Climatology of dust storms in northern China and Mongolia:

Results from MODIS observations during 2000–2010

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Abstract: The climatology of dust storms in northern China and Mongolia (33°N–54°N, 73°E–136°E) is characterized at a 1-km resolution based on Moderate Resolution Imaging Spectroradiometer (MODIS) thermal observations during 2000–2010. The dust was extracted with the dynamic reference brightness temperature differences (DRBTD) dust detection algorithm. The major dust source regions are deserts, including the Tarim Basin, Hexi Corridor, Gobi in Mongolia and northern China, Horqin Sandy Land and Qaidam Basin. Dust storms occur most frequently in the Tarim Basin, with a maximum frequency (above 10%) in the eastern narrow inlet of the Taklimakan Desert around Lop Nor. Significant annual and seasonal variations are found for dust events. More than 63.8% of dust events occur in spring from March to May, with the maximum proportion (up to 29.6%) occurring in April. Severe dust storms occur mainly in the deserts in northern and northwestern China, and the largest source region is the eastern narrow inlet and the southern margin of the Taklimakan Desert.

Keywords: dust storm; climatology; northern China and Mongolia; MODIS

1 Introduction

Dust is one of the main causes of air pollution in Asia (Lai and Cheng, 2008). Potentially, it can also affect the global climate (e.g., Yu *et al.*, 2006; Atkinson *et al.*, 2013; Yang *et al.*, 2013) and biogeochemical cycles (Jickells *et al.*, 2005). The climatology of dust events helps us to understand the detailed characteristics of the earth surface and atmosphere. Many deserts lie in northern China and Mongolia, making it a major global source region for dust storms (Prospero *et al.*, 2002). Dusts generated here are transported by strong easterly winds to neighboring countries and even travel a full circuit around the globe (Uno *et al.*, 2009). The distribution and temporal variation of dust storms in this region is a prerequisite for earth observation and understanding the roles of these storms in the earth radiative budget

Received: 2015-03-30 **Accepted:** 2015-06-12

Foundation: National Natural Science Foundation from China, No.41301354; No.41171285; Youth Science Funds of LREIS, CAS, No.08R8B6G0YA

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and global biogeochemical cycles (Nobileau and Antoine, 2005).

Satellite remote sensing is a powerful tool for monitoring dust storms, with measurements in ultraviolet, visible and thermal channels. For example, a global daily UV-absorbing aerosols index product has been generated using ultraviolet measurements from the Total Ozone Mapping Spectrometer (TOMS), with a spatial resolution of $50\text{ km} \times 50\text{ km}$ (Herman *et al.*, 1997) and the Ozone Monitoring Instrument (OMI), with a resolution of $13\text{ km} \times 24\text{ km}$ at nadir. The Moderate Resolution Imaging Spectroradiometer (MODIS) has provided global aerosol optical depth (AOD) data at a spatial resolution of 10 km (at nadir) based on observations in the visible bands since 2000. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard the CALIPSO satellite provides information about global aerosol properties with high vertical resolution during both day and night since 2006. These data have been used to analyze the climatology of aerosols (Luo *et al.*, 2014; Huang *et al.*, 2013) and identify the global distribution for sources of atmospheric soil dust (Prospero *et al.*, 2002). However, TOMS, OMI and MODIS aerosol data are coarse in spatial resolution, while CALIOP measurements are limited in spatial coverage due to its narrow track, which may not represent the detailed spatial patterns of dust events on a regional scale.

MODIS measurements in the thermal infrared channels serve as an effective data source to detect dust with daily and 1-km resolution, which can provide more details on dust patterns and identify small point dust sources (e.g., Wald *et al.*, 1998; Rivas-Perea *et al.*, 2013). A dynamic reference brightness temperature differences (DRBTD) index (D) has been developed to automatically detect airborne dust based on MODIS thermal infrared observations with a spatial resolution of 1 km (Liu *et al.*, 2013). In this article, the algorithm is applied to produce and evaluate the climatology of dust storms in northern China and Mongolia (33°N – 54°N , 73°E – 136°E) using MODIS thermal infrared observations from 2000 to 2010. The major dust source regions are identified, and the annual and seasonal distributions, as well as the intensity of dust storm events, are characterized.

2 Data and methods

2.1 Data

The MODIS, aboard the Terra and Aqua satellites, has provided the observations of the Earth's entire surface every 1 to 2 days since February 2000 and July 2002, crossing over the equator at 10:30 and 13:30 local time (LT) during the day, respectively. It provides a reliable data source for dust monitoring, with its better spectral, temporal and spatial resolutions, as well as georeferencing and calibration accuracy. The radiative measurements are acquired with a one-day repeat cycle over the study area in 16 thermal infrared channels and 20 visible and shortwave infrared spectral channels. The Terra and Aqua MODIS Level 1B Calibrated Radiances 5-Min Swath Data Set (MOD021KM and MYD021KM) contains global-calibrated and geolocated aperture radiance values for all 36 bands with a spatial resolution of $1\text{ km} \times 1\text{ km}$ at nadir. In this letter, the Terra and Aqua MODIS MOD021KM (MYD021KM) daytime radiances at wavelengths (λ) of $8.6\text{ }\mu\text{m}$ (Band 29), $11\text{ }\mu\text{m}$ (Band 31), and $12\text{ }\mu\text{m}$ (Band 32) for the period from February 2000 to December 2010 were converted to standard gridding with a spatial resolution of $1\text{ km} \times 1\text{ km}$. Then, for Terra and Aqua MODIS daytime data, the gridded images were composited separately for each day. For those pixels

with more than one Terra/Aqua observation during a day, the measurement with the minimum view zenith angle was selected to avoid manual preference of clear-sky or dusty observations. Thus, the statistic results of dust storm frequency and area are comparable for each pixel. Next, the gridded daily radiances were converted into brightness temperature to determine dust storm distributions over the desert regions in northern China and Mongolia.

The MODIS Level 2 Global Daily Aerosol Product (MOD04_L2) provide global AOD data with a spatial resolution of 10 km based on the Deep Blue algorithm (Hsu *et al.*, 2006), which could represent the dust intensity of dust events by comparison to ground measurements (Zheng *et al.*, 2014). These AOD products were compared with the DRBTD algorithm results to evaluate the relationship of our dust index with AOD.

2.2 Methods

The DRBTD dust detection algorithm uses dynamic reference brightness temperature differences (BTD) to eliminate the effect of varying surface temperatures based on the significant linear relationships among BTs at thermal infrared bands. Based on atmospheric radiative transfer simulations, a highly linear relationship was found between the brightness temperature (BT) at the 12 (BT12) and 11 μm (BT11) channels as well as between the BTs at 8.6 (BT8.6) and 11 μm (BT11) channels in the standard atmospheric profiles without clouds, aerosol or water vapor (the ideal pristine line), and this relationship is independent of temperature. When there is dust, clouds or water vapor in the atmosphere, the relationship departs from the ideal pristine line, but it is still linear under the same atmospheric conditions. Dust points are above the ideal pristine lines, and they are distant from the ideal pristine line with an increase in the optical depth of the dust layer. Here, we use the distance between the observed BT and the pristine lines to detect dust and represent the density of dust layer. The pixel by pixel most clear-sky linear relationship between the BT12 and BT11 and the relationship between the BT 8.6 and BT11 were regressed to approximate to the ideal pristine line by regressing upper envelopes for BT12/BT11 and the lower envelopes for BT8.6/B11 with the MODIS observations for the 9-year period from 2000 to 2008. Based on these relationships, the reference BTDs are calculated dynamically according to the observed brightness temperatures, which represent the BTD under clear-sky conditions. Then, the differences between the observed BTD and the reference BTD for 8.6 and 11 μm ($D_{8.6}$) and for 12 and 11 μm (D_{12}) are calculated as follows:

$$D_{8.6} = T_{8.6\text{obs}} - (a_{8.6} + b_{8.6} \times T_{11\text{obs}}) \quad (1)$$

$$D_{12} = T_{12\text{obs}} - (a_{12} + b_{12} \times T_{11\text{obs}}) \quad (2)$$

where $T_{8.6\text{obs}}$, $T_{11\text{obs}}$ and $T_{12\text{obs}}$ are the observed BT in the 8.6, 11 and 12 μm bands, respectively. The $a_{8.6}$ (a_{12}) and $b_{8.6}$ (b_{12}) variables represent the enhancements and slopes of the linear functions between the clear-sky top of atmosphere (TOA) BT at the 8.6 (12) μm channel and that in the 11 μm channel for each pixel, which are regressed from the multi-year MODIS observations.

Index D is defined as the summation of $D_{8.6}$ and D_{12} to separate the dust from clear-sky surface and clouds.

$$D = D_{8.6} + D_{12} \quad (3)$$

The brightness temperatures in the 8.6, 11 and 12 μm bands were calculated from the

gridded Terra and Aqua MODIS L1B TOA radiance product MOD021KM (MYD021KM), and D was calculated and composed for the study area (33°N–54°N, 73°E–136°E) for each day from February 2000 to December 2010 for Terra and July 2002 to December 2010 for Aqua. The pixels with D_{12} or $D_{8.6}$ values less than -0.5 were labeled as clouds (Liu *et al.*, 2013).

The DRBTD algorithm effectively discriminates mineral dust, even over bright surfaces. Index D shows a good positive correlation with OMI AI, MODIS AOD and CALIOP dust AOD for several cases of dust events during both daytime and night-time, with r values above 0.77 (Liu *et al.*, 2013). To evaluate the quantitative and representative relationship between D and dust AOD, the D maps were resampled to a 10-km resolution by averaging valid non-cloud values and comparing them with the MODIS AOD from MOD04_L2 based on the Deep Blue Aerosol algorithm from 2000 to 2008. All of the D values in the study area during this period were divided into 0.1 K intervals. For each D bin, the corresponding MODIS AOD values were found for the corresponding sites and observation times and were then used to calculate the mean MODIS AOD and standard deviation for this D bin. Figure 1 shows the mean value (black dot) and standard deviation (error bar) of MODIS AOD to D . A significant positive correlation relationship is presented between D and the MODIS AOD. The D value is approximately zero for clear-sky surface, with a mean MODIS AOD value less than 0.2, and its value increases with the increasing of dust AOD and reaches 4.5–8 K when the MODIS AOD is above 2. The D is not very sensitive to dust AOD when D value less than 1.5, and corresponding AOD value may close to zero, which may be due to low sensitivity of satellite thermal infrared observations to dust event of low intensity. When the dust index is above 2.0, a positive linear relationship is presented between the D and MODIS AOD, and this relationship is approximately linear when D is between 1.5 and 5. In addition, several dust event cases also suggest that dust could be detected by MODIS D is greater than 2 K (Liu *et al.*, 2013). Here, dust pixels are identified with a threshold of 2 K for D , with a corresponding mean MODIS AOD of 0.75. That is, a pixel with $D > 2$ is labeled as dust, and a pixel with $D \leq 2$ as non-dust. As the value of D increases, the intensity of a dust event increases. Here, the threshold of 3 K is chosen for labeling severe dust storm pixels, with a corresponding mean MODIS AOD of 1.3.

Figure 1 Relationship between D and MODIS Deep Blue AOD from 2000 to 2008 over the study area. The black dots represent the mean value of MODIS AOD to each D bin with an interval of 0.1 K, and the error bars represent corresponding standard deviation.

The spatial distribution and temporal variation of dust events over the study area were characterized using the MODIS daily TOA radiance observations (MOD021KM/MYD021KM) from February 2000 to December 2010. The dust event frequency was calculated by dividing the occurrence of dust, i.e., the number of days when a pixel is identified as dusty, by the total number of observation days from 2000 to 2010. The annual dust area was calculated by

summing the area of dust pixels for each year for all of the daily Terra MODIS *D* maps from 2001 to 2010 and Aqua MODIS *D* maps from 2003 to 2010. The monthly dust area was also calculated by averaging the accumulated area of dust pixels from the 10-year data during 2001–2010 for each month. Since both the Terra and Aqua MODIS *D* maps are used from 2003 to 2010, the dust area is summed if the pixel is labelled as dusty for either Terra or Aqua MODIS maps during the same day to calculate the monthly dust area for each month and annual dust area in those years. For those days with both Terra and Aqua MODIS *D* are identified as dusty, the area of this dust pixel is only summed once. In addition, the frequency distributions of dust events with difference intensities were also evaluated with the thresholds of 2 K and 3 K for *D* from 2000 to 2010.

3 Results

3.1 Spatial distribution

Figure 2 shows the distribution of dust event frequency during the 11-year period between February 2000 and December 2010 over the study area. Clearly, dust events affect most areas in northern China (35°N–45°N). The major dust source regions are identified on the basis of the appearance of persistent spatial-temporal patterns for remote sensing dust detection (Prospero *et al.*, 2002). According to the frequency map, the dust hotspots are the deserts regions in northern China, including the Tarim Basin, Hexi Corridor, Gobi in Mongolia and northern China and Horqin Sandy Land. The frequency distribution of dust events derived from the meteorological records of dust event categories also suggest that the Tarim Basin, Gobi Desert and Hexi Corridor are the major source regions of dust events in China (Shao and Dong, 2006; Zhao *et al.*, 2013). In addition, the Qaidam Basin was identified as an important dust source area.

Figure 2 Distribution of dust event frequency (%) over the study area during the period of 2000–2010

The dust events observed in Figure 2 occur most frequently in the Tarim Basin, which includes the Taklimakan Desert, one of the largest sandy deserts in the world (272,000 km²). These results are consistent with the findings based on the synoptic data of dust event categories (Shao and Dong, 2006) and TOMS Aerosol Index (AI) products (Prospero *et al.*, 2002). The dust event frequency is above 9% in the western part of the Tarim Basin, and the maximum frequency (above 10%) is found in the eastern narrow inlet of the Taklimakan Desert around Lop Nor. Despite the low rainfall in the Tarim Basin, there are many oases

along the edges of the basin due to the runoff of melting ice and snow from the surrounding mountains, especially on the northern side. Our results also capture less frequent dust occurrence (Figure 2) compared to the other parts of the basin, which is a benefit of the high spatial resolution of the D maps (1 km).

3.2 Temporal variation

3.2.1 Annual variation

Figure 3a presents the annual dust area time series in the study area from 2001 to 2010. The total dust area varied from 22 million to 89 million km² during the 10-year period studied. Generally, the annual dust area increased from 2001 to 2010, with a slope of 0.6817×10^7 km²/year (significant at 99% confidence level). This is consistent with the observational dust record in the meteorological network stations, which suggested that dust events in northern China shows a decreasing trend in the mid-1960s through the end of the 1990s and a slightly increasing trend from 2000 to 2007 (Mao *et al.*, 2011). The annual dust area was greater than 42 million km² in 2001. A marked decrease in dust events frequency was observed in 2002, with the annual dust area reaching approximately 22.9 million km². The annual dust area is approximately 53.0 million km² from 2003 to 2005. The dust storm frequency has increased notably since 2006 and reached the largest value of the 10-year period in 2009, with an area greater than 88.4 million km². Many factors have impacts on the occurrence of dust events, such as underlying surface, strong wind, precipitation, temperature (Xiao *et al.*, 2008), and even Arctic Oscillation (Mao *et al.*, 2011). In the studied decade (2000–2010) in this study, the annual dust area experiences remarkable inter-annual fluctuations, which may be related to the fluctuation of climate and underlying surface state.

Figure 3 Annual and seasonal variations of dust event occurrence over the study area during the period of 2001–2010

(a) Annual dust area; (b) Monthly dust area. The annual dust area was calculated by summing the area of dust pixels for all of the daily D maps for each year during the period of 2001–2010. The monthly dust area was also calculated by averaging the accumulated dust area during 2001–2010 for each month. The error bars in Figure 3b represent the standard derivation of dust area among the years for each month.

3.2.2 Seasonal variation

Figure 3b shows the monthly dust area and its standard derivation among the years. A significant seasonal variation of dust events is observed in the study area. Dust storms occur most frequently in spring, with a maximum dust area of up to 19.2 million km² occurring in

April, which is consistent with the results from synoptic records (Shao and Dong, 2006). More than 29.6% of dust events occur in April, and when March and May are included, the proportion reaches 63.8%. Dust frequency is low from July to January, with the monthly dust area ranging from 1.1 (1.7%) to 3.3 (5.2%) million km². The seasonal variation agrees with the monthly dust outbreak frequency from meteorological observations obtained from the SYNOP report in northern China, and it is consistent well with that of strong-wind frequency (Kurosaki and Mikami, 2003), which is a direct factor resulting in dust storms (Xiao *et al.*, 2008).

3.3 Distribution of dust storm intensity

Different threshold values were used to characterize the dust event distribution of various intensities. Figure 4a shows the dust event frequency with D values falling between 2 K and 3 K, and Figure 4b presents the severe dust storm frequency with D values greater than 3 K.

Severe dust storms occur mainly in the deserts of northern and northwestern China, and the highest frequency occurs in the Taklimakan Desert, which provides an abundance of dust particles. The severe dust event frequency is the highest in the eastern narrow inlet and southern margin of the Taklimakan Desert, which is located along the northern foot of the Kunlun Mountains. Shao and Dong (2006) suggested that severe dust storms occur mostly in Mongolia and Inner Mongolia using a dust event classification according to visibility from synoptic records during 1998 and 2003. This difference is probably related to the sparse distribution of weather stations in the Tarim Basin, different study periods (1998–2003 against 2000–2010) and cloud cover. Synoptic records were not affected by cloud cover, while the DRBTD approach based on satellite measurements missed dust pixels underneath cloud cover.

Figure 4 Distribution of dust events frequencies (%) from 2000 to 2010 with D threshold values of (a) 2 to 3 and (b) greater than 3

As Figure 4a shows, dust storms with low intensity have affected most regions of northern China. These dust events mostly originated from deserts in China and Mongolia by the Mongolian Cyclone, which is the prevailing synoptic system in the Gobi region in spring. The Mongolian Cyclone system often leads to strong northwesterly flow near the surface wind and generates dust storms; the system then transports dust particles to eastern China, Korea and Japan. Dust events reduce rapidly in northeastern China (125°E–136°E), which is probably due to the barrier effects of the Greater Hinggan Mountains

(121.2°E–127°E, 50.2°N–53.6°N). This observation confirms that dust events in northeastern China mainly originated from the deserts in northern China.

4 Discussion

The climatology in this letter is derived from polar-orbit satellite observations, which could only provide limited measurements per day. Thus, uncertainties may be introduced in the statistic analysis due to cloud cover, dust movements and limited observations.

Notable spatial and seasonal variations are presented for cloud cover. The cloud frequency is relative low in southwestern part of the study area, including the Tarim Basin, Qaidam Basin and the Hexi Corridor, while this percentage is high in northern and eastern parts, including the Gobi in Mongolia and northern China and Horqin Sandy Land. These observations suggest that the impacts of cloud are smaller in the southwestern part than that in eastern and northern parts of the study area. The occurrence of cloud cover is much higher in summer from June to August, while it is much lower in spring from March to May when above 63.8% dust events occur, especially in the southwestern part of the study area. These results indicate that the impacts of cloud are relative small due to low frequency if cloud cover in spring.

Although these limiting factors affect the climatology, satellite observations still provide large areal coverage and spatial continuous distribution of dust storms, which is important for remote arid areas. Besides, the spatial and temporal patterns of dust events from long-term satellite observations should prove to be similar to that from field measurements. In this letter, both the Terra and Aqua MODIS measurements are used to detect dust storms and derive dust climatology to reduce these impacts.

5 Conclusions

In this study, the climatology of dust storms in northern China and Mongolia is characterized by applying the DRBTD dust detection algorithm to MODIS satellite observations from 2000 to 2010. The detailed and spatial continuous patterns of dust storms in northern China and Mongolia were characterized at a spatial resolution of 1 km using satellite thermal infrared measurements. The main conclusions are as follows:

(1) The major source regions of dust are the deserts in northern and northwestern China. Dust events are observed to occur most frequently in the Tarim Basin, and the maximum dust frequency is found in the eastern narrow inlet of the Taklimakan Desert around Lop Nor (above 10% from February 2000 to December 2010). The high spatial resolution *D* maps show less frequent dust occurrence along the edges of the basin, especially on the northern side.

(2) Notable annual and seasonal variations of dust events are presented in the study area. The annual total dust area varies from 22 million to 89 million km² during the 10-year period from 2001 to 2010; the low dust frequency years from 2001 to 2005 have an area of approximately 50 million km², and the high dust frequency years during 2006–2010 have an area ranging from 80 to 89 million km². More than 63.8% of dust events occur in spring from March to May, with the maximum proportion occurring in April (up to 29.6%); while, the monthly dust area ranges from 1.1 (1.7%) to 3.3 (5.2%) million km².

(3) Severe dust storms occur mainly in the deserts in northern China, and the largest frequency occurs in the eastern narrow inlet and the southern margin of the Taklimakan Desert.

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