Long-range transport of spring dust storms in Inner Mongolia and impact on the China seas

Sai-Chun Tan a,b,*, Guang-Yu Shi a, Hong Wang c,d

a State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
b Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology, Nanjing 210044, China
c Centre for Atmosphere Watch and Services, Chinese Academy of Meteorological Sciences, Beijing 100081, China
d State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081, China

A R T I C L E   I N F O

Article history:
Received 29 March 2011
Received in revised form 18 August 2011
Accepted 27 September 2011

Keywords:
Dust storm
Transport
Deposition
Probability
The China seas

A B S T R A C T

Analysis of daily observations from 43 meteorological stations in the Inner Mongolia Autonomous Region, China, showed the distribution of spring dust storm events during 2000–2007. Guaiizihu and Sunitezuoqi stations had the highest frequencies of dust storms. The interannual and seasonal variations of dust storms were closely related to weather conditions, especially the wind speed. A forward trajectory model and satellite observations were used to investigate the transport paths and dust layers of dust storms from Guaiizihu and Sinitezuqi stations to the China seas and their probability of influencing the seas during spring 2000–2007. Forward trajectories showed that dust storms at Guaiizihu and Sinitezuqi stations had the highest probability of affecting the Yellow Sea, followed by the Bohai Sea, the East China Sea, and the southern South China Sea. The dust particles from Sinitezuqi station affected these four seas directly through coastal areas, while those from Guaiizihu station were transported via the Inner Mongolian deserts and/or the Loess Plateau. The dust storms from Sinitezuqi station impacting the four seas were characterized by a single dust source and a short transport distance, while those from Guaiizihu station were characterized by multiple sources and relatively long transport distances. The dust particles from these two stations were mostly transported in a <4 km layer from the source regions to the seas. The satellite vertical profile also indicated that dust particles were mainly contained in a 0–4 km layer over the source regions and the four seas. An aerosol index retrieved from satellite observations and the estimated dust deposition also supported the influence derived from the forward trajectory model, with large aerosol index and dust deposition values occurring on the dust days affecting the four seas. The average deposition over the four seas was 18.7 g m$^{-2}$ during spring 2000–2007.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

The dust aerosols carried by dust storm events in East Asia have major effects on local ecosystems, the environment, and human society, as well as large impacts in downwind areas such as Japan, Korea, the North Pacific, and North America through long-range transport (Mikami et al., 2006). Eolian dust particles in the atmosphere could affect climate via radiative forcing (Sokolik et al., 2001) and could play important roles in marine biological activities, which are closely related to the global carbon cycle and marine aerosol production (Bishop et al., 2002; Meskhidze et al., 2005; Levasseur et al., 2006; Yuan and Zhang, 2006; Jo et al., 2007; Tobo et al., 2010). This, in turn, could cause feedback effects on climate and dust production (Jickells et al., 2005). Consequently, understanding the characteristics of dust storm events and their influence on seas is important.

Asian dust events primarily occur in springtime (March–May) (Qian et al., 2006). Simulated springtime dust emissions for the period 1960–2002 indicated that Asian dust mainly originated from 10 source areas in the deserts of Mongolia, northern China, and Kazakhstan (Zhang et al., 2003b). Both observations and simulations showed that the Inner Mongolia Autonomous Region (Inner Mongolia) in China is one of the most important source regions for Asian dust (Zhang et al., 2003b; Wang et al., 2005, 2010;
Qian et al., 2006) and is responsible for approximately 31% of the total dust production (Zhang et al., 2003b).

Transport of dust particles is closely related to synoptic conditions and the characteristics of the source regions (Tsai et al., 2008). Asian dust is usually associated with frontal systems and/or cyclones (Sun et al., 2001; Uno et al., 2004; Tsai et al., 2008). Dust particles can be transported by surface-level northerly winds associated with the Asian winter monsoon over the Asian continent and by westerly winds in the free troposphere from the eastern Asian continent to the Pacific Ocean (Uematsu et al., 1983; Uno et al., 2004; Zhao et al., 2006). Lidar observations and model simulations indicated that dust particles from the Gobi Desert are usually entrained in a lower layer (<3 km) and can be deposited in proximal regions. Dust from the Taklimakan Desert uplifted to ≥5 km has a better chance of being transported over long distances, because the surrounding high mountains exceed 5 km in height and the stronger westerly jet dominates in this altitude range (Iwasaka et al., 1983, 2003; Sun et al., 2001; Matsuki et al., 2003; Uno et al., 2004).

Many studies of the transport of Asian dust to downwind areas, including the China seas, have been reported. Zhang and Gao (2007) analyzed the source and movement route of dust storms to downwind seas during 2000–2002 based on meteorology data from the Meteorological Information Comprehensive Analysis and Process System (MICAPS). Gao et al. (2009) reviewed previous studies of the transport pathways of Asian dust and its influence areas. However, most studies concentrated on the transport of dust storms across the continent (Zhang et al., 2003a; Chen et al., 2006) or performed a case study of the influence of Asian dust storm on downwind areas or seas (Iwasaka et al., 1983; Liu et al., 1998; Fang et al., 1999; Husar et al., 2001; Kim and Park, 2001; Lin et al., 2007). Studies of the long-term impacts of dust storms on the seas are still rare. In addition, lidar and balloon observations and model simulations were used to monitor and understand the vertical distribution and transport processes of dust storms generally. With advances in remote sensing technology, satellites will increasingly be able to monitor dust transport, including even the vertical structure of transported dust (Winker et al., 2009). In this study, we tried to clarify the influence of dust storms on the China seas during a long-term period.

We investigated the impacts of spring (March–May) dust storms on the China seas (the Bohai Sea, Yellow Sea, East China Sea, and South China Sea) through combinations of surface observations, satellite observations, trajectories, and dust model simulations during the period 2000–2007. First, the transport processes of dust storms from the source regions to the seas were analyzed using a forward trajectory model and satellite vertical observations. Second, the probability of spring dust storms affecting the China seas was examined through the forward trajectory model. Finally, satellite-derived aerosol index and dust deposition from a numerical model were used to test the influence of dust storms on the China seas derived from the forward trajectory model.

### 2. Data and methods

The daily occurrence time records of dust storms at 43 meteorological observation stations in Inner Mongolia, China during 2000–2007 were obtained from the National Meteorological Information Center of the China Meteorological Administration (NMIC/CMA). The records contained the starting and ending times of dust storms each day at each station, allowing for calculation of the occurrence frequency of dust storms (days month−1 or days year−1) at each station. At each station, dust storm weather phenomena were defined as storms with minimum visibility of ≤1 km and instantaneous maximum wind speed of ≥10 m s−1 (Qian et al., 1997).

Daily mean wind speed, pressure, temperature and relative humidity and daily rainfall (mm) datasets at the same 43 meteorological stations were used to examine the relationships of these factors to dust storm occurrence frequency. These data were also provided by the NMIC/CMA.

The aerosol index is an effective measure of the dust loading in the atmosphere (Herman et al., 1997). Many studies found that the aerosol index correlated closely with modeled dust loading (Uno et al., 2004; Zhao et al., 2006). Here, we used the aerosol index to measure the dust loading over the China seas. From 2000 to 2004, the aerosol index was retrieved from the Total Ozone Mapping Spectrometer (TOMS, resolution $1.25^\circ \times 1^\circ$), and from 2005 to 2007 it was retrieved from the Ozone Monitoring Instrument (OMI, resolution $1^\circ \times 1^\circ$). The TOMS data were interpolated into the same spatial resolution as the OMI data.

Dust deposition (including dry and wet depositions) from the Global/Regional Assimilation and Prediction System/the Chinese Unified Atmospheric Chemistry Environment for Dust Atmospheric Chemistry Module (GRAPES/CUACE-Dust) numerical model was also used to detect the impacts of spring dust storms in Inner Mongolia on the China seas. The GRAPES/CUACE-Dust model was developed by the Numerical Prediction Research Center, CMA, and Center for Atmosphere Watch and Services of the Chinese Academy of Meteorological Sciences (Wang et al., 2010). The model domain covers $70^\circ – 140^\circ$ E and $15^\circ – 60^\circ$ N, including the source regions of dust storms in East Asia. Comparisons of real-time prediction outputs with surface observations and the TOMS aerosol index have indicated that the model can predict the outbreak, development, transport and depletion processes of dust storms accurately over China and the East Asian region (Wang et al., 2010). Details of the model have been described by Wang et al. (2010). Dust deposition was used in this study at 0.5° × 0.5° spatial resolution.

The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) is a two-wavelength polarization lidar. It is the primary instrument on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite. CALIOP has provided a direct measure of the vertical structure of aerosols in the troposphere and lower stratosphere since June 2006 (Winker et al., 2009). The aerosol type data from CALIOP Level 2 products were used to detect the vertical structure of dust aerosols in this paper. Six distinct aerosol types were labeled desert dust, smoke, clean continental, polluted continental, clean marine and polluted dust (Dubovik and King, 2000; Omar et al., 2005; Winker et al., 2009). The vertical resolution was 30 m for altitudes from –0.5 to 8.2 km, 60 m for altitudes from 8.2 to 20.2 km and 180 m for altitudes from 20.2 to 30.1 km.

To understand the impacts of dust storms from different source areas on the China seas, a forward trajectory analysis was
performed using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph, 2010) with inputs from the National Centers for Environmental Prediction/the National Center for Atmospheric Research (NCEP/NCAR) global reanalysis meteorological data. The data were on a latitude-longitude grid with a spatial resolution of 2.5°. The internal scaling height of HYSPLIT was 25 km. An air parcel appearing in the middle of a dust storm event at the source stations was traced forward.

3. Results and analysis

3.1. Characteristics of the occurrence frequency of spring dust storms in Inner Mongolia during 2000–2007

Fig. 1 shows the distribution of the annual mean occurrence frequency of spring dust storm events (days year⁻¹) averaged from 2000 to 2007, as derived from the 43 meteorological observation stations. The standard deviation (SD) at the 43 stations is from 0.5 to 9.5 days year⁻¹. There were two regions with high dust storm frequency: the deserts in the west of Inner Mongolia (including the Badain Jaran Desert, Ulan Buh Desert, and Tengger Desert) and Hunshandake Desert. The two stations with the highest frequencies of dust storms were Guaiizihu (960 m above sea level) and Sunitezuoqi (1036.7 m above sea level) stations. The annual mean occurrence frequencies of spring dust storms at these two stations were 11 days year⁻¹ (SD = 3) at Guaiizihu and 14 days year⁻¹ (SD = 9.5) at Sunitezuoqi (Fig. 1). Guaiizihu and Sunitezuoqi are located in the Gobi Desert, which is bounded by the Hexi Corridor and the Tibetan Plateau to the southwest and by the North China Plain to the southeast. The simulated springtime dust emissions for 1960–2002 also indicated that deserts in western Inner Mongolia and the Hunshandake Desert were the two source areas of Asian dust. The deserts in western Inner Mongolia, in particular, have been identified as one of three major sources (the others being Mongolia and the Taklimakan Desert) (Zhang et al., 2003b).

There was apparent interannual variation in spring dust storms in Inner Mongolia during 2000–2007. The maximum occurrence
frequency (days year\(^{-1}\)) appeared in 2001, followed by 2006 with the second highest frequency (Fig. 2a). Dust storms in Inner Mongolia occurred most frequently in spring (Fig. 2b). During 2000–2007, spring dust storms accounted for 77.2% of the annual total in Inner Mongolia.

The interannual and seasonal variations in dust storms were closely related to weather conditions. Significant correlation existed between the dust storms and environmental factors, including daily mean wind speed (m s\(^{-1}\)), relative humidity (%), pressure (hPa), and rainfall (mm) (Fig. 3). Dust storms were positively correlated to wind speed and negatively correlated to rainfall, relative humidity, and pressure. However, there was no significant correlation between dust storms and temperature. The interannual variation in spring dust storms correlated to wind speed with a correlation coefficient of 0.75 (significance level = 0.05), whereas the monthly climatological variation correlated to wind speed with a correlation coefficient of 0.94 (significance level = 0.01) and to relative humidity with a correlation coefficient of −0.82 (significance level = 0.01).

3.2. Characteristics of spring dust storms during transport

Statistically, the stronger the intensity of the dust storm, the longer its duration time will be. This may induce a greater chance of long-range transport of dust particles. Therefore, dust storms with short duration time were excluded from the analysis, and dust storms with duration times over 1 h at representative stations were used for the forward trajectory analysis. Because Guaizihu and Sinitezuuqio had the highest dust storm occurrence frequencies, the storms at these two stations were used to analyze the influence of dust on the China seas. During spring 2000–2007, 77 and 79 dust storms with durations over 1 h were recorded at Guaizihu and Sinitezuuqio, respectively.

3.2.1. Trajectory analysis of transport paths from dust source regions to the seas

The transport paths of dust storms from Guaizihu station to the China seas passed by some Inner Mongolia deserts and/or the Loess Plateau and the North China Plain (sometimes over Beijing/Tianjin city) and then (1) entered the Bohai Sea from Tianjin city, Hebei, Liaoing, or Shandong Province (Fig. 4a); (2) entered the Yellow Sea through Tianjin city and Bohai Sea, Hebei, Liaoing, Shandong, or Jiangsu Province (Fig. 4b); (3) entered the East China Sea through Shandong, Jiangsu, Zhejiang, or Fujian Province, Shanghai city and/or Yellow Sea (Fig. 4c); or (4) entered the South China Sea through Shandong, Jiangsu, Zhejiang, Fujian, or Guangdong Province and/or Bohai Sea, Yellow Sea, and East China Sea (Fig. 4d). These paths were characterized by long distances and multiple sources.

Fig. 4. The transport paths of dust storms at Guaizihu station (pentacle in the figure) to the Bohai Sea (a), Yellow Sea (b), East China Sea (c) using 72-h forward trajectory analysis and South China Sea (d) using 96-h trajectory. The top and bottom panels show horizontal and vertical motion, respectively. LP: Loess Plateau area. A–G are Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian and Guangdong Province. AGL means above ground level.
The transport paths of dust storms from Sunitezuoqi station to the China seas were as follows. The dust particles were deposited into the China seas through Beijing/Tianjin city and/or Hebei, Liaoning, or Shandong Province (Fig. 5). As with the paths from Guaiizihu, sometimes the dust entered East China Sea via Bohai Sea and/or Yellow Sea and entered South China Sea via Bohai Sea, Yellow Sea and/or East China Sea. Rarely, the dust arrived over the Bohai Sea and Yellow Sea by way of the Horqin Desert (Fig. 5a and b). These paths were characterized by relatively short movement distances and a single dust source.

The movement routes to the Bohai Sea, Yellow Sea and East China Sea were similar to the routes observed by Zhang and Gao (2007) based on MICAPS meteorology data for 2000–2002. There, an Asian dust storm from Mongolia/eastern Inner Mongolia was deposited into the Bohai Sea and Yellow Sea by way of Hunsandake and Horqin deserts; Asian dust from Mongolia/western Inner Mongolia branched into three paths and then entered the Bohai Sea, Yellow Sea and East China Sea. The movement routes to the Yellow Sea, East China Sea, and South China Sea were also consistent with previous backward trajectories and model simulations. Dust in Korea in April 1998 was traced to Mongolia by way of Inner Mongolia and Yellow Sea (Chun et al., 2001). Combined simulations and backward trajectories of the Asian Pacific Regional Characterization Experiment (ACE-Asia) perfect dust storm (Julian days 94–104 in 2001) indicated that the dust layer during one of the dust storms from the Gobi region during the transport was below 2 km in height. This dust storm was split into two parts: one was transported to the north (affecting Bohai Sea and Yellow Sea), while the other was transported to lower latitudes around Taiwan (affecting East China Sea) (Uno et al., 2004). The path to South China Sea sometimes passing through East China Sea was similar to the result of Fang et al. (1999). They found that the Asian dust aerosols reached Hong Kong by way of East China Sea.

Asian dust is usually associated with frontal systems and/or cyclones (Sun et al., 2001; Uno et al., 2004; Tsai et al., 2008). Dust particles can be transported southeastward or eastward by northwesterly winds associated with frontal systems and/or cyclones and westerly winds in the free troposphere (Uematsu et al., 1983; Sun et al., 2001; Uno et al., 2004; Zhao et al., 2006; Tsai et al., 2008). The transport type of a dust event strongly depends on the source areas relative to the synoptic conditions. The dust particles from Guaiizihu usually passed deserts in the Ordos Plateau (including the Kubuqi and Maowusu deserts) and/or Loess Plateau during transport, and thus the dust could mix with local dust storms. In contrast, most dust storms at Sunitezuoqi station could be transported southeastward or southward to the China seas directly, without passing the Horqin Desert. This was why the former station observed dust from multiple sources, while the latter station observed dust from a single source.

Fig. 5. Same as Fig. 4, but for Sunitezuoqi station and all figures are 72-h forward trajectories.
3.2.2. The transport of two dust storms

The transport pathways of two dust storms observed by satellite were consistent with those derived from the forward trajectories. Figs. 6 and 7 show the vertical structures of aerosol types from CALIPSO satellite along the altitude-orbit cross-section. The bright yellow color in the figures represents dust aerosol.

The first dust storm event occurred on 30 March 2007 at Guaizihu and Sunitezuoqi. Meteorological station observations indicated that the dust storm occurred at Guaizihu at UTC 01:26–04:15 and Sunitezuoqi at UTC 07:35–12:00 on 30 March 2007. The trajectories of the dust storm (Supplementary Fig. S1) suggest that the dust storm at Guaizihu arrived over the Bohai Sea around half a day later (30 March) and Yellow Sea after about 1 day (31 March). The dust storm at Guaizihu and Sunitezuoqi arrived over the East/Japan Sea around a day and a half later (31 March) and over the northwestern Pacific after around 2 days (1 April). This result was consistent with the CALIPSO satellite observations (Fig. 6). The CALIPSO data showed that the dust from Guaizihu was transported to the east of Guaizihu after around 4 h (Fig. 6a), to the Bohai Sea around 15 h later (Fig. 6b) and to the Yellow Sea around 27 h later (Fig. 6c). The dust over the East/Japan Sea (Fig. 6d) and the Pacific (Fig. 6e) was attributed to Guaizihu and Sunitezuoqi.

Fig. 6. The altitude-orbit cross-section of CALIPSO aerosol types during transport process of dust storm at Guaizihu and Sunitezuoqi on 30 March 2007. The altitude refers to above local mean sea level. The purple line displays the local surface elevation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.3. Dust layers over dust source regions and the China seas

Figs. 6 and 7 also show vertical information on the dust layers. The results showed that dust layers over the source regions, including the west and middle of Inner Mongolia and Loess Plateau areas, were mainly located up to 4 km above ground level (Figs. 6a and 7a). The dust particles were mainly contained in the layer from the surface to 6 km above the mean sea level over Bohai Sea (Fig. 6b and c), from 0 to 4 km over Yellow Sea (Fig. 6b and c, and Fig. 7c and d), from 0 to 6 km over East China Sea (Fig. 7c and d), and from 0 to 4 km over South China Sea (Fig. 7e). Fig. 7c shows that sometimes a higher dust layer (>7 km) appeared over the Yellow Sea and East China Sea. The dust layers (<4 km) over source regions and the China seas were consistent with the trajectories shown in Figs. 4 and 5.

3.3. Probability of impact of different dust sources over the China seas

The probability of spring dust storms impacting the China seas was defined by the ratio of dust storms arriving over the seas to the total dust storms, using a trajectory analysis. Forward trajectory
analysis showed that dust storms at Guaizihu and Sunitezuoqi stations had the largest probability of affecting Yellow Sea. Next most probable was Bohai Sea, followed by East China Sea, with the smallest probability in South China Sea (Table 1). Dust storms from Guaizihu had a larger probability of affecting the seas than did those from Sunitezuoqi.

Dust particles from Guaizihu to Yellow Sea were mostly transported at altitudes below 4 km (Table 1 and Fig. 4), as with dust storms from Sunitezuoqi (Table 1 and Fig. 5). For example, for the dust storm events occurring at Guaizihu station that affected Yellow Sea, there were 39% events transported through the > 4 km layer, but 61% transported through the < 4 km layer. At Sunitezuoqi station, the percentage of dust storms transported in the < 4 km layer (90%) was nine times larger than that in the > 4 km layer (10%). This was the same for dust storms transported from these two stations to the other three seas (i.e., the Bohai Sea, East China Sea and South China Sea).

### Table 1
The percentage of spring dust storms at Guaizihu and Sunitezuoqi stations affecting the China seas during 2000–2007 through HYSPLIT model.

<table>
<thead>
<tr>
<th>Seas</th>
<th>Percentage</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Guaizihu</td>
<td>Affecting the sea</td>
<td>Affecting the sea</td>
<td>Sunitezuoqi</td>
</tr>
<tr>
<td></td>
<td></td>
<td>through &lt; 4 km layer</td>
<td>through &lt; 4 km layer</td>
<td></td>
</tr>
<tr>
<td>Bohai Sea</td>
<td>50.6</td>
<td>26</td>
<td>24.1</td>
<td>19</td>
</tr>
<tr>
<td>Yellow Sea</td>
<td>59.7</td>
<td>36.4</td>
<td>25.3</td>
<td>22.8</td>
</tr>
<tr>
<td>East China Sea</td>
<td>27.3</td>
<td>23.4</td>
<td>10.1</td>
<td>10.1</td>
</tr>
<tr>
<td>South China Sea</td>
<td>10.4</td>
<td>10.4</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

3.4. Aerosol index and dust deposition on the days of spring dust storms in Inner Mongolia affecting the seas during 2000–2007

3.4.1. Aerosol index

The satellite-retrieved aerosol index was used to further verify the influence of dust storms on the China seas derived from the forward trajectory model. According to the forward trajectories, after 1–4 days of dust storms occurring at Guaizihu and Sunitezuoqi stations, the dust arrived over the Bohai Sea, Yellow Sea, East China Sea, or northern South China Sea (north of 19°N). The average aerosol index values for the days of dust storms affecting the different seas are shown in Fig. 8a. The total numbers of dust days affecting the Bohai Sea, Yellow Sea, East China Sea and South China Sea were 54, 64, 28 and 11, respectively. The aerosol index was large when dust particles arrived over the seas, with average index values of 2.4, 1.9, 1.4, and 1.7 for the Bohai Sea, Yellow Sea, East China Sea, and northern South China Sea, respectively. Previous
research indicated that an average aerosol index of 1.5–2 may reflect dust source regions well. Large aerosol index can be used to identify the outbreaks of dust storms over source regions and downwind areas (Darmenova et al., 2005). Hence, the high aerosol index supported that the forward trajectory analysis.

The aerosol index over most areas of the southern South China Sea was <1.3 and the average value was small (0.9). This indicated that Asian dust may not affect the southern South China Sea. This is identical to the results of a previous study (Lin et al., 2007).

3.4.2. Dust deposition amount

Dust deposition in spring 2000–2007 over the China seas was estimated by the deposition in spring 2006 as simulated by the GRAPES/CUACE-Dust model. First, dust deposition over the China seas simulated from GRAPES/CUACE-Dust model was compared to OMI aerosol index (Al) in spring 2006. Results showed a close correlation between them, with a relationship of deposition (g m\(^{-2}\)) = 22.292–50.370 × AI + 28.127 × AI\(^2\) (\(R^2 = 0.55\), significance level < 0.0001). This relationship was used to estimate dust deposition for spring 2000–2007 over the China seas, according to the aerosol index shown in Fig. 8a. The spatial distribution of the estimated dust deposition is shown in Fig. 8b.

The average deposition values for the days of dust storms in Inner Mongolia affecting the different seas during spring 2000–2007 were 58, 30, 7 and 21 g m\(^{-2}\) for the Bohai Sea, Yellow Sea, East China Sea, and northern South China Sea respectively, with an average of 18.7 g m\(^{-2}\). The total deposition amount over the above four seas (total area of \(\sim 1.95 \times 10^8\) km\(^2\)) was about 36 million tons. Uematsu et al. (2003) calculated a value of 21 g m\(^{-2}\) over the coastal sea for the whole year from March 1994 to February 1995. The spring deposition should be at least 12.6 g m\(^{-2}\) because the ratio of spring dust storms to the whole year is >60%, which is comparable to our result.

The total atmospheric input of mineral dust was 225 million tons for the seven major events in April 2006, based on GRAPES/CUACE-Dust model simulation (Wang et al., 2010). The total emission of dust storms in Inner Mongolia in April 2006 was about 70 million tons on the basis of spring dust emission flux accounting for 31% of the total Asian dust (Zhang et al., 2003b). From the ratio of dust storm occurrence days in April 2006 (2.26 days) to spring 2006 (5 days, see Fig. 2a), the estimated total emission in spring 2006 was about 155 [70/(2.26/5)] million tons. The estimated total emission of spring dust storms in Inner Mongolia during 2000–2007 was about 785 million tons (the emission amount in each year was estimated from the dust occurrence days in each year shown in Fig. 2a/5 days in spring 2006 × 155 million tons). Hence the deposition amount over the China seas was about 4.6% of the total emission.

4. Conclusions

In this study, the transport of spring dust storms in Inner Mongolia during 2000–2007 and its influence to the China seas were examined based on daily observations at meteorological stations, satellite observations, forward trajectory model, and modeled dust deposition. The main conclusions were as follows:

(1) During spring 2000–2007, dust storms occurred mostly in the west of Inner Mongolia and Hunshandake Desert, and Guaizihu and Sunitzeuqi were the two stations with the highest dust storm frequencies. The interannual variation in spring dust storms correlated well with wind speed. The monthly climatological variation correlated well with wind speed and relative humidity.

(2) Forward trajectories showed that the dust from Sunitzeuqi station arrived over the China seas directly through coastal areas. The dust coming from Guaiizihu station affected the China seas through coastal areas by way of the Inner Mongolia deserts and/or the Loess Plateau. The transport paths of dust storms at Sunitzeuqi to the China seas were characterized by short distance and a single dust source, while those at Guaiizihu were characterized by relatively long distance with multiple sources. In addition, two case studies of dust storms occurring at Guaiizihu and Sunitzeuqi showed that the paths of the storms estimated from forward trajectories were consistent with CALIPSO satellite observations.

(3) Dust storms from Guaiizihu and Sunitzeuqi stations were mostly transported in a <4 km layer from source regions to the China seas. CALIPSO satellite observations indicated that dust particles were mainly contained in the 0–4 km layer over the dust source regions and the China seas, and sometimes dust at a high level (>7 km) could occur over the Yellow Sea and East China Sea. This lower dust layer (<4 km) over the source regions and the China seas was consistent with the forward trajectories.
(4) Forward trajectory analysis indicated that dust storms at Guaiuzhi and Sunitezuoqiu stations had the highest probability of affecting the Yellow Sea, followed by the Bohai Sea and the East China Sea, with the smallest probability in the South China Sea. The probability of affecting the seas was larger for dust storms from Guaiuzhi than for storms from Sunitezuoqiu.

(5) The satellite-retrieved aerosol index and modeled dust deposition also supported the influence derived from the forward trajectory model. The average index values for the days of dust storms affecting the different seas were 2.4, 1.9, 1.4, and 1.7 for the Bohai Sea, Yellow Sea, East China Sea, and northern South China Sea, respectively. The average deposition over these four seas was 18.7 g m⁻². The total deposition amount for the days of dust storms affecting the China seas was about 36 million tons, which amounts to 4.6% of the total emission of spring dust storms in Inner Mongolia during 2000–2007.

Acknowledgments

The authors would like to thank the National Natural Science Foundation of China (Grant No. 41005080), Open Research Program of Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology (Grant No. KLMED110) and the Ministry of Science and Technology of China (Grant No. 2010DF2A2770) for funding this study.

Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.atmosenv.2011.09.058

References


