Identifying the regional thermal-IR radiative signature of mineral dust with MODIS
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[1] We use MODIS Terra Level 1B data containing calibrated and geolocated radiances to investigate a regional signature of wind-blown mineral dust in the thermal-IR. MODIS data over oceans for the 2000–2004 time period were examined for the presence of dust plumes that originate from the main dust sources located in East and South Asia, Middle East, Northern Africa, and Australia. A number of representative cases for different source regions were selected and analyzed in terms of brightness temperatures at three IR channels centered at 8.55, 11.03, and 12.02 μm. The distinct differences in the thermal-IR signature of atmospheric dust for the considered regions were found. Our analysis indicates that these differences are likely due to different mineralogical composition, although other factors (e.g., multilayered vertical distribution) may be also involved. Implications of our findings to the detection of dust based on the techniques using brightness temperature differences are discussed. Citation: Darmenov, A., and I. N. Sokolik (2005), Identifying the regional thermal-IR radiative signature of mineral dust with MODIS, Geophys. Res. Lett., 32, L16803, doi:10.1029/2005GL023092.

1. Introduction

[2] Atmospheric dust aerosols can affect the Earth’s climate system via a number of complex processes. Given the large geographical areas affected by dust transport and the heterogeneous distribution of dust sources around the world, satellite remote sensing provides very often the only tool for characterization of dust plumes, especially over oceans. Several techniques have been proposed for detecting mineral dust and volcanic ash using thermal-infrared observations [Prata, 1989; Ackerman, 1997; Legrand et al., 2001; Prata and Grant, 2001]. Detection is based on brightness temperature differences (BTD) either in two or three channels. The former is called the bispectral split-window technique and the latter is the trispectral approach. Although the split-window techniques that use observations near the 11 and 12 μm bands have been primarily applied to volcanic aerosols, they have also been used for the detection of dust. For instance, Dunion and Velden [2004] relied on this technique to investigate how atmospheric dust affects Atlantic tropical cyclone activity. Ackerman [1997] argued that a combination of three IR channels near the 8, 11, and 12 μm bands, i.e., a trispectral approach, is likely to provide a more robust dust detection. Using satellite observations of AVHRR and HIRS/2 of dust outbreaks over the Arabian Peninsula and adjacent Arabian Sea in July 1985, Ackerman [1997] demonstrated that analyzing brightness temperature differences between the 8 and 11 μm channels against BTD between the 11 and 12 μm channels enables to discriminate dust from the clear sky over both oceans and lands. The Ackerman study implied that a universal threshold in the BTD values could be used to detect dust over the diverse geographical regions. However, mounting evidence suggests that the properties of dust strongly vary between dust sources. In particular, the mineralogical composition, which is a key factor controlling the IR radiative properties of dust, exhibits strong regional differences [Claquin et al., 1999; Caquineau et al., 2002]. Considering several representative mineral mixtures, a modeling study by Sokolik [2002] showed that the differences in composition, especially differences in the amount of clays and quartz, have a large impact on spectral brightness temperatures. Given a lack of dust composition data as well as a number of critical assumptions involved in the IR radiative transfer modeling, finding observational evidence of the regional radiative signature of atmospheric dust would be of great importance. The goal of this paper is to investigate the thermal-IR radiative signature of atmospheric dust originating from the main world’s dust production regions and explore the implications to the dust detection over oceans with the techniques based on brightness temperature differences by using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra satellite over oceans.

2. Approach and Data

[3] The key to our study was unambiguous selection of dust plumes to provide a “truth” in testing BTD techniques as well as to study the radiative signature. We were not able to use MODIS aerosol products because of a number of known limitations in the case of dust, especially under the heavy dust load (MODIS Atmosphere-Known problems, http://modis-atmos.gsfc.nasa.gov/MOD04_L2/qa.html) [Remer et al., 2005; Darmenova et al., 2005]. Therefore, our approach was based on manual scene classification using true color MODIS images. Out of about 180,000 images accumulated over the entire globe for the period from 24 February, 2000, to 30 April, 2004, about 600 images showed dust over oceans. Each image represents a true color composite of a single Level 1B daytime 5-min granule of MODIS data. Figure 1 schematically shows seven geographical regions selected in this study. For each region, a number of representative cases were chosen for which we obtained the Level 1B data containing calibrated and geolocated at-aperture radiances in 36 spectral bands at the 1 × 1 km resolution. Our final selection for this study consisted of 49 images with an unambiguous presence of dust. For each
true color image, the pixels were manually classified as “clear”, “partly cloudy”, “cloudy”, “mixed dust and cloud”, “dust” and “heavy dust”.

Figure 1 indicates that the selected regions cover dust outbreaks originating from all main dust sources of the world. In the case of North Africa, we identified three different regions representative of westward, northward, and eastward transport. Dust observed in region 1 is likely to originate from one or a combination of the sources located in Mauritania, Morocco, Algeria, and Bodele Depression, whereas regions 2 and 3 represent dust from the Libyan and Nubian deserts, respectively. Those sources were described recently by Prospero et al. [2002]. A number of studies have pointed out that several distinct sources can contribute to westward transport (our region 1) [Chiapello et al., 1997]. To address this issue, we sorted dust outbreaks with similar westward transport into three latitudinal groups based on their location off the west coast of North Africa: 8°–16°N, 16°–24°N, and 24°–28°N. Dust plumes in the first group are most likely to originate from Algeria and Bodele Depression, while dust outbreaks in 16°–24°N and 24°–28°N latitudinal bands are from Algeria and Mauritania, respectively [Chiapello et al., 1997; Prospero et al., 2002]. Selecting cases with similar transport routes of dust outbreaks also helps to minimize differences introduced by varying atmospheric conditions. Also, several regions were selected for Asian sources. Regions 4 and 5 represent dust outbreaks originating from the Iranian and Thar deserts, whereas the region 6 represents dust plumes that likely originated from the Gobi and Taklamakan regions [Darmenova et al., 2005]. Region 7 represents dust from the Australian deserts. We were able to identify only three cases for this source, and all of them were associated with eastward transport. We were not able to identify the dust outbreaks originating from the American sources, such as Patagonia and Baja. It is likely that dust plumes from those deserts are not often transported over the ocean and/or too weak for detection by satellite imagery.

3. Results and Discussion

Here we used the data from MODIS 29, 31, and 32 channels with central wavelengths of 8.55, 11.03, and 12.02 μm, respectively. Brightness temperatures (BT) for each channel were calculated from the Level 1B radiances using the inverse Planck function in the wavelength domain. Then the BTD between channels 29 and 31 (\(BT_{8} - BT_{11}\)) and channels 31 and 32 (\(BT_{11} - BT_{12}\)) were computed and analyzed on a case-by-case basis.

First, we examined regional differences in the BTD in the context of the split-window method. As an example, Figure 2 compares two cases of dust outbreaks in regions 2 (top panel) and 6 (bottom panel). Shown are the true color images as well as calculated \(BT_{8} - BT_{11}\) and \(BT_{11} - BT_{12}\) differences (in K). The former is commonly used in the split-window method. For the clear sky over oceans, \(BT_{8} - BT_{11}\) are negative, while \(BT_{11} - BT_{12}\) have positive values in both regions. This behavior of BTD has been already pointed out by previous studies [e.g., Ackerman et al., 1998] and explained by spectral differences in water vapor absorption. Because these MODIS channels lie in the thermal-IR window, absorption by other atmospheric gases is negligibly small. Over the Mediterranean Sea (region 2), \(BT_{11} - BT_{12}\) are negative in the presence of dust, while for clear sky and cloudy areas \(BT_{11} - BT_{12}\) are positive. Similarly, nega-
positive $BT_{11}-BT_{12}$ are caused by Asian dust over the Yellow Sea (region 6). However, negative $BT_{11}-BT_{12}$ are also caused by some clouds in region 6. Over the Mediterranean Sea, $BT_8-BT_{11}$ for dust are negative and smaller than those for clouds but larger than $BT_8-BT_{11}$ for clear skies. In contrast, over the Yellow Sea, $BT_8-BT_{11}$ are positive for dust and for some cloudy areas.

[7] To further address the dust radiative signature on the regional level, a subset of pixels representing different scenes was selected and analyzed. Figure 3 shows the trispectral diagrams for the pixels classified as “heavy dust”, “cloudy” and “clear”. Each data point represents the mean BTD and the bars show the standard deviation of the mean calculated for the selected subset of pixels. Notice that “clear” data are confined by the similar BTD values and show low variability (i.e., small standard deviation). These imply that the factors controlling BTD variability for clear skies (such as amounts of water vapor, different temperature profiles, variations in the ocean emissivity and temperature, and possibly some sea salt aerosols and/or some thin cirrus missed in the process of classification) cannot be responsible for the large differences observed in “heavy dust” cases between the regions, pointing out that dust itself is a key controlling factor. Nevertheless, the BTD ranges for clear skies apparently differ from those observed in the presence of heavy dust. However, examining Figure 3, one can conclude that discriminating dust from clear sky or clouds may be possible for a single granule by adjusting a BTD threshold, but this is not true in the general case. Regions 1, 2, and 4 pose a particular challenge for dust discrimination from clouds because of the overlap of “heavy dust” and “cloudy” data points. Although similar overlap is evident in $BT_8-BT_{11}$ for other regions, there is a good separation in $BT_{11}-BT_{12}$. For example, discrimination between “heavy dust” and “cloudy” pixels would be possible for regions 3, 5, 6, and 7 with $BT_{11}-BT_{12}$ thresholds of 0.5, −0.2, −1.0, and −0.4 K, respectively.

[8] Figure 4 summarizes the mean BTD and standard deviations calculated for “heavy dust” cases along with clear sky cases. The dust BTD values show specific features depending on the particular region. Some of the regions appear to group on the trispectral diagram. Regions 1(16°–24°N), 1(24°–28°N), 3, and 4 form one group with $BT_{11}-BT_{12}$ and $BT_8-BT_{11}$ values of about −0.1 K and −1.7 K, respectively. Regions 7 and 5 form another group with the $BT_{11}-BT_{12}$ difference of −1.0 K and $BT_8-BT_{11}$ of −1.1 K. Regions 1(8°–16°N), 2, and 6 differ from the others, showing several distinct features such as positive $BT_{11}-BT_{12}$ in regions 1(8°–16°N) and 2, and positive $BT_8-BT_{11}$ in region 6. The question arises: Can we isolate the factors that control the infrared signature of atmospheric dust? Differences in the satellite viewing geometry may play a
role. However, in our analysis the pixels with dust were observed at random locations within the granules, thus for a large enough number of granules the geometry effect would increase the data scatter but will not change the mean. This was confirmed by analyzing plots similar to the ones shown in Figure 3, but for different cosine of the viewing angle ranging from about 0.6 to 1 in a discrete interval of 0.1. As expected, a shift in data points was observed with changes of the viewing angle, however various regional differences between the BTD points remained. Furthermore, previous studies showed that the BTD are relatively insensitive to changes in the size distribution compared to changes in the mineralogical composition [Sokolik, 2002]. Therefore we conclude that the different regional mineralogical composition of dust, which controls its radiative properties in the IR spectrum, is likely the main reason for observed differences in the regional dust signature as was suggested by previous modeling studies [Sokolik et al., 1998; Sokolik, 2002]. It seems that, by accounting for the angular geometry, one can constrain the regional dust composition based on the results shown in Figure 4. Unfortunately, an additional complexity arises from the fact that dust exhibits a complex multilayered vertical distribution during mid- and long-range transport in the atmosphere. Dust properties can be dissimilar from layer to layer and thus can hamper the interpretation of regional BTD in terms of differences in the dust mineralogical composition. Collocated MODIS and new space lidar CALIPSO observations will provide valuable data to further explore the nature of the dust regional radiative signature.

4. Summary

[9] In this study we utilized the MODIS data in the thermal-IR to investigate the radiative signature of atmospheric dust on a regional basis and implications to dust detection. Forty-nine scenes with the clear presence of dust plumes were analyzed for seven different regions over the oceans during the 2000–2004 time period.

[10] Our analysis demonstrated that automated discrimination between cloudy and dusty pixels based on the split-window or the trispectral approach with a fixed BTD threshold is not reliable. For some of the regions it is still possible to use BT_{11} - BT_{12} difference as a simple, regionally dependent single value threshold test. An interesting finding that confirms the presence of the regional radiative signature of dust is that clear sky pixels tend to group in a tight cluster on the trispectral diagram while the dusty data show significant scatter. In the presence of dust, BTD values for some of the regions tend to group, while others have some distinct features. For instance, regardless of the viewing angle, regions 1(8°–16°N) and 2 tend to have positive BT_{11} - BT_{12}, whereas region 6 has positive BT_{12} - BT_{11}.

[11] Based on our analysis, we conclude that the regional radiative signature of dust observed in the MODIS data is likely due to the different mineralogical composition controlled by the diverse dust sources, although the multilayered vertical distribution may also be important. This is in agreement with previous modeling studies. Thus, one has to consider the origin of atmospheric dust in order to utilize the BTD difference techniques in their full potential. In turn, the regional IR signature may be helpful in identifying the origin of dust plumes from remote sensing observations. A combination of passive IR remote sensing and the space lidar CALIPSO has a high potential to provide an additional constraint on dust regional properties.

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References


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