Differentiating airborne dust from cirrus clouds using MODIS data

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[1] A method for detecting and differentiating dust from cirrus using satellite remote sensing has been developed. Using the differences in the reflective and emissive properties of each, it is shown that combining short-wave reflectance ratio tests with long-wave brightness temperature differences produce individual parameters that are able to specifically detect cirrus and dust. Through successive employment of both parameters, a method is established that separates dust from cirrus. Two case studies using Moderate resolution Imaging Spectroradiometer (MODIS) data are presented that show the effectiveness of the procedure. Citation: Roskovensky, J. K., and K. N. Liou (2005), Differentiating airborne dust from cirrus clouds using MODIS data, Geophys. Res. Lett., 32, L12809, doi:10.1029/2005GL022798.

1. Introduction

[2] Thin cirrus cloud and atmospheric dust are often indistinguishable by automated satellite cloud detection algorithms. This is due to a number of reasons. First, dust that is transported horizontally large distances is generally located around 5 km in altitude. At this altitude, it is located above much of the water vapor and can produce a relatively high 1.38 μm reflectance, a channel that is used to detect cirrus. Second, the visible optical depth of dust associated with dust storms is regularly above 0.5, far above the average global aerosol optical depth, especially over the oceans. Third, dust in the atmosphere is common around deserts, places where the atmospheric column water vapor amount is low. Finally, fine dust particles produce emissivity differences between 8.6 μm and 11 μm that create brightness temperature differences similar to those of thin cirrus.

[3] Shenk and Curran [1974] attempted to use the Nimbus-THIR (Temperature Humidity Infrared Radiometer) 11 μm brightness temperature to differentiate dust in the atmosphere from desert surface based on the severe daytime temperature gradients in the boundary layer. This one channel method is limited because changes in surface emissivity lead to brightness temperature changes and clouds can often be misinterpreted as dust. Ackerman [1997] investigated the sensitivity of the thermal window region wavelengths to dust among other aerosols and found that brightness temperature differences between 11 μm and 12 μm were observed to be negative during dust storms. The MODIS cloud mask [Ackerman et al., 2002] has incorporated this simple suspended dust flag for the 11–12 μm BTD less than −1 K. Recently, visible techniques have also been identified as having potential to detect airborne dust. Hutchinson and Jackson [2003] showed that the reflection by sand increases steadily with wavelength in the 0.4 to 1.0 μm spectral region. They have implemented a 0.41 μm threshold test to identify clouds over desert surfaces in the new Visible-Infrared Imaging-Radiometer Suites (VIIRS) cloud mask for the future National Polar-Orbiting Operational Environmental Satellite System (NPOESS). Following this conceptual approach, a dust detection parameter has been developed that can be used in conjunction with the cirrus detection parameter, described by Roskovensky and Liou [2003], to separately identify thin cirrus clouds from airborne dust. Theoretical calculations and the methodology development are presented in section 2, followed by a discussion in section 3 of validation of the new detection scheme using two MODIS scenes containing dust events. Conclusions are given in the last section.

2. The Cirrus and Dust Detection Method

[4] Figure 1 shows the theoretical (a) 1.38 μm/0.65 μm reflectance ratio (RR), (b) 8.6–11 μm brightness temperature difference (BTD), and (e) resulting P-parameter, for airborne dust. The theoretical curves (solid) so that the P-parameter mistakenly classifies dust with an optical depth of about 0.45 as cirrus. Changing the A and B parameters can prohibit this misclassification but only at the expense of reducing the P-parameter’s effectiveness of detecting thin cirrus. The right column of Figure 1 shows the theoretical values of a new parameter (D) that is designed to detect dust defined as

\[
P = \exp\left(\frac{[RR*A + (BTD - B)]}{C0}\right)
\]

where A is a scaling factor and B is the 8.6–11 μm BTD offset. Radiative transfer calculations were made using the adding/doubling method [Takano and Liou, 1989] that includes the scattering and absorption properties of nonspherical ice crystals [Liou, 2002]. A cirrus cloud is assumed to be located between 8 and 10 km with an ice crystal size distribution used by Roskovensky and Liou [2003] having a mean effective size of 24 μm. The scattering and absorption properties of dust were taken from D’Almeida et al. [1991] where a spherical shape was assumed. The computational results shown in Figure 1 pertain to using 50° as the solar and viewing zenith angles and 135° as the relative azimuth. Also, the A and B parameters used were 10 and 0, respectively. It can be seen that the dust curves (dotted) appear to mimic the cirrus curves (solid) so that the P-parameter mistakenly classifies dust with an optical depth of about 0.45 as cirrus. Changing the A and B parameters can prohibit this misclassification but only at the expense of reducing the P-parameter’s effectiveness of detecting thin cirrus. The right column of Figure 1 shows the theoretical values of a new parameter (D) that is designed to detect dust defined as

\[
D = \exp\left(-[rr*a + (btd - b)]\right)
\]
where \( rr \) represents the 0.54 \( \mu \text{m} / 0.86 \mu \text{m} \) reflectance ratio and \( a \) is its scaling factor and \( b \) is the 11–12 \( \mu \text{m} \) BTD offset. The two specific tests comprising this parameter, \( rr \) and \( bt\), are shown in Figures 1b and 1d, respectively. The 0.41 \( \mu \text{m} \) band that has been previously used over dust surfaces, has been replaced by the 0.54 \( \mu \text{m} \) band since it is known that the shorter wave MODIS band often saturates in cloud filled pixels. It can be seen that the 0.54 \( \mu \text{m} / 0.86 \mu \text{m} \) reflectance ratio value is greater than 1 with no cirrus or aerosol present due to the large molecular scattering differences between the channels at this long two-way path length. This ratio decreases with increases in both cirrus and dust optical depths. Cirrus eventually produces a ratio near 1 as would be expected, but the dust ratio decreases below 1 due to lower reflectance in the shorter wavelength. In this case, the cirrus and dust curves do not separate until their optical depths become 1. With smaller zenith angles, calculations show that the initial clear atmosphere ratio falls closer to a value of 1 and that the separation in the curves begins almost immediately with small optical depths. The dust and cirrus 11–12 \( \mu \text{m} \) BTD curves in Figure 1d change in opposite directions with increasing optical depth up to 1.5.

As opposed to the P-parameter, larger \( rr \) and \( bt\) values produce lower D values. It is clearly seen from Figure 1e that by using \( a \) and \( b \) parameters of 0.8 and 2, respectively, the D-parameter can detect dust with an optical depth below 0.2 using the threshold of 1, and at the same time cirrus can be separated. By tuning the \( a \) and \( b \) values, dust with smaller optical depths can easily be identified. The reason that this parameter cannot be used in place of the P-parameter is that it cannot separate cirrus from low clouds or clear sky.

3. Data and Case Studies

Two MODIS dust scenes from 2001 were chosen to test the D-parameter, and the grayscale versions of their MODIS true color images are displayed in Figures 2a and 2b, respectively. In the first scene from March 20 (0255 UTC), a large band of airborne dust is seen skirting the Asian coast and traversing the Korean peninsula. In the second scene from April 4 (0530 UTC), airborne dust is clearly seen in the middle of the Gobi desert. Also seen are cirrus clouds in the top right corner and snow on the mountains around the desert. Results from the MODIS Cloud Mask (MCM) for the two scenes are also displayed in Figure 2. Clear sky areas, defined with Clear Sky Probability (CSP) greater than 95% as described by Ackerman et al. [2002], for a 1100 pixel \( \times \) 700 pixel region of the March 20 scene and a 1000 pixel \( \times \) 1000 pixel region...
of the April 4 scene are shown in Figures 2c and 2d, respectively. Cloudy regions are defined as non-clear. It can be seen that the MCM misclassifies the entire dust plume and most of the ocean as cloudy in the March 20 case. As a result, routine ocean aerosol properties were not retrieved in these regions. Similarly, in the April 4 case, the airborne dust is misclassified as cloud along with a good deal of the mountain snow.

[7] In order to determine the \(A\), \(B\), \(a\), and \(b\) values for the P and D-parameter in these two scenes, data in the form of histograms were examined from small sections identified to contain clear sky, dust, and cirrus in the true-color imagery, shown by the boxes labeled A, B, and C, respectively, in Figures 2a and 2b. By using the midpoint between the clear sky and cirrus or dust histograms of the two reflectance ratios and brightness temperature differences in the March 20 ocean case, \(A\) and \(B\) values of 3 and 1, respectively, for the P-Parameter were assigned, while \(a\) and \(b\) values of 1.1 and 0, respectively, were found for the D-parameter. For the April 4 land (desert) case, P-parameter \(A\) and \(B\) values were assigned 5 and 1, respectively, and D-parameter values of \(a\) and \(b\) were set to 3 and 0, respectively. It was necessary to increase the value of \(A\) and \(a\) to diminish the effect of the reflectance ratios, because the clear sky values were lower than in the ocean case.

[8] To perform cirrus and dust detection, both the P and D-parameter tests were run on all pixels of each partial MODIS scene using the separate \(A\) (\(a\)) and \(B\) (\(b\)) values for ocean and land that were stated above. Dust was determined solely on the D value being greater than or equal to 1. This test superseded the P-parameter test in that cirrus was only determined if the P value was greater or equal to 1 and the D value was less than 1. If both the P and D values were less than 1, neither cirrus nor dust was assumed to be present. This procedure is summarized in Figure 3. The combined results for the March 20 case are shown in Figure 2e. The identified areas of dust and cirrus seem to correlate well with the MODIS true color image in Figure 2a. This is especially true for the ocean pixels in the top, right corner where cirrus appear to overrun dust. It is unclear from the MODIS imagery whether the clouds over land are cirrus or low-level clouds. No validation of cloud height has been made. It is important to note that no apparent false detection of dust occurred over the land or ocean.
When comparing the April 4 results in Figure 2f to the MODIS true color image in Figure 2b, good separation of cirrus from dust is seen in the northeastern region. Possible over-dusting in the desert basin may have occurred. When comparing these results to the single 11–12 μm BTD test with −1 K threshold analogous to the MCM suspended dust flag (not shown), it was seen that the addition of the reflectance ratio reduced the amount of false detection of dust over desert. It also appears that both the P-parameter and MCM may be over-detecting cirrus and clouds over the mountains.

4. Conclusion

The detection and separation of dust from cirrus are important from the perspectives of the global remote sensing of cirrus clouds and identification of the source of dust storms. However, only a static infrared window brightness temperature difference test has been used to detect dust operationally at this point. By combining the infrared signal with visible reflectance ratios, we have demonstrated that the newly developed D-parameter in combination with the P-parameter defined in our previous paper published in this journal are genuinely robust enough to accurately decipher dust and cirrus from the satellite perspective. In this paper, we have shown the underlying mechanics of the cirrus and dust detection tests through radiative transfer simulations and the effectiveness of using both tests in concert with the presentation of two case studies over ocean and desert surfaces. By using the P-parameter, cirrus clouds can be detected separately from other low clouds and clear sky, aerosol-filled pixels. Additionally, employing the D-parameter makes it possible to separate cirrus clouds from high altitude airborne dust. This detection method will be useful for simultaneously retrieving thin cirrus and dust properties described by Roskovensky et al. [2004] by identifying regions suspected of containing thin cirrus over dust. Future improvements can take into account differences in surface type including emissivity and bi-directional reflectance as well as atmospheric water vapor concentration.

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