MODIS資料在亞洲地區沙塵天氣分類之應用
Applying MODIS Data for Asian Dust Weather Categorization

Tang-Huang Lin[1], N. Christina Hsu [2], Si-Chee Tsay [2] , and Gin-Rong Liu[1]

[1]Center for Space and Remote Sensing Research, National Central University, Jhongli, 32001 Taiwan
[2]Earth Sciences Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA

Abstract

This study categorizes various types of dust weather by means of satellite remote sensing over central Asia. Datasets consisting of collocated products from MODIS/Aqua and surface measurements are analyzed. Results suggest an exponential relationship between the surface visibility and the satellite retrieved aerosol optical depth (AOD), which is subsequently utilized to categorize dust weather. The satellite-derived spatial frequency distributions in the dust weather types are seen to be quite consistent with China's weather station reports during 2003, indicating that dust weather classification with satellite data is highly feasible. Although the period during the springtime from 2004 to 2007 may be not sufficient statistical significance, our results reveal an increasing tendency in both intensity and frequency of dust weather over Central Asia during this time period.

Key Words: Dust weather categorization, Aerosol optical depth, Visibility, MODIS

1. Introduction

In recent decades, dust storms originating from the arid regions in Central Asia have become more powerful and frequent (e.g., Qiu and Yang, 2000; Wang et al., 2004). The concentration of suspended particles increases dramatically when a dust storm forms. Such particles can travel in long distances, swiftly reaching regions such as China, the Korean Peninsula, Japan, Taiwan, and even North America (Ichikawa and Fujita, 1995; Arndt *et al.*, 1998; VanCuren and Cahill, 2002; Hsu *et al.*, 2006). They can affect, among many things, the regional air quality, environment and the energy budget of the atmosphere and surface (Siheng *et al.*, 1999; Liu and Shiu, 2001; Li *et al.*, 2004; Liu and Lin, 2004; Yoshioka *et al.*, 2007).

Aside from the important dust storm intensity research, extensive investigations on the source areas, frequency, pathway, condition and trend of Asian dust storms have been performed over the past two decades, as well. In most studies, the intensity of dust weather has often been categorized using standard visibility observations (CCMB, 1979) from ground-based weather stations. However, it is difficult to ensure that the measurement standard is consistent among hundreds of stations located in China. Since satellite remote sensing can retrieve relevant atmospheric and/or surface variables more consistently over large geographic areas, it is a more viable tool in obtaining a more spatially and temporally coherent categorization of dust weather. As improvements continue to be made in techniques that retrieve dust properties near source regions from satellite measurements, comprehensive analysis of these observations provide scientists with a better understanding of the spatial distribution, frequency and trend of dust storms (Hsu *et al.*, 2004 and 2006; Remer *et al.*, 2005). Given the different observational aspects of the problem, establishing a correlation between the remotely sensed aerosol properties and surface visibility for dust weather categorization is not an easy task, and has been a subject of many ongoing studies (Qiu and Yang, 2000). In this study, satellite retrieved aerosol properties, such as optical depth, particle size and turbidity coefficient, are analyzed with ground-based weather stations' visibility data. Their respective correlation is subsequently used to categorize the corresponding dust weather.

2. Methodology

In this study, the newly developed *Deep Blue* algorithm by Hsu *et al.* (2004) was employed to characterize the aerosol properties over and near the dust storm source regions. The surface reflectance for a given pixel was determined from a clear-scene database based upon its geo-location. The reflectance measured at the 412, 470, and 650 nm channels (from MODIS) were subsequently compared to the radiances in a lookup table for different solar zenith, satellite zenith and relative azimuth angles, surface reflectance, AOD (a measure of aerosol loading) and single scattering albedo (SSA; the probability of scattering). Finally, the dust particles can be distinguished from the fine-mode pollution particles based upon the Ångström exponent (AE or α; an indicator of size mode) derived by the *Deep Blue* algorithm. In regard to the atmospheric turbidity, Ångström turbidity coefficient (β), AOD and Linke turbidity (T_L) are typically used in turbidity measurements. The Ångström turbidity coefficient can be obtained with the retrievals of AOD and α, while the Linke turbidity is defined as the ratio of total optical depth to that of a clean and dry atmosphere (Zakey et al., 2004). Due to the aerosol properties can be provided from satellite data regularly, Ångström turbidity coefficient is employed to examine the correlation to the visibility in this study.

Despite the different observed directions (vertical and horizontal), the long-term and short-term surface measurements still reveal an inverse relationship between the AOD and visibility (Solis, 1999). The correlation between the visibility and surface aerosol concentration (PM10) in the Pearl River Delta Region under heavy haze had been examined by the observation of ground stations (Deng *et al*., 2008). The correlation coefficient was about 0.8 based on an exponential function under a high aerosol concentration, which may have been caused by anthropogenic pollutants. The result suggests that the relationship between the AOD and visibility appears to be exponential rather than linear, but somehow differs with the behavior of dust particles revealed by remotely sensed data. They also pointed out that there was a weak association between the aerosol concentration (PM10) and visibility range during a low visibility event. Therefore, this study attempts to shed light on the association between the station-measured visibility data and satellite-retrieved AOD during dust weather events. Although many studies have already been made in calculating the correlation between the AOD and visibility, they are mostly not for dust weather circumstances.

In general, four types of dust weather (dust haze, blowing dust, dust storm and dust devil) are considered for the daily observations in China (CCMB, 1979; Qian *et al*., 2002). As satellites observe very few dust devil events, only the first three types of dust weather are investigated in this study. After constructing the relationship between the AOD and visibility, the type of dust event will be discerned and categorized by satellite data based on the aforementioned definition.

3. Data and results

In order to identify the dust weather characteristics in eastern Asia, a region ranging from 20° N to 60° N and from 70° E to 130° E was selected for our study area (figure 1). Two kinds of datasets are used for the dust weather analysis. The first contains satellite retrieval data from the MODIS/Aqua atmosphere daily level 3 product (available at http://ladsweb.nascom.nasa.gov) covering the regions of interest in this study during springtime from 2003 to 2007. The second is the ground-measured visibility data observed every 3 hours from about 200 ground stations located within the study area during April 2006 (figure 1). Our analysis also utilizes the pertinent dust weather reports (from http://www.duststorm.com.cn), which was mainly used for verifying the dust weather classification result by means of satellite remote sensing.

The investigation period was focused on the springtime, which usually marks the highest level of sandstorm activity. As stated in the methodology section described above, aerosol properties, such as the AOD, AE, and SSA, can be retrieved from satellite data by using the newly developed Deep Blue approach. Figure 1 shows the AOD and AE distributions estimated from the MODIS/Aqua data from 1 February to 31 May in 2007. The AOD data displayed in figure 1a are the composite products of Deep Blue (over land) and Dark Target approaches (over ocean; Kaufman *et al.*, 1997). There are two regions with high AOD values in the study area. One is near the northern Taklimakan Desert and the other is below the city of Beijing. The AOD values over the two areas were quite similar but, as shown by figure 1b, the AE values were different. This indicates that the two regions' particle size distribution contained different particle types.

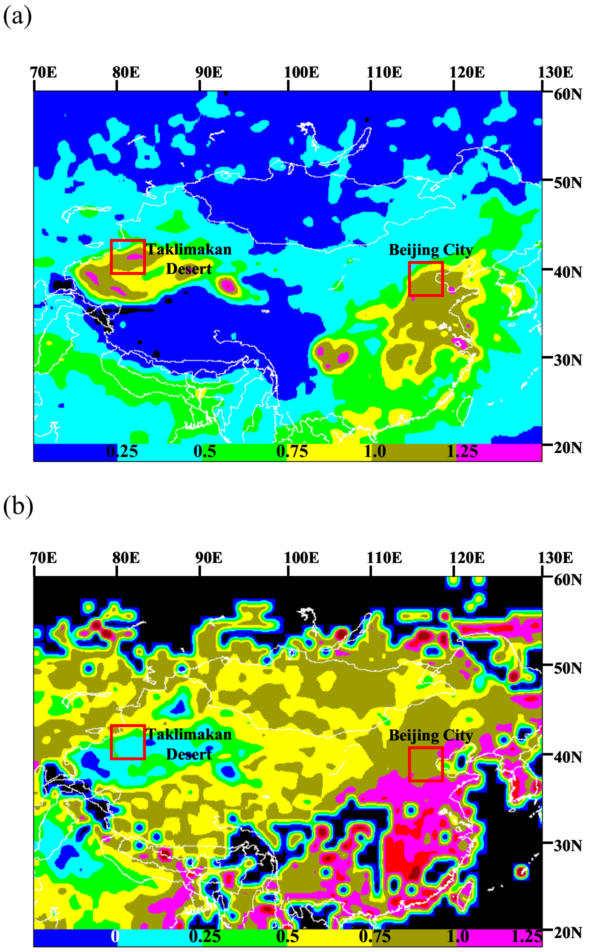


Figure 1. The aerosol properties retrieved from the MODIS/Aqua data during 1 February to 31 May in 2007, (a) Averaged AOD, (b) Averaged AE.

The results shown in figure 1 completely correspond to the actual local environment, where dust particles are the main aerosol composition (Coarse mode: The average AE is about 0.25) over the Taklimakan Desert, and anthropogenic pollutants (Fine mode: The average AE is about 0.75 to 1.0) are heavily concentrated nearby Beijing. Thus, the AE parameter serves as the principal indicator for dust weather circumstances (i.e., dust particle identification) in the satellite analysis.

3.1 Case study of dust storm event

According to the previous discussion, the satellite-observed data of a significant dust storm event (26-28 March 2004) in China was examined to determine the characteristics of the particle size distribution (AE) in categorizing areas affected by dust weather. During the ACE-Asia field campaign in April 2001 (Huebert *et al.*, 2003), the monthly AE values from the AERONET measurements in Beijing and Inner Mongolia sites were 0.78 and 0.82, respectively. Accordingly, the average AE (0.8) was selected to identify the dust particles for the dust weather classification.

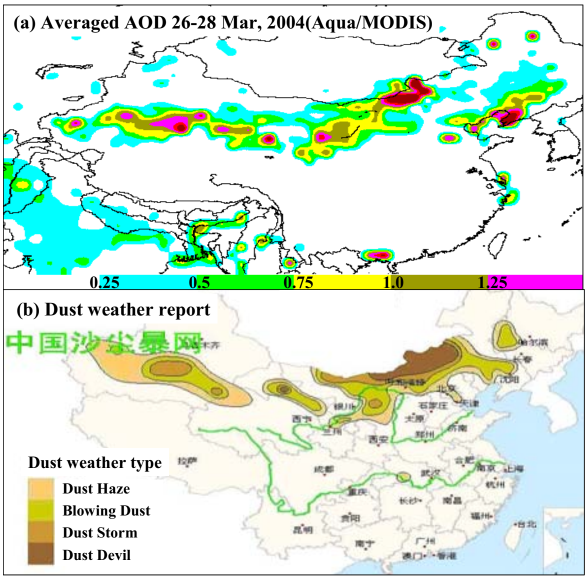


Figure 2. Dust event during 26 - 28 March in 2004. (a) The spatial distribution of the AOD (for values of AE less than 0.8) retrieved from MODIS. (b) The surface report of dust weather types from a spatial distribution perspective (from http://www.duststorm.com.cn).

Dust storm outbreaks occurred over the Taklimakan Desert and Mongolia Plateau on 25 March 2004. The time series AOD variations from the MODIS data illustrated clearly that the dust storms from the Mongolia Plateau passed through Inner Mongolia and moved southeast during 26-28 March. The spatial distribution of the AOD (for AE values less than 0.8) showed that the area around the Inner Mongolia Plateau experienced a strong dust storm. Meanwhile, the formation of a dust storm at the Hexi Corridor, located to the west of the Taklimakan Desert area, could also be seen (figure 2a). In addition, a heavy aerosol plume over the region near Bohai Bay and Yingkou City was detected by the MODIS data, but was not found in the surface weather reports. The discrepancy may have been caused by the combination of dust particles and pollutants in the plume. However, the overall AOD distribution was quite consistent with the ground-based observations (see also figure 2b). These results indicate that dust weather can indeed be categorized by satellite-observed aerosol properties.

3.2 Correlation between AOD and visibility

The visibility observations from 204 ground stations scattered within the study area during April 2006 were gathered in this study. The observation frequency and quality of the visibility data from each station was first inspected. Only stations with more than 20 observations and visibility values not limited to 3 constant values are qualified for inclusion in the analysis of the correlation with the satellite-retrieved AOD. figure 3a displays an exponential relationship with a high correlation coefficient (about 0.75) between the AOD values and visibility. A similar result was observed from the in-situ measurements during 5-day period over South-West Germany, and the reciprocal relationship between the horizontal visibility and the vertical AOD was demonstrated (Baumer *et al.*, 2008). In addition to the AOD, the correlation between Ångström turbidity and visibility was also examined and depicted in figure 3b. From figure 3, it can be seen that since the relationship between the AOD and visibility was stronger than that of the turbidity and visibility, the AOD retrieved from MODIS data was applied to estimate the visibility in the following dust weather categorization discussion.

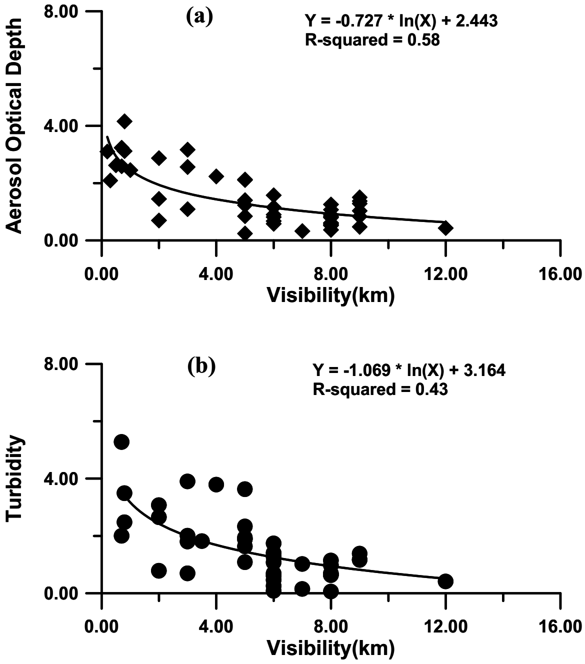


Figure 3. (a) Respective visibility and AOD scatter plot of the study area during April 2006, (b) Same as (a) but for the visibility and turbidity.

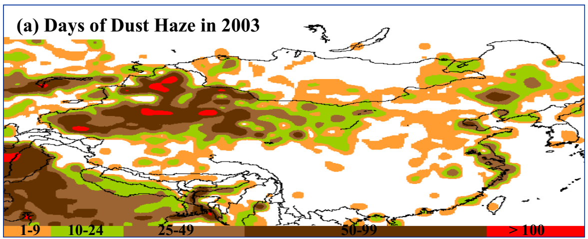
3.3 Results of dust weather categorization

As shown in figure 3a, the surface visibility can be calculated from the satellite-retrieved AOD when the AE value is constrained. The criteria of the dust weather categorization with respect to AOD and AE values and the levels of visibility over China are shown in table 1. From the criteria listed in the table, three types of dust weather were categorized for 2003 using the MODIS/Aqua products.

Table 1. Criteria used for dust weather classification in China (CCMB, 1979).

Dust Weather	AOD	AE	VIS (km)
Dust Haze	< 0.769	< 0.8	> 10
Blowing Dust	0.769 ~ 2.443	< 0.8	1 ~ 10
Dust Storm	> 2.443	< 0.8	< 1

The results for dust haze, dust blowing and dust storm spatial frequency derived from MODIS are shown in figure 4a, 5a, and 6a, respectively, along with the associated dust weather reports (figure 4b, 5b, and 6b). For dust haze, the distributions shown by the satellite products and the weather reports are quite consistent, excluding the North Taklimakan Desert (figure 4). For blowing dust weather, discrepancies are seen for the regions around the east Tibet Plateau, the Hexi Corridor to Inner Mongolia Plateau, and the eastern coastal areas (figure 5). The spatial frequency distribution of the dust storm analyzed by the satellite observations matched well with the weather reports, except for the area around the central Tibet Plateau and the Hexi Corridor to Inner Mongolia Plateau (figure 6).


(a) Days of Dust Haze in 2003

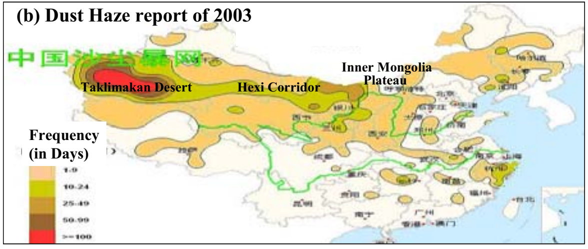
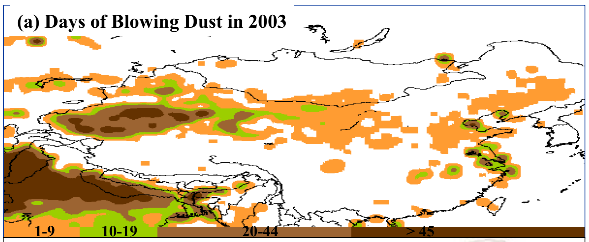

(b) Dust Haze report of 2003

Figure 4. (a) The result of dust haze spatial frequency from MODIS/Aqua in 2003, (b) The dust weather reports of 2003 (from http://www.duststorm.com.cn).


(a) Days of Blowing Dust in 2003

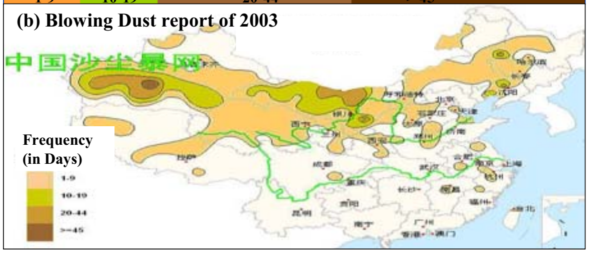
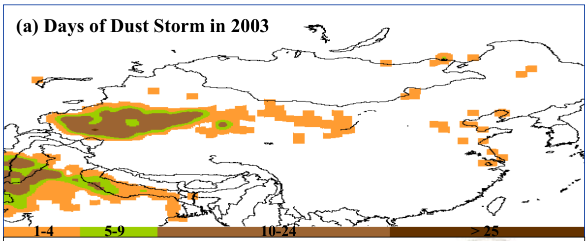

(b) Blowing Dust report of 2003

Figure 5. Same as figure 4, but for blowing dust cases.


(a) Days of Dust Storm in 2003

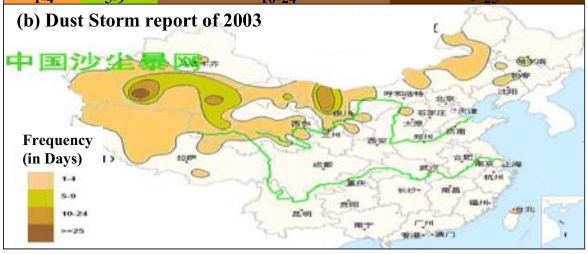

(b) Dust Storm report of 2003

Figure 6. Same as figure 4, but for dust storm cases.

The discrepancies may be caused by the lack of satellite-observed AOD, due to the cloudy pixels or absence of ground observations. An analysis of the number of days where aerosol information was retrieved from MODIS/Aqua in 2003 indicated that aerosol products over areas around the Tibet Plateau and the Inner Mongolia Plateau were frequently absent in 2003. In particular, fewer than 40% of the days contained retrievals for the region between the Tibet Plateau and Yangtze River Basin. This is possibly caused by the terrain effect or frequent cloud cover. Although some areas like the Tibet Plateau and the Inner Mongolia Plateau exhibited differences in the number of dust weather days between the satellite observations and weather reports, the overall spatial frequency dust weather distributions from the satellite observations were quite similar to the dust weather reports made by the ground stations.

4. Summary

In this paper, the ability to use satellite product to categorize dust weather has been verified by comparison to ground truth data. Due to their wide spatial coverage and highly consistency, satellite remote sensing offers an alternative to uncertain and limited spatial-surface dust storm observations. Comparisons between ground station and satellite measurement revealed an exponential relationship with a high correlation coefficient (greater than 0.75) between the visibility and retrieved AOD under dust weather conditions. Thus, the AOD criteria can be used as a substitute for the levels of visibility in dust weather categorization provided that the AE value is constrained to be lower than 0.8. The results of dust weather classification generally conform to the dust storm reports, except for the areas near the Hexi Corridor and Inner Mongolia, which underestimated the spatial distribution of dust storms during 2003. The main reason for the discrepancy is the lack of satellite observations due to some cloudy cases. The effect is significantly mitigated when long-term data is applied. Overall, it can be seen that the dust weather categorization using remote sensing data can be more consistently and efficiently delineated, especially for long-term dust weather investigations.

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