Dynamic Monitoring of the Strong Sandstorm Migration in Northern and Northwestern China via Satellite Data

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ABSTRACT

Sand and dust storms (hereafter, "sandstorms") not only damage the ecological environment in northern and northwestern China but also influence the economic and social development of the affected regions and constitute a threat to human health. This study focuses on monitoring sandstorms and analyzing the sandstorm migration process in northern and northwestern China. These sandstorms are characterized by their high frequency occurrences, strong dust intensity, long durations and highly destructive effects. The dry climate conditions and low degree of vegetation coverage in this region increase the difficulty of sandstorm monitoring. This paper proposes a remote sensing monitoring method for sandstorms in northern and northwestern China based on Moderate Resolution Imaging Spectroradiometer (MODIS) data and the radiation characteristics of the research region and of the sandstorms. A strong sandstorm that occurred on April 23–25, 2014, is analyzed to illustrate the proposed monitoring method. Information on the sandstorm is validated and analyzed through visual interpretation and comparison with Meteorological Information Comprehensive Analysis and Process System (MICAPS) ground measurements. The spatial distribution of the sandstorm is highly consistent with the true-color MODIS data. The comparison of the results of the remote sensing monitoring of the sandstorm with the MICAPS measurements yields a high coincidence rate of 96.3%. Additionally, the migration process of the sandstorm can be clearly recognized in 6 MODIS images captured during the 3-day sandstorm. Based on the above results, we conclude that the proposed method can be used for dynamic remote sensing monitoring of sandstorms in northern and northwestern China.

Keywords: Sandstorm; Migration process; Monitoring; Northern and northwestern China; Satellite data.

INTRODUCTION

Sandstorms are serious natural disasters that damage global and regional ecological systems, resulting in industrial and agricultural losses and affecting transportation (IPCC, 2007; Zhao et al., 2010). They seriously pollute atmospheric environments and lower urban air quality, which has a negative impact on human health (Claquin et al., 1998; Stone et al., 2011). Rapid high-accuracy monitoring of sandstorms is necessary to reduce industrial and agricultural losses and to improve air quality. Conventional sandstorm monitoring relies on ground monitoring stations. However, due to the limited number of these stations, sandstorm activity is difficult to describe comprehensively. Fortunately, remote sensing techniques can help remedy the shortcomings of conventional monitoring methods via high-frequency measurements and wide spatial coverage (Griggs, 1975; Stowe et al., 1997; Amato et al., 2006). Thus, remote sensing techniques can obtain high temporal resolution information about sandstorm distributions and can be used to analyze the process of sandstorm development.

The northern and northwestern regions of China are among the most sandstorm-prone areas in the world (Sun et al., 2001; Qian et al., 2004; Huang et al., 2007; Fu et al., 2012). Sandstorms in this region have the following four characteristics. 1) The sandstorms are frequent. Due to the arid nature of northern and northwestern China and the limited water content in the soil, bare soil is easily blown away by strong winds. This process allows large sandstorms to form in the winter and spring seasons, when 82.5% of the strong sandstorms occur (Zhou and Zhang, 2003; Zhang and Gao, 2007). 2) The sandstorms in this area are intense. Northern and northwestern China are among the most sandstorm-impacted areas in the world. The limited water content in the soil, bare soil is easily blown away by strong winds. This process allows large sandstorms to form in the winter and spring seasons, when 82.5% of the strong sandstorms occur (Zhou and Zhang, 2003; Zhang and Gao, 2007). 2) The sandstorms in this area are intense. Northern and northwestern China are among the most sandstorm-impacted areas in the world. Due to the distribution of large desert areas, severe sandstorms are very common in this region (Wang et al., 2004; Creamean et al., 2014). Additionally, due to the influence of the continental climate and the East Asian monsoon, windy weather is...
common in northern and northwestern China in the winter and spring (Sun et al., 2001; Tsolmon et al., 2008; Gao et al., 2010; Fang et al., 2016). 3) These conditions lead to sandstorms with long durations (Zhao et al., 2010; Fan et al., 2013). 4) Sandstorms in northern and northwestern China are highly destructive. The relatively flat topography of the area leads to sand and dust being transported over long distances, causing huge economic losses and casualties in the eastern and coastal areas (Cottle et al., 2012; Li et al., 2015; Tan et al., 2016).

Numerous dust storm monitoring studies have been conducted in the northern and northwestern regions of China. Using data from three aerosol property detection sites and meteorological measurements in northwestern China as part of the observational program for Asian Dust Storms (ADS), Fu et al. (2012) analyzed the turbulence properties during dust storms in northwestern China over a three-year period (2004–2007). Based on the analysis of data from 174 meteorological stations collected over the last 40 years, Sun et al. (2001) estimated the dust transport routes andolian source regions in China. Furthermore, based on station observations of dust storms and the NCEP/NCAR reanalysis data, Ding et al. (2005) analyzed the variations in spring dust storms in northwestern China for the period from 1960 to 2003. Ground measurements play an important role in detecting the properties of dust storms, but the limited number of stations means that this method cannot be used to effectively describe the distribution characteristics and environmental effects of dust at the large scale.

Satellite remote sensing can play an important role in the dynamic monitoring of the strong, high-frequency sandstorms in this region, leading to a better understanding of the sandstorm distributions, their development process, and the best means to eventually reduce sandstorm-related damage. However, due to the arid and semi-arid climate conditions and the sparse vegetation coverage, the underlying surface reflectance in this area is very high, especially in the area covered with desert and Gobi. Thus, the surface reflectance in this area is very high, especially in conditions and the sparse vegetation coverage, the underlying and the best means to eventually reduce sandstorm-related sandstorms in this region, leading to a better understanding of the sandstorm distributions, their development process, and the environmental effects of dust at the large scale.

The Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument aboard both the Terra (EOS AM) and Aqua (EOS PM) satellites. Terra/MODIS and Aqua/MODIS capture images of the full surface of the Earth every 1 to 2 days, acquiring data in 36 spectral bands ranging from 0.4 µm to 14.4 µm at varying spatial resolutions of 250 m, 500 m and 1 km. Table 1 shows some of the channel parameters of MODIS. The moderate spatial resolution, high temporal resolution, and broad wavelength coverage make MODIS a rich source of information for sandstorm monitoring.

Reflected radiation in the visible to near-infrared wavelengths, i.e., the reflectance, and the brightness temperatures are used to identify sandstorms using MODIS data. Both parameters can be calculated from the radiance value via Eq. (1):

\[ L = \text{radiance\_scales} \times (\text{DN} - \text{radiance\_offsets}) \]  

(1)

where \( L \) is the radiance, \( \text{DN} \) is gray value of a certain band, and \( \text{radiance\_scales} \) and \( \text{radiance\_offsets} \) are the coefficients provided by the MODIS data.

The reflectance can be calculated by the following equation (Eq. (2)):

\[ R = \frac{\pi \times L \times d^2}{\text{ESUN} \times \cos \theta} \]  

(2)

where \( d \) is the Earth-sun distance in astronomical units, \( \text{ESUN} \) is the mean of the solar exoatmospheric spectral irradiances, and \( \theta \) is the solar zenith angle.

The brightness temperature can be converted from Eq. (3):

Table 1. Some of the channel parameters of MODIS.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Wavelength (µm)</th>
<th>Central wavelength (µm)</th>
<th>Spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.620–0.670</td>
<td>0.645</td>
<td>250 m</td>
</tr>
<tr>
<td>3</td>
<td>0.459–0.479</td>
<td>0.469</td>
<td>500 m</td>
</tr>
<tr>
<td>4</td>
<td>0.545–0.565</td>
<td>0.555</td>
<td>500 m</td>
</tr>
<tr>
<td>6</td>
<td>1.628–1.652</td>
<td>1.64</td>
<td>500 m</td>
</tr>
<tr>
<td>20</td>
<td>3.600–3.840</td>
<td>3.75</td>
<td>1 km</td>
</tr>
<tr>
<td>24</td>
<td>4.433–4.498</td>
<td>4.465</td>
<td>1 km</td>
</tr>
<tr>
<td>31</td>
<td>10.780–11.280</td>
<td>11.03</td>
<td>1 km</td>
</tr>
<tr>
<td>32</td>
<td>11.770–12.270</td>
<td>12.02</td>
<td>1 km</td>
</tr>
</tbody>
</table>
\[
T_i = \frac{C_2}{\lambda_i (1 + \frac{C_1}{\lambda_i L_i})}
\]

where \(T_i\) and \(L_i\) are the brightness temperature and radiance, respectively; \(\lambda_i\) is the wavelength; and \(C_1\) and \(C_2\) are constants \((C_1 = 1.191 \times 10^8 \text{ W} \mu\text{m}^4 \text{ sr}^{-1} \text{ m}^{-2}, C_2 = 1.439 \times 10^4 \text{ W} \mu\text{m}^4 \text{ sr}^{-1} \text{ m}^{-2})\).

**Study Areas**

Located in the hinterland of Eurasia, most of the areas of northern and northwestern China are arid to semi-arid regions, including an area of approximately 1,300,000 km² covered by desert and Gobi (Liu et al., 2003; Shao and Dong, 2006; El-Askary et al., 2015). Precipitation is scarce throughout most of this region, with an annual precipitation of less than 500 mm (Xu et al., 2012). Due to the arid continental climate conditions, this area is dry and experiences severely windy weather during most of the year (Liu et al., 2004; Gao et al., 2010). Under the influence of global warming, evaporation in this area is increasing and the availability of water resources is decreasing, thereby degrading the already fragile ecological environment (Wang and Cheng, 2000). In addition, industrial development and mining have continued to expand and have led to population increases in recent years, which in turn have caused significant damage to the ecological environment and further reductions in the vegetation coverage. Natural factors and anthropogenic influences have exacerbated the desertification process in northern and northwestern China, contributing to the expansion of areas characterized as desert, Gobi and sparsely vegetated (Fig. 1) (Di et al., 2016; Sun et al., 2016). This area contributes to approximately 60% of the Asian sandstorms (Zhang et al., 2003, Wang et al., 2008; Xu et al., 2011).

**REMOTE SENSING SANDSTORM MONITORING METHOD**

Normally, true-color images or aerosol optical thickness (AOT) data can be used to identify dust storms with high precision because of the significant spectral differences between dust storms and typical land surfaces. However, in most areas in northern and northwestern China, the current existing approaches have difficulty distinguishing dust storms from the land because the sandstorms have similar radiation characteristics as the high-brightness land surfaces, especially desert and Gobi areas. Additionally, AOT is not easy to retrieve with high precision in such bright areas and consequently cannot be used to effectively detect sandstorms. Based on the spectral characteristics of sandstorms, clouds and typical land types in northern and northwestern China, a multichannel sandstorm monitoring method was developed to detect sandstorms in these areas. The MODIS reflection bands 1, 3, and 6 and the brightness temperature bands 20, 24, 31, and 32 are used in combination in this sandstorm monitoring method.

**Sandstorm Identification Using Reflection Bands**

The central wavelengths of MODIS bands 3 and 6 are 0.469 µm (blue band) and 1.64 µm (shortwave infrared band), respectively. The signal from cloud reflectance is high in band 3 but low in the band 6. The cloud reflectance difference between band 6 and band 3 is therefore negative. The reflectance values of snow and ice are similar to those of clouds; thus, higher thresholds are needed to distinguish between clouds and snow (Di et al., 2016). The maximum reflectance value of sand appears in band 6 and is much higher than that in band 3. This reflectance value exhibits similar radiation characteristics in both desert and Gobi areas. Thus, the sand reflectance difference between band 6 and band 3 is positive. With normalization, the discrimination function for band 6 and band 3 is \((B6 - B3)/(B6 + B3) > 0\), which is used to distinguish sand from clouds and snow.

The central wavelength of the first band of MODIS is 0.645 µm (red band). Compared with other reflection bands, the reflectance values of dust are much different from those of clouds, snow and land surfaces, and these differences can be used to define another identification index. The useful range

![Fig. 1. Surface types of northern and northwestern China.](image-url)
is 0.16–0.46, which distinguishes dust from high-reflectance clouds and snow and from low-reflectance land surfaces.

The above methods are effective for separating thick dust from clouds, snow and land surfaces, but blowing sand and floating dust particles are easily confused with desert and Gobi signals. Additionally, false negatives and false positives remain when applying the method to thin and broken clouds.

**Sandstorm Identification Using Brightness Temperature Bands**

The analysis of the radiation characteristics of the MODIS thermal infrared bands demonstrates that the brightness temperatures of desert and Gobi areas are similar and that they have the highest brightness temperatures, followed by ice and snow, then clouds. The brightness temperature of sandy dust is between that of clouds and the underlying surface. Therefore, the brightness temperature can be used to detect sandstorms and to make up for the limited ability to extract sandy dust data from the reflection bands.

The central wavelengths of MODIS band 31 and band 32 are 11.03 µm and 12.02 µm, respectively. As these bands are located in the thermal infrared range, the atmospheric absorption of this radiation is relatively small, and the atmospheric transmittance is high. The brightness temperatures of clouds and the underlying land surface at 11.03 µm are higher than those at 12.02 µm, whereas the emissivity of the dust particles is lower at 11.03 µm than at 12.02 µm (Ackerman, 1997; Tu et al., 2015). As a result, the brightness temperature of sand particles at 11.03 µm is lower than that at 12.02 µm. The sandy dust discrimination function for band 31 and band 32 is (BT31−BT32) < −1 K. Generally, the split-window brightness temperature of clouds is slightly positive and can be used to effectively detect thin and broken clouds (Hu et al., 2008). However, challenges remain in distinguishing the desired information from the high-reflectance, underlying surfaces.

The radiation at the wavelength of 3.75 µm comes from two components: one is the radiation emitted from the dust particle itself, and the other is back-scattered solar radiation. However, radiation at 11.03 µm is only emitted by the dust particle. Therefore, the brightness temperature of sandy dust is relatively high at 3.75 µm and relatively low at 11.03 µm. Due to the large brightness temperature difference between the two bands, sandy dust can be identified from clouds and underlying surfaces (Ackerman, 1989; Zheng et al., 2001; Hao and Qu, 2007). Consequently, the threshold of (BT20−BT31) > 20 K can be applied to extract sandy dust information and to differentiate it from underlying surfaces when the thresholds meet the following conditions: BT31 < 290 K and BT20 > 300 K.

In some areas with strong sandstorms, visibility can be so low and the air so stagnant that the channel difference meets (BT31−BT32) > −1 K but is larger than the given threshold. In this case, sandy dust information cannot be extracted (Luo et al., 2003; Hu et al., 2008). Based on the analysis of the brightness temperature distributions, sandy dust information can be extracted when (BT20−BT24) > 80 K and (BT20−BT31) > 30 K and when BT31 < 290 K and BT20 > 300 K. These conditions reduce the likelihood of false negatives of sandstorms.

The above analysis indicates that the MODIS-derived reflectance values and brightness temperatures of pixels in sandstorm monitoring should meet all the conditions in the following chart (Fig. 2).

**MONITORING THE MIGRATION PROCESS OF A STRONG SANDSTORM**

A sandstorm occurred in northern and northwestern China on April 23–25, 2014 was the strongest sandstorm with the widest area of influence in that year (Di et al., 2016; Fang et al., 2016). Here, the proposed sandstorm monitoring method is used to monitor and analyze the distribution and migration process of this sandstorm.

**Monitoring Results and Validation**

Using the proposed method, we identified sandy dust in the twice-daily remote sensing images and overlapped true-color composite images. The monitoring results are shown in Fig. 3. Through visual interpretation, the sandy dust regions

![Fig. 2. Flow chart of the discrimination method for sandstorm remote sensing monitoring.](image-url)
identified in the extraction results and the true-color images are consistent.

The validation data in this study are the ground observation data from the Meteorological Information Comprehensive Analysis and Process System (MICAPS), a satellite communication and database-supported human-computer interaction system used to produce weather forecasts. The main function of this system is to display graphs and images of meteorological data, to edit and process meteorological graphs and to provide a working platform.

Fig. 3. MODIS true-color images of RGB bands 1, 4, and 3 and sandy dust monitoring results.
for weather forecasting at medium and short time scales. MICAPS records information including weather conditions, visibility, wind speed, pressure, and precipitation, etc. (Luo et al., 2006).

To validate the results of the remote sensing monitoring of sandstorms, the weather conditions of the MICAPS ground observation data are acquired at 11:00 and 14:00 during the period of interest and are then processed (Table 2). Fig. 3 shows the MODIS true-color composite images for April 23–25, 2014, and the corresponding images for the sandy dust monitoring results. The dots represent the ground observation sites, with red points indicating dust weather records and blue sites indicating non-dust weather records. The monitoring validation results in Table 3 show that 382 stations have sandy dust identification records, of which 232 are correct and 150 are invalid. Of the 150 stations, 141 were covered by clouds and 9 were unidentified. Eliminating those stations covered by clouds, the data from 96.3% of the stations are consistent with the results of the remote sensing monitoring. Compared with the MICAPS data, the monitoring results are largely consistent with the ground observations. Checking the nine sites that were unidentified, we find that at the edges of the sandstorm, where it is too thin to identify, some of the thin sand areas are missing, and most of them are distributed in the desert and Gobi areas.

Thus, the proposed method has a high precision and can be applied in the dynamic monitoring of sandstorms in northern and northwestern China. However, the method is limited by the cloud distribution, and the precision is poor in the areas of thin sand distribution, especially in desert and Gobi areas, which have high reflectance values.

**Sandstorm Migration Process**

The images of the dust monitoring results in Fig. 3 reflect the whole process of the occurrence, development and dissipation of the sandstorm, allowing for continuous, large-scale, dynamic monitoring of the sandstorm. On the morning of April 23, 2014, the sandstorm originated in the Taklimakan Desert in southern Xinjiang and in the Gurbantunggut Desert in northern Xinjiang. Floating dust or the start of the sandstorm appeared over most of Xinjiang, western Gansu, western Inner Mongolia, and southwestern Mongolia. Approximately three hours later, the sandstorm moved eastward along the Hexi Corridor and the area of its influence expanded to the east. On the morning of April 24, Xinjiang, northern Qinghai, Gansu, Ningxia, Shaanxi, Shanxi, Inner Mongolia, the southern part of Mongolia and other regions were affected by some degree of sand and dust weather. That afternoon, the dust storm continued to move to the northeast and expanded over parts of Russia and was then transported to Northeast Asia. On the morning of April 25, the sandstorm continued to move to the northeast. The region of influence was significantly reduced compared with that of April 24, and the dust weather in most areas of northern and northwestern China gradually subsided. In the afternoon, the region of influence continued to decrease, eventually only covering Inner Mongolia, Gansu and a small area of Mongolia, before gradually dissipating.

The route and area of influence of the sandstorm are

<table>
<thead>
<tr>
<th>Code</th>
<th>Meaning</th>
<th>Code</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Floating dust</td>
<td>7</td>
<td>Floating dust</td>
</tr>
<tr>
<td>8</td>
<td>Dust devil</td>
<td>9</td>
<td>Sandstorm</td>
</tr>
<tr>
<td>30</td>
<td>Mild sandstorm weakened in the past hour</td>
<td>31</td>
<td>Mild sandstorm</td>
</tr>
<tr>
<td>32</td>
<td>Mild sandstorm enhanced in the past hour</td>
<td>33</td>
<td>Strong sandstorm weakened in the past hour</td>
</tr>
<tr>
<td>34</td>
<td>Strong sandstorm</td>
<td>35</td>
<td>Strong sandstorm enhanced in the past hour</td>
</tr>
</tbody>
</table>

**Table 3. Validation results of the new sandstorm monitoring method.**

<table>
<thead>
<tr>
<th>Imaging time</th>
<th>Observation time</th>
<th>Ground station number</th>
<th>Identified station number</th>
<th>Station covered with clouds</th>
<th>Unidentified station number</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014.04.23 AM</td>
<td>2014.04.23</td>
<td>21</td>
<td>9</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>2014.04.23 PM</td>
<td>2014.04.23</td>
<td>29</td>
<td>17</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>2014.04.24 AM</td>
<td>2014.04.24</td>
<td>92</td>
<td>39</td>
<td>50</td>
<td>3</td>
</tr>
<tr>
<td>2014.04.24 PM</td>
<td>2014.04.24</td>
<td>122</td>
<td>63</td>
<td>59</td>
<td>0</td>
</tr>
<tr>
<td>2014.04.25 AM</td>
<td>2014.04.25</td>
<td>59</td>
<td>55</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>2014.04.25 PM</td>
<td>2014.04.25</td>
<td>59</td>
<td>49</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>Ground station number</td>
<td>382</td>
<td>232</td>
<td>141</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Percentage</td>
<td>60.7%</td>
<td>36.9%</td>
<td>2.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy rate (eliminating cloud influence)</td>
<td>96.3%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
indicated by the monitoring results. In terms of its route, the sandstorm originated in the desert and Gobi areas of northern and southern Xinjiang, western Inner Mongolia and southern Mongolia, under the strong wind associated with cold front or cold air outbreak, moved eastward and arrived at the Hexi Corridor, resulting in a strong sandstorm. After moving through the Badain Jaran and Tengger Deserts, the sandstorm moved eastward to the Ordos Plateau and then to the northeast. In conclusion, sandstorms can be transported via long-range transport to downstream regions, including northern and northwestern China, northeastern Asia, and even portions of the North Pacific and the western coast of North America.

CONCLUSIONS

Combining reflectance characteristics in the visible and near-infrared bands with brightness temperature characteristics in the thermal infrared band, a multichannel, combined, sandstorm monitoring method was proposed for northern and northwestern China using data from MODIS.

The proposed method was applied to a strong sandstorm that occurred in northern and northwestern China. The information obtained using this method was then validated and analyzed via visual interpretation and MICAPS ground observation data. The results showed that the proposed method can be used for dynamic remote sensing monitoring of sandstorms in northern and northwestern China. The migration process of the sandstorm in this region was analyzed via the MODIS-based monitoring results. This analysis showed that the migration process can be well described using multiple satellite datasets. The area influenced by the sandstorm is clearly recognized, and the duration of the sandstorm, as well as its strength, can be estimated before the arrival of the sandstorm.

The dynamic remote sensing monitoring method in this study can achieve accurate sandstorm monitoring and can be used to extract a wide range of sandy dust information in northern and northwestern China. However, sandy dust information was unable to be fully extracted due to cloud coverage. In future studies, the use of multiple satellites should be considered to reduce the impact of cloud coverage on sandstorm monitoring.

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REFERENCES


Hsu, N.C., Tsay, S.C., King, M.D. and Herman, J.R. (2004). Aerosol properties over bright-reflecting source...


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