALIPSO altitude–orbit cross–section measurements of* ***(a), (e)*** *the aerosol sub–type,* ***(b), (f)*** *532 nm total attenuated backscatter intensity (km^{-1} sr^{-1}),* ***(c), (g)*** *volume depolarization ratio, and* ***(d), (h)*** *1 064 nm/532 nm backscatter color ratio over Western China for* ***(a–d)*** *10 and* ***(e–h)*** *12 March 2013.*

4. Conclusions

Evolutions of visibility, total suspended particulate matter, PM$_{10}$ and total dust concentrations and the sources of dust during the severe regional dust event occurred during 9–14 March 2013 were identified in this study using in situ data, CALIPSO and MODIS satellite data and backward trajectory analysis at Lanzhou, Northwestern China. Further analysis on the dust transport revealed different source regions on different days during the dust event.

The total suspended particulate matter mass concentration larger than 8 000 μg m^{-3} on 9 March was the highest among seven dust days with the visibility lower than 500 m. The dust at low levels (500 and 1 000 m AGL) mainly originated from the Hexi (River West) Corridor and Western and Central Inner Mongolia Plateau. The air masses moved very slowly and circulated around the desert regions in western and central Inner Mongolia before arriving at Lanzhou, while that initialized at 03:00 UTC 9 March moved much faster and traveled all the way from the Gobi Desert in Northeastern Xinjiang / Northwestern Gansu, and arrived at Lanzhou by passing through the desert regions in western Inner Mongolia. Nevertheless, the air masses at higher altitudes (2 000 and 3 000 m AGL) were transported from the Taklamakan Desert and the Qaidam basin, and arrived at Lanzhou. Most interesting, the air masses from Badain Jaran and Tengger Deserts and their outer edges brought dust particles on the transportation pathways into atmosphere led to increases of particle pollutant concentrations due to tightly adherent ground movement of air masses.

Acknowledgments

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