Asian Dust Storm Monitoring Combining Terra and Aqua MODIS SRB Measurements

John J. Qu, *Member, IEEE*, Xianjun Hao, *Member, IEEE*, Menas Kafatos, *Member, IEEE*, and Lingli Wang

***Abstract*—Sand and dust storms (SDSs), which present environmental risks and affect the regional climate, have been worsened in the East Asian regions over the last decade. Monitoring SDS from space using satellite remote sensing (RS) has become one of the most important issues in this field. At present, satellite RS of SDS is limited to using true-color images or aerosol optical thickness (AOT), or a new algorithm called "Deep Blue." Using current existing approaches makes it difficult to identify SDS from clouds. The authors have detected SDS by combining Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) solar reflectance band (SRB) measurements. Based on the dust spectral characteristic, this letter proposes a normalized difference dust index (NDDI) using MODIS reflectance measurements and applies it to the Asian SDS cases. The simple NDDI index is found to be able to identify SDS and clouds easily. The results suggest that NDDI could be used to detect SDS over bright surfaces where the MODIS AOT product is not available.**

***Index Terms*—Aerosol, Asian, Moderate Resolution Imaging Spectroradiometer (MODIS), normalized difference dust index (NDDI), sand and dust storm (SDS), satellite remote sensing (RS), Terra and Aqua.**

I. INTRODUCTION

ASIAN sand and dust storms (SDSs) are a very important environmental issue, and one of the major natural hazards in the Mongolian regions and northern China [1], [2]. Major dust storms, usually from the Mongolian desert, occur over these regions nearly every spring. Due to the limited ground environmental and climatic observations in the relevant regions, satellite remote sensing (RS) has become an important approach to detect dust storms in Asia. As we know, RS can not only provide initial parameters for model simulations but also be used for verification and validation of model simulations [3], [4]. Multisatellite observations such as TOMS, SeaWiFS, AVHRR, and the Chinese FY-1C/D series have been used in Asian dust storm monitoring. But at the present time, RS of dust storms can only provide near global horizontal coverage with limited vertical resolutions [5].

Early research has shown that Asian dust could transport across the Pacific Ocean and reach as far as the western U.S. [6]. Several international collaborative programs, such as the Aerosol Characterization Experiment (ACE)-Asia and Asian Dust Network (AD-Net), have been established [1]. The aerosol properties over the ocean are also evaluated by Moderate Resolution Imaging Spectroradiometer (MODIS) during ACE-Asia [7]. The dust storm formation mechanisms are very complex; they are related to the local weather system, short-term precipitation, soil moisture, and extent of deforestation, long-term increased drought, land use/land coverage changes, as well as other human activities.

As a key research instrument of the NASA Earth Observing System (EOS) missions, MODIS was successfully launched onboard the Terra and Aqua satellites. MODIS senses the Earth's entire surface in 36 spectral bands, spanning from the visible (0.415 μm) to the infrared (14.235 μm) regions of the spectrum with spatial resolutions of 1 km, 500 m, and 250 m at nadir, respectively; therefore, MODIS products could be very useful to determine dust storm properties and monitor dust transport. However, the current MODIS aerosol optical depth algorithm is limited to dark surfaces [8]. There have been limited works attempting integrated approaches to study dust and pollution haze. Earlier works have produced results based on true-color images or aerosol optical thickness (AOT), but there are no MODIS AOT measurements over bright surface regions, such as desert regions. Miller demonstrated a new satellite-based multispectral radiometer technique for daytime enhancement of airborne dust over water and land using MODIS measurements [9]. The Deep Blue (minimum of 412-nm reflectance as a gridded background) approach has also been used to physically retrieve aerosol optical properties, even over bright surfaces, such as bright desert, semiarid, and urban background [10].

In this letter, we describe a new index using MODIS channels centered near 0.469 and 2.13 μm for Asian dust detection, and apply the index to a pair of Terra and Aqua MODIS data sets. We also discuss the index threshold to distinguish the thick airborne dust storm from the surface features.

II. METHOD AND ANALYSIS

A. Dust Spectrum Characterization Analysis

MODIS has three different spatial resolutions including 250 m (bands 1–2), 500 m (bands 3–7), and the 1-km (bands 8–36). There are a total of 20 solar reflectance bands (SRBs) (1–19 and 26) from 0.41–2.13 μm [11].

There are spectral signatures for hundreds of materials in the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) spectrum library, which is used as a reference for material identification [12]. We analyzed the spectral signatures of sand, grass, soil, urban residential,

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J. J. Qu is with George Mason University, Fairfax, VA 22030 USA and also with the Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, MD 20771 USA (e-mail: jqu@scs.gmu.edu).

X. Hao, M. Kafatos, and L. Wang are with George Mason University, Fairfax, VA 22030 USA.

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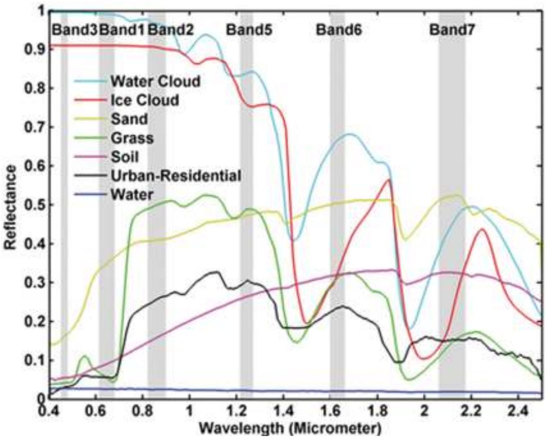


Fig. 1. Reflectance of water and ice cloud, sand, grass, soil, urban residential, and water in the 0.4–2.5-μm spectrum.

and water in the ASTER spectrum library and cloud signatures from J. Dozier (http://www.brenucsb.edu/fac_staff/fac/dozier/Talks/RSS.mht!RSS_files/frame.htm). The reflectance of water and ice cloud, sand, grass, soil, urban residential, and water, and the locations of MODIS SRB bands (0.4–2.5 μm), are shown in Fig. 1. It is clear that the reflectance of dust (sand and soil) generally increases with wavelength between 0.4 and 2.5 μm with a minimum value in MODIS band 3 (0.469 μm) and a maximum value in MODIS band 7 (2.13 μm). This spectrum characteristic of sand and soil makes it easy to distinguish SDS from cloud, which has the highest reflectance in MODIS band 3. Therefore, SDS features can be discerned using the dust spectrum characteristics as described here.

B. Normalized Difference Dust Index (NDDI)

Several indices have been proposed based on the spectrum characteristics, e.g., Gao proposed the normalized difference water index (NDWI) for monitoring vegetation water content with the 0.86-μm band and either the 1.64-μm band or the 2.13-μm band [13].

The spectral characteristic of sand suggests that strong SDS signals can be obtained using the difference between the 2.13-μm band signal, which is high, and the 0.469-μm band, where the signal is relatively much lower. This difference distinguishes rather well between SDS and water or ice clouds. Because of this strong discrimination possibility, we propose an NDDI to detect SDS. The NDDI can be written as

$$\mathrm{NDDI} = (\rho_{2.13\,\mu\mathrm{m}} - \rho_{0.469\,\mu\mathrm{m}})/(\rho_{2.13\,\mu\mathrm{m}} + \rho_{0.469\,\mu\mathrm{m}}) \quad (1)$$

where $\rho_{2.13\,\mu\mathrm{m}}$ and $\rho_{0.469\,\mu\mathrm{m}}$ are reflectances at the top of atmosphere (TOA) in the 2.13- and 0.469-μm bands, respectively.

To investigate the feasibility of NDDI for detecting SDS, we studied nine cases of SDS over the Gobi region and analyzed the NDDI ranges of dust, cloud, and surface features. For clouds, the NDDI value is negative (NDDI < 0.0) because of the higher reflectance at the 0.469-μm band and lower reflectance at the 2.13-μm band. We found that the NDDI values of surface features are less than 0.28, while the NDDI values of dust pixels are higher than 0.28, over the Gobi desert areas. It suggests that NDDI can effectively separate SDS from water or ice clouds and ground features (except ground sand and dust) in Gobi regions with a threshold of 0.28. To identify airborne and ground sand and dust, we analyzed the brightness temperature (BT) of MODIS band 31 (10.78–11.28 μm) (Fig. 2). Airborne sand and dust pixels are cooler compared with ground sand and dust. By checking the BT of band 31, SDS can be separated from ground sand and dust. In the study area, the BT threshold of 275 K is used to determine the airborne or ground sand and dust. The thermal method has greatly reduced errors of commission.

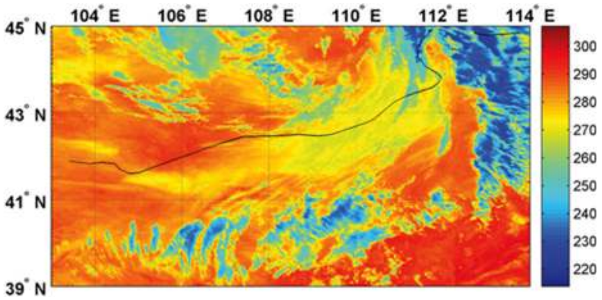
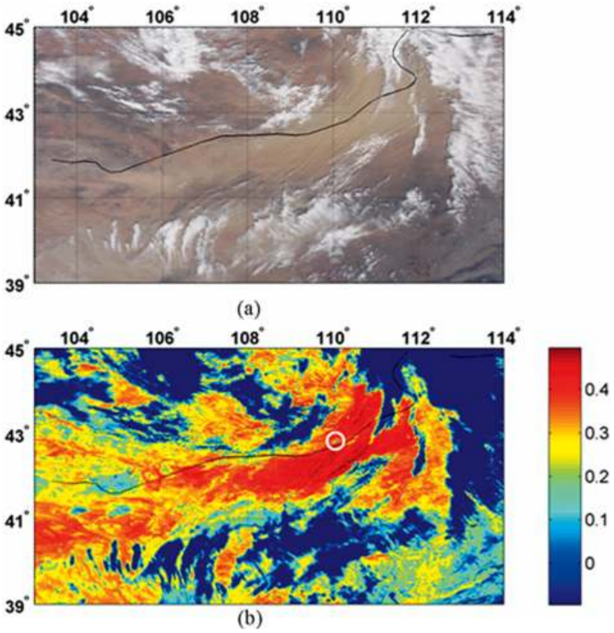


Fig. 2. BT image of Terra MODIS band 31 (10.78–11.28 μm) (3:40 UTC, March 27, 2004).



(a)

(b)

Fig. 3. (a) Terra MODIS true-color image (3:40 UTC, March 27, 2004) shows Asian dust storm over Northern China and Southern Mongolian regions. (b) Terra MODIS NDDI image shows the clouds and dust storms. The cloud and dust storm can be easily identified (for cloud NDDI < 0.0 and for dust storm NDDI > 0.28).

C. Results for Asian SDS Detection Using NDDI

We apply NDDI to monitor SDS by using both Terra and Aqua MODIS data over the East Asian region. Fig. 3(a) shows a subsetted true-color image of SDS across the Gobi desert in Northern China and Southern Mongolia from the Terra/MODIS at 3:40 UTC, March 27, 2004. About

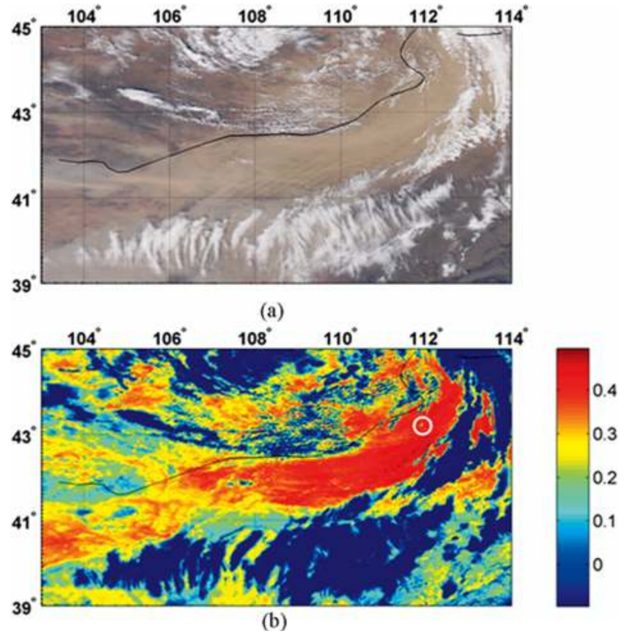


Fig. 4. (a) Aqua MODIS true-color image (05:15 UTC, March 27, 2004) shows major dust storm moved into the Inner Mongolian regions. (b) Aqua MODIS NDDI image shows the clouds and dust storms after Terra MODIS passed over this region (around 1 h and 35 min later).

70 million people in 11 provinces were affected by this SDS on March 27 and 28 according to the Chinese news agency. This SDS was the worst of recent SDSs in Inner Mongolia (http://visibleearth.nasa.gov/). The solid line in Fig. 3(a) is the country boundary between China and Mongolia. Fig. 4(a) shows the subsetted and mosaicked true-color image for the same region from Aqua/MODIS at 05:15 UTC, March 27, 2004. From these two true-color images, it is difficult to detect SDS from other phenomena such as clouds, haze, and surface features. It is also difficult to clearly identify SDS boundaries.

NDDI is computed with the SRB reflectance measurements at TOA from both Terra and Aqua MODIS. Figs. 3(b) and 4(b) show the NDDI images corresponding to Figs. 3(a) and 4(a). The SDS horizontal transport with the weather system can be detected clearly, and the clouds and SDS can be separated easily from NDDI images. The deep blue regions (NDDI < 0.0) show the clouds, while the red regions (NDDI > 0.28) show the SDS. Therefore, clouds and SDS can be separated easily using the simple index NDDI. Moreover, with two daytime overpasses of MODIS (Terra MODIS and Aqua MODIS) each day, it is feasible to analyze the transport of SDSs. When we tracked the SDS transport between Terra and Aqua NDDI images [Figs. 3(b) and 4(b)], we found this SDS not only moved to the southeast direction with the weather system but also was swept into this system. The blue dot in the white circle moved about 2° longitude along the northeast direction from 110° in Fig. 3(b) to 112° in Fig. 4(b).

III. DISCUSSION AND CONCLUSION

We have demonstrated our approach to monitor SDS with a new index called NDDI. By using this index, airborne dust can be discriminated from other features. This study indicates that NDDI is a promising index to effectively separate SDS from water/ice clouds and ground features except ground sand and dust. The BT of MODIS band 31 is used to separate airborne SDS with ground sand and dust. The NDDI has been tested over African regions [14]. We found that the NDDI is working with different threshold values there. Further studies will be conducted in the near future, which may include validating the NDDI for SDS detection over different regions, identifying the NDDI threshold values in different regions, and developing multithreshold approaches to detect SDS by combining MODIS SRB and thermal emissive band measurements.

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