Case study of dust event sources from the Gobi and Taklamakan deserts: An investigation of the horizontal evolution and topographical effect using numerical modeling and remote sensing

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ABSTRACT

A severe dust event occurred from April 23 to April 27, 2014, in East Asia. A state-of-the-art online atmospheric chemistry model, WRF/Chem, was combined with a dust model, GOCART, to better understand the entire process of this event. The natural color images and aerosol optical depth (AOD) over the dust source region are derived from datasets of moderate resolution imaging spectroradiometer (MODIS) loaded on a NASA Aqua satellite to trace the dust variation and to verify the model results. Several meteorological conditions, such as pressure, temperature, wind vectors and relative humidity, are used to analyze meteorological dynamic. The results suggest that the dust emission occurred only on April 23 and 24, although this event lasted for 5 days. The Gobi Desert was the main source for this event, and the Taklamakan Desert played no important role. This study also suggested that the landform of the source region could remarkably interfere with a dust event. The Tarim Basin has a topographical effect as a “dust reservoir” and can store unsettled dust, which can be released again as a second source, making a dust event longer and heavier.

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Introduction

Dust events have drawn a great deal scientific attention in arid and semi-arid areas of East Asia over the last four decades. Many studies have revealed that mineral dust aerosols have a potent impact on human health, Earth’s energy budget and atmospheric chemistry. High particulate matter concentrations during dust events induce lung disease as well as cardiovascular inflammation (Sun et al., 2005). Dust aerosol interrupts the radiative balance of Earth’s atmospheric system directly and indirectly. The particles are brightly colored and tend to scatter solar radiation in multiple directions, thereby reducing the radiation that reaches the ground (Mahowald et al., 2014; Wang et al., 2013). Additionally, dust aerosol can act in the atmosphere to condense clouds or ice nuclei (Ackerman et al., 2004; Sassen et al., 2003), thereby forcing an indirect effect on radiative energy budgets. Moreover, dust aerosol can provide surfaces for some photochemical reactions (Ramazan et al., 2004; Cwiertny et al., 2008).

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The Gobi and Taklamakan Deserts are two main dust sources over East Asia (Fig. 1a, b). The total area of these deserts is approximately 1,632,000 km² and accounts for 13.8% of the entire East Asian region. Because precipitation is rare and both strong gusts and high surface air temperature exist, the annual dust production has been estimated to be as much as half of the global total (Zhang et al., 1997), which ranges from 500 to 6000 Tg/yr (Huneeus et al., 2011; Prospero et al., 2010). The enormous source region and attributes of the local climate indicate that East Asian dust is not confined at its emission area but could have various influences over the entire northern hemisphere (Uno et al., 2009; Cottle et al., 2013). Furthermore, the annual frequency of East Asian sandstorms oscillates over a 10-year period (Yang et al., 2013). Statistical analyses indicate that two-thirds of the sandstorms in the northern hemisphere can be observed in the springtime, and the summer has the lowest frequency of sandstorms (Hsu et al., 2013; Wang et al., 2013).

Although the above studies reveal important chemico-physical properties of East Asian dust and represent our knowledge about it, the effects of the unique landforms around source regions for a dust event seem to have been neglected. To study these effects, we applied the Weather Research and Forecasting Chemistry (WRF/Chem) model combined with the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model (Peters-Lidard et al., 2015) to provide preliminary results regarding dust's horizontal evolution and the topographical effect of the surrounding landform. In addition, a dataset using moderate resolution imaging spectroradiometer (MODIS) was also considered to assess the model simulation. The model's reality and reliability have been demonstrated by previous WRF/Chem-GOCART simulations in different global regions (Tie et al., 2007; Chapman et al., 2009; Zhang et al., 2010; Grell et al., 2011), indicating that this model system can profile aerosol properties, meteorology and atmospheric chemistry.

1. Model system and remote sensing

1.1. Model description

The Weather Research and Forecasting Model (WRF) is a mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting. The system contains an Advanced Research WRF (ARW) dynamical solver, which was primarily developed at NCAR (National Center for Atmospheric Research). The ARW solver uses a Runge–Kutta 2nd or 3rd order time integration scheme to solve non-hydrostatic equations on horizontal Arakawa-C (Arakawa and Lamb, 1977) grids and vertical mass-based terrain-following coordinates. The model gives the user a choice of 2nd to 6th order advection schemes for spatial discretization (Skamarock and Klemp, 2008). WRF with ARW is a fully compressible and Euler non-hydrostatic model. The model comprises a series of microphysical processes, parameterization schemes and dynamical options from simple to sophisticated. For the physics in this case, cloud-resolving
microphysics were represented by the Purdue Lin scheme (Lin et al., 1983) and sub-grid clouds were parameterized by the Grell-3 scheme (Grell and Dévényi, 2002). Long- and short-wave atmospheric radiations were represented by the multi-spectral RRTM (Mlawer et al., 1997) and Goddard schemes (Chou et al., 1994), respectively. For multi-layer surface physics, the model setup used a revised MM5 Monin–Obukhov surface layer scheme (Monin and Obukhov, 1954) and a unified Noah land-surface model (Chen and Dudhia, 2001). The planetary boundary layer (PBL) was parameterized by the Yonsei University (YSU) scheme (Hong et al., 2006).

Because WRF was combined with an atmospheric chemistry (Chem) model in 2002, WRF/Chem has evolved to version 3.7 by now. The WRF/Chem system is available online with the chemistry part running simultaneously and sharing information with the meteorological part. Both parts use the same horizontal and vertical grids, time intervals, parameterizations for cloud-resolving microphysics and sub-grid convections. All chemical species and aerosols transport is conducted by the meteorological part simultaneously. The Chem part consists of dry deposition, several choices for gaseous and aqueous phase chemical mechanisms, photolysis rates, aerosol schemes and surface emissions (Grell et al., 2005). Start-up for running WRF/Chem is not difficult because the WRF Preprocessing System (WPS), comprising a series of programs, can simplify the work. Different ready-to-use meteorological datasets can drive WRF/Chem. In this study, the dataset was obtained from National Centers for Environmental Prediction Final Analysis (NCEP-FNL, Research Archive at NCAR, Computational and Information Systems Laboratory, Boulder, CO.) (Shea, 1996) with the spatial resolution set at 1° × 1° and 6-hour intervals used for WRF/Chem driving.

The aerosol scheme is pivotal in a dust study. The Goddard Chemistry Aerosol Radiation and Transport (GOCART, Chin et al., 2002) model is naturally included in the most recent WRF/Chem version. It was originally designed for “offline” use and ran only at low resolution (Schubert et al., 1993). It can simulate several types of tropospheric aerosol types, including dust, sea salt, sulfate, black carbon (BC) and organic carbon (OC). GOCART converts dust and sea salt mass concentrations into hypothetical modal distributions and separates four size bins for dust. The dry deposition scheme includes gravitational settling and surface deposition. The GOCART model calculates the vertical dust emission flux by using the following empirical expression developed by Gillette and Passi (1988):

\[
F_p = \begin{cases} 
C S_{sp} t_{sp} \mu_3 \left( u_{10} m - u_c \right) & \text{if } u_{10} m > u_c \\
0 & \text{otherwise}
\end{cases}
\]

where \( F_p \) is the dust emission flux for dust size bin \( p \); \( C \) is an empirical constant equal to \( 1 \text{ (\mu g \text{ s}^{-2})/m^2} \); \( S \) is the source function, as described below; \( u_{10} m \) is the horizontal wind speed above the surface at 10 m; \( u_c \) is the threshold wind speed, assuming no dust emissions below \( u_c \); and \( \mu_3 \) is the fraction for each size bin: 0.1 for 0.1–1 \( \mu \text{m} \), 0.25 for 1–1.8 \( \mu \text{m} \), 1.8–3 \( \mu \text{m} \), and 3–6 \( \mu \text{m} \) (Ginoux et al., 2001). Threshold speed is hard to determine because it is a function not only of particle size and air density but also of soil moisture (Ginoux et al., 2001). Kimura and Shinoda (2010) combined observation and modeling to probe the threshold speed in northeast Asia. Based on their research, a \( u_c \) equal to 10 m/sec was selected. The source function \( S \) is defined from an erodibility map representing the fractional grid cell area of alluvium available for wind erosion, expressed as Eq. (2):

\[
S = \left( \frac{z_{\text{max}} - z_i}{z_{\text{max}} - z_{\text{min}}} \right)^5.
\]

where \( S \) is the percentage of erodibility in the grid cell \( i \) of altitude \( z_i \) and \( z_{\text{max}} \) and \( z_{\text{min}} \) are the maximum and minimum elevations in the surrounding \( 10° \times 10° \) topography, respectively (Ginoux et al., 2001). Fig. 1b presents the percentage of erodibility over the model domain. GOCART is now naturally “online” combined with WRF/Chem and shares the same model grids and time intervals. Aerosol direct and indirect effects (long- and short-wave radiation), photolysis and micro-physical processes can be activated for WRF/Chem combined with the GOCART model system (Table 1).

To simulate the dust event sources from the Gobi and Taklamakan deserts between April 23 and 27, 2014, the bug-fixed and stable WRF/Chem-GOCART v3.6 was run over a computational domain, as shown in Fig. 1a, b, with 45-km horizontal grid spacing and a 1-hr time resolution. The domain contained 120 west-east and 98 south-north horizontal grid points as well as 40 vertical levels. The model top was 50 hPa. The chemical initial and boundary conditions were represented by an idealized, northern hemispheric, mid-latitude, clean environmental profile from the NOAA Aeronomy Lab Regional Oxidant Model (NALROM, Liu et al., 1996). The gaseous phase chemistry mechanism was represented by the second version of the Regional Acid Deposition Model (RADM2, Chang, 1991), which included 158 reactions among 36 species. Dust emissions were calculated using Eq. (1) during the model run, and anthropogenic and biomass emissions were not involved in this dust-storm episode. The 1.8–3 \( \mu \text{m} \) size bin was selected to represent the dust distribution because particles in this size bin only have an airborne lifetime of a few days, which was the maximum mass among the four bins (Dubovik et al., 2002). The remaining bins were

Table 1 - Model components and configurations.

<table>
<thead>
<tr>
<th>WRF/Chem components</th>
<th>Schemes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longwave radiation</td>
<td>RRTM (Mlawer et al., 1997)</td>
</tr>
<tr>
<td>Shortwave radiation</td>
<td>Goddard (Chou et al., 1994)</td>
</tr>
<tr>
<td>Land surface</td>
<td>Noah (Chen and Dudhia, 2001)</td>
</tr>
<tr>
<td>Surface layer</td>
<td>Monin-Obukhov (Monin and Obukhov, 1954)</td>
</tr>
<tr>
<td>Planetary boundary layer</td>
<td>YSU (Hong et al., 2006)</td>
</tr>
<tr>
<td>Cumulus parameterization</td>
<td>Grell-3 (Grell and Dévényi, 2002)</td>
</tr>
<tr>
<td>Microphysics</td>
<td>Purdue Lin (Lin et al., 1983)</td>
</tr>
<tr>
<td>Gaseous phase chemistry</td>
<td>RADM2 (Chang, 1991)</td>
</tr>
<tr>
<td>Photolysis</td>
<td>Fast-J (Wild et al., 2000)</td>
</tr>
<tr>
<td>Aerosol module</td>
<td>GOCART (Chin et al., 2002)</td>
</tr>
<tr>
<td>Effective radius of modal dust bins</td>
<td>0.5, 1.4, 2.4, and 4.5 ( \mu \text{m} ) (Ginoux et al., 2001)</td>
</tr>
</tbody>
</table>

RRTM: Rapid Radiative Transfer Model; YSU: Yonsei University Scheme; RADM2: Second version of Regional Acid Deposition Model; GOCART: Goddard Chemistry Aerosol Radiation and Transport Model.
discarded because we did not investigate dust’s optical properties, which strongly depend on the size distribution (Ginoux et al., 2001). Large particles (3–6 μm) were neglected because they generally have a lifetime of less than a few hours (Tegen and Fung, 1994), while clay (0.1–1 μm) was assumed not to change during transport (Ginoux et al., 2001). The model ran from April 18 to April 27, 2014. The first five days were considered to be spin-up, and the remaining days were used for analysis. The WRF/Chem-GOCART model setup is described above and summarized in Table 1.

1.2. Satellite-based remote sensing

Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument built by Santa Barbara Remote Sensing and carried on Terra and Aqua platforms, which belong to NASA’s

Fig. 2 – Qualitative comparison of natural color images (left column) over the source region and modeled column-integrated dust loading (CIDL) with effective radius 2.4 μm.
Earth Observing System. Because the instruments circle at a near-polar and sun-synchronous orbit, they can image the entire Earth every two days and measure Earth’s spectral radiation within 36 bands ranging from 400 nm to 14,400 nm. The spatial resolution of these 36 bands ranges from 250 m to 1000 m at the nadir. The combinations of different bands that have the same resolution can reveal the Earth’s land, ocean, and atmospheric properties. MODIS provides a global view of the aerosol optical depth (AOD). The classical AOD-retrieval algorithm is based on the hypothesis that the AOD can only be retrieved over “dark surfaces” (such as vegetation) but cannot be retrieved over “bright targets” (such as deserts). Dust aerosol is categorized as a “bright target.” It can brighten the dark background and invalidate the classical algorithm. For this reason, a more advanced algorithm, the Aqua MODIS “Deep Blue” AOD-retrieval algorithm at 550 nm over land (Hsu et al., 2004), was used in this case. It has the capacity to retrieve the AOD over bright surfaces, such as deserts. Therefore, the “Deep Blue” Level 3 products (MYD08_D3 v051) were used at a spatial resolution of 1° × 1° and were provided by NASA. Moreover, the MODIS Level 1B dataset was used to retrieve natural color images (Fig. 2). The MODIS data products were validated by sun-photometer observations, which usually have a relative error of less than 20% (Li et al., 2003).

2. Results and discussion

2.1. Horizontal and temporal distribution of dust

MODIS collects Earth’s spectral radiation in 36 bands. The combination of bands 1, 4 and 3 at the same resolution (here, 1000 m at nadir) provides a natural color (RGB) image over each granule. Fig. 2 shows those time-ordered composite images captured by Aqua MODIS over this dust event from April 22, 2014, at 07:10 UTC (Coordinated Universal Time) to April 27 at 07:30 UTC, an event that covered most of the area of the Taklamakan and Gobi deserts. These natural color images present the instantaneous status of the dust event and reveal its temporal development over the source region. NASA Goddard Earth Sciences Data and Information Services Center (NASA, 2014) filed this event’s burst-out on April 23. A dust storm-front could be clearly discerned blowing into the Tarim Basin because it was distinctly brighter in color than the Basin’s soil (see Fig. 2, UTC 2014-04-23 07:55). Natural color images were also used to verify the model’s performance. In the right column of Fig. 2, each image shows the modeled column-integrated dust loading (CIDL) range from 25 to 300 g/m² with an effective particle radius of 2.4 μm, paired with its left natural image at approximately the same time and exactly in the same region. From Fig. 2 (UTC 2014-04-24), it can be seen that both natural color and CIDL images reflect an arch-like “dust passageway” that exists between 90°E and 100°E. Fig. 1a explains the formation of this “dust passageway”, which is mainly attributed to its surrounding landforms. The comparison between the natural color and model results illustrates that the current version of WRF/Chem-GOCART reproduces spatial distributions of the dust plume fairly well. Fig. 3 shows daily AOD derived through MODIS observation with a resolution of 1° × 1°. The white area with no data could be attributed to the algorithm of “Deep Blue” AOD.

To investigate the dust’s origin and transport during this event, the NCEP-FNL daily sea level pressure (SLP), surface...
temperature, 10-m wind vectors, modeled 2.4-μm CIDL and dust emission flux (EF) are included in Fig. 4. Fig. 4 shows that a palpable pressure system switch took place on April 23, 24 and 25. On April 23 (Fig. 4, UTC 2014-04-23), a High Pressure System (HPS) from the northwest, centered at contour line 1035 hPa, approached a Low Pressure System (LPS), centered at contour line 1000 hPa. Both pressure systems moved eastward, but the HPS moved faster than the LPS, so the LPS met the eastern side of the HPS. As a result, a strong pressure gradient occurred between these two pressure systems, a trough occurred near the Gobi Desert and a ridge dominated over the Taklamakan. Because of this pressure pattern, powerful northwest winds were generated over the source region, inciting a severe dust event. The dust emissions were mainly located in the western part of the Gobi Desert, and daily average dust fluxes peaked at 886.6 μg/(m²·sec) on April 23. The trough directed the northwest airstream to the east and moved dust in the same direction, and the ridge directed

![Fig. 4](image-url)

**Fig. 4** - NCEP-FNL daily averaged surface temperature, sea-level pressure (left); NCEP-FNL daily averaged 10-m wind vectors, daily modeled column-integrated dust loading (CIDL) (middle) and daily averaged modeled dust emission flux (EF) (right) during a dust event. FNL: Final Analysis; NCEP: National Centers for Environmental Prediction.
the stream to the southwest, while blowing dust into the Tarim Basin (see Fig. 2). Aside from the meteorology, the topography of the source region significantly influenced the horizontal dust distribution. At the divergence zone of the northwest stream, the value of the modeled 2.4-μm CIDL was high. CIDL gradually faded along the northern margin of the Qinghai–Tibetan Plateau; then, it stretched to the west and east. The extension of the western dust branch was much smaller compared with the eastern dust branch, indicating that the Tarim Basin could trap the dust and confine the dust plume’s extension. On April 24 (Fig. 4, UTC 2014-04-24), the HPS completely dominated the source region and the trough-ridge system hovered over the middle part of the Gobi Desert between 100°E and 110°E, directing the wind to the east and south. Dust emissions were also located in the middle part of the Gobi Desert, and the daily average dust fluxes peaked at 221.7 μg/(m²·sec), which was less than the peak on April 23.

The two-day analysis indicated that, from the time of the burst-out from April 23 to April 24, the Taklamakan Desert was not the major dust source for this event and winds in the Taklamakan Desert were not as powerful as they were in the Gobi Desert. The dust plume was broken into two branches: one blew into the Tarim Basin and the other moved toward the east. Each branch had a high CIDL center. The Tarim Basin’s dust branch mainly originated in the western part of the Gobi Desert, but its extension was confined by surrounding landforms. Meanwhile, the middle and western Gobi Desert contributed to the far more extensive eastern branch, showing that the Gobi Desert played a significant role in dust emission. After April 24, Fig. 4 shows no further conspicuous dust emissions over the source region. The strength of the HPS gradually decreased, the trough-ridge system faded away, and although a second LPS (UTC 2014-04-25) centered at 985 hPa approached, it diverted to the northeast before arriving at the source region.

### 2.2. Topographical effect

Fig. 1a demonstrates the landform of the Tarim Basin. The Basin is an approximately oval area surrounded by high altitude mountains, yet there is a break at approximately 90°E, 40°N on its east side. This special land structure could cause the Tarim Basin to act like a “dust reservoir” under certain meteorological conditions. As described previously, when the HPS perished, no obvious dust emissions occurred after April 24. Therefore, this case provided an excellent opportunity to study the behavior of unsettled dust and the topographical effect of the Tarim Basin related to this dust event. From the start to the end of the study period, the model results showed that the Taklamakan Desert was not the main emitter of dust. Instead, the dust in the Basin was mainly derived from the western part of the Gobi Desert. Wind brought dust in from April 23 to 24, so the unsettled dust was trapped and accumulated in the Tarim Basin on these two days. Fig. 4 (UTC 2014-04-23 and 24) shows the prevailing wind direction over the Tarim Basin was inward, toward the Basin, and the CIDIL extension fits the Basin’s landform shape well. On April 25, probably because of the second LPS that occurred on the northwestern side of the Tarim Basin, the prevailing wind direction was inverted. Therefore, it blew unsettled dust out of the Tarim Basin, affecting the area north of the Basin. After April 25, wind over the Tarim Basin was weaker than it had been on previous days, and due to deposition and outward transport, CIDIL over the Tarim Basin, it gradually decreased.

The above analysis illuminates the role of the Tarim Basin, which acts, as previously described, like a “dust reservoir.” The Basin could store unsettled dust until the dust settles. Nevertheless, if meteorological conditions change during dust deposition in the Tarim Basin, the unsettled dust would become a new source that would be much easier to release than ground soil sources. Fig. 4 (UTC 2014-04-27) shows that the dust plume released by the “dust reservoir” could stretch to Lake Baikal. In addition to this effect, the “dust reservoir” is assumed to prolong the duration of dust events. If the second LPS dominated the source region after April 25 instead of moving northeasterly, the “dust reservoir” would release more dust and exacerbate this dust event.

### 3. Conclusions

During springtime, sandstorms often occur in the Taklamakan and Gobi deserts. In this case, a severe sandstorm that burst out on April 23, 2014, and lasted until April 27 was investigated by the WRF/Chem-GOCART model. By integrating MODIS satellite observations, the model’s ability to simulate dust emissions and the dust horizontal distribution was examined. Ten-day simulation began on April 18, 2014. The results between April 22 and 27 were considered. NCEP-FNL data were used to reveal the meteorological dynamic, showing that the cause of this event was a forceful pressure gradient, which was attributed to a trough-ridge system over the source region on April 23.

As in the formation of most sandstorms, there was nothing special about this episode. However, it provided a good opportunity to investigate the topographical effect of the Tarim Basin during a dust event. The study results showed that modeled dust emissions occurred on April 23, with an emission flux of 886.6 μg/(m²·sec). After April 24, no significant emissions continued. The lifted dust was divided into two branches and propagated into the Tarim Basin and Eastern China. The unsettled dust in the Tarim Basin was mainly derived from the western part of the Gobi Desert, while the Taklamakan Desert played no important role in the emissions. On April 25, the wind direction in the Tarim Basin inverted and unsettled dust in this basin was released again (Fig. 4). We defined the topographical effect of the Tarim Basin as a “dust reservoir.” As such, it could trap blown-in dust, which would otherwise gradually deposit if the meteorological conditions were stable. However, if the meteorological conditions changed during the depositing process, the trapped, unsettled dust could become a second source and might prolong and exacerbate a dust event.

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