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Distinguishing tropospheric aerosols from thin cirrus clouds for improved aerosol retrievals using the ratio of 1.38-μm and 1.24-μm channels

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[1] The scattering of solar radiation by cirrus clouds often contaminates aerosol products retrieved from satellite-based measurements using channels located in the visible and near-IR spectral region. Previously, it was demonstrated that a narrow satellite channel located near 1.38 μm is very effective in detecting the high level thin cirrus clouds. In this paper, we describe a ratio technique using the 1.38-μm channel and the 1.24-μm channel for identifying pixels contaminated by thin cirrus clouds so that improved aerosol and dust products can be obtained. The multi-channel data acquired with the NASA Moderate Resolution Imaging SpectroRadiometer (MODIS) on the Terra Spacecraft are used to demonstrate this technique. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1640 Global Change: Remote sensing; 1694 Global Change: Instruments and techniques. **Citation:** Gao, B. C., Y. J. Kaufman, D. Tanre, and R. R. Li, Distinguishing tropospheric aerosols from thin cirrus clouds for improved aerosol retrievals using the ratio of 1.38-μm and 1.24-μm channels, *Geophys. Res. Lett.*, *29*(18), 1890, doi:10.1029/2002GL015475, 2002.

1. Introduction

[2] The status on satellite remote sensing of aerosols from measurements acquired with heritage instruments, such as those of the NOAA Advanced Very High Resolution Radiometer (AVHRR) instruments, was reviewed by *Kaufman* [1995] and *King et al.* [1999]. Recently, more advanced algorithms have been developed for remote sensing of aerosols over the land [*Kaufman*, 1997; *Chu et al.*, 2002] and ocean [*Tanre et al.*, 1997; *Remer et al.*, 2002] from multi-channel imaging data acquired with the MODIS instrument [*Salomonson et al.*, 1989; *King et al.*, 1992] on the Terra Spacecraft platform. Sophisticated atmospheric correction algorithms [*Gordon and Wang*, 1994; *Gordon*, 1997] for ocean color applications have also been developed. Aerosol models and optical depths have been derived from both the Sea Viewing Wide Field-Of-View Sensor (SeaWiFS) and MODIS data as the bi-products of atmospheric correction algorithms. The aerosol optical depths (~0.6) retrieved from SeaWiFS data (M. Wang, Personnel communication, 1999) over areas near Hawaii in the Pacific Ocean can be significantly greater than those inferred from ground-based upward-looking sunphotometers [~0.1; *Smirnov et al.*, 2002]. Thin cirrus contamination is identified as the main source of the problem for the over-estimates of aerosol optical depths and under-estimates of Angstrom exponents from the SeaWiFS data.

[3] Major efforts have been made to identify cloud-contaminated pixels and to exclude these pixels during the development of algorithms for operational retrievals of aerosol parameters from MODIS data over land [*Kaufman et al.*, 1997; *Chu et al.*, 2002] and ocean [*Tanre et al.*, 1997; *Remer et al.*, 2002; *Martins et al.*, 2002]. However, residual cloud contamination effects are sometimes still present in the derived aerosol products. Figure 1a shows a MODIS color image acquired over ocean areas near Hawaii on February 14, 2001 at UTC 21:20. The 0.55-μm channel detects solar radiation scattered by the upper level ice clouds and the lower level water clouds and aerosols. Figure 1b shows the image over the same area for the 1.38-μm channel, which is very effective in detecting the upper level cirrus clouds [*Gao et al.*, 1993; *Gao and Kaufman*, 1995]. The signal received by this channel is essentially the solar energy scattered by cirrus and attenuated by absorption from water vapor above the cirrus. The sensitivity of this channel to lower level water cloud and aerosols is weaker because of strong absorption near 1.38 μm by atmospheric water vapor below cirrus clouds. Figure 1c shows the image of aerosol optical depths at 0.55 μm derived with an earlier version of the operational ocean aerosol algorithm. By comparing Figure 1c with Figures 1a and 1b, it is seen that areas covered by thick clouds are masked out and no aerosol retrievals are made. However, areas covered by thinner cirrus clouds are not masked out and aerosol retrievals for these pixels are made. Figure 1d shows the scatter plot between the 1.38-μm channel apparent reflectance and the retrieved aerosol optical depths (0.55 μm). A linear relationship between the two quantities exists. This means that thin cirrus clouds are not completely screened out in the MODIS aerosol data products, resulting in an overestimate of aerosol optical depth for each of the cirrus-contaminated pixels.

[4] In this article, we report a simple and effective technique for improving the screening of thin cirrus clouds. We will show that the ratio of the 1.38-μm channel over the 1.24-μm channel is quite useful for distinguishing between the upper level thin cirrus clouds and the lower level aerosols and dusts in MODIS data.

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2. Cirrus Masking With the 1.38-μm/1.24-μm Channel Ratio

[5] In order to develop an improved thin cirrus screening technique for better retrievals of information on lower level aerosols and dusts, we have made many case studies of MODIS data sets acquired over areas covered by thin cirrus clouds, aerosols, Asian dusts, Sahara dusts, smoke particles, and clear ocean in different geographical regions. We illustrate the development of the 1.38-μm/1.24-μm channel ratio technique for thin cirrus masking through an example.

[6] Figure 2a shows a color image (red: 0.66-μm channel; green: 0.55-μm channel; blue: 0.47 μm channel) of a MODIS scene. The data were acquired over China and the Korean Peninsula at UTC 02:55 on March 20, 2001 during the Asian dust season. A dust band extending from the Shangdong Peninsula, across the China Sea, Korea, to areas northeast of the Korean Peninsula is seen. Thin cirrus clouds are seen in the lower right portion of the image. Figure 2b shows the 1.38-μm image for the same scene. Thin cirrus clouds are seen more clearly in this image, and the dust band is weakly seen. Because the 1.38-μm channel has weak sensitivity to the dust layer, it is not possible to select a simple radiance/reflectance threshold for the 1.38-μm channel to separate cirrus pixels from dust pixels. In order to find out which channels are most useful for distinguishing between cirrus clouds from dusts, we averaged separately the radiances over small areas with dusts and with cirrus clouds for all the 36 MODIS channels, and plotted in Figure 2c the apparent reflectances [*Kaufman et al.*, 1997] for relevant visible and near-IR channels as a function of wavelength. From this plot it can be seen that large contrast exists between the 1.24-μm channel and the 1.38-μm channel. Therefore, the 1.38-μm/1.24-μm channel ratio would provide a mechanism to separate dust-pixels from cirrus-pixels. Figure 2d shows the channel ratio image. Dust pixels have ratios of 0.1 or less, while the cirrus pixels have ratio values greater than 0.3.

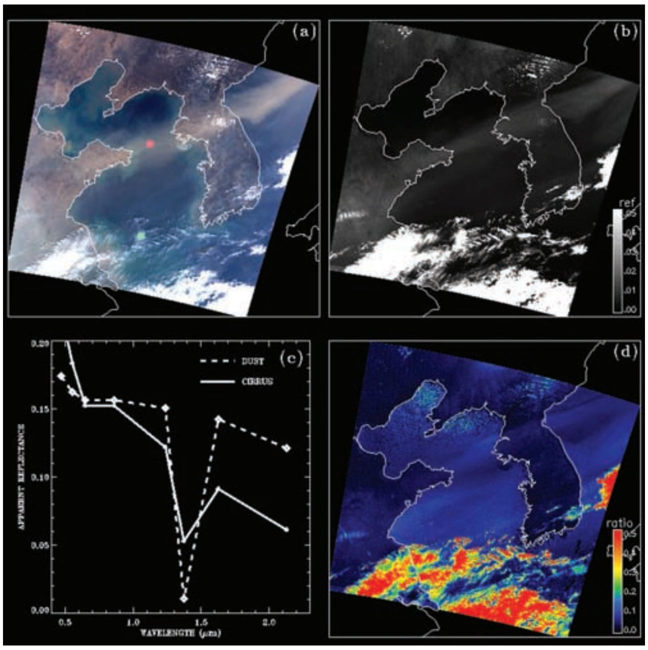

Figure 2. (a) a color image (red: 0.66-μm channel; green: 0.55-μm channel; blue: 0.47 μm channel) processed from a MODIS data set acquired over China and the Korean Peninsula at UTC 02:55 on March 20, 2001 during the Asian dust season; (b) the 1.38-μm channel image over the same scene; (c) apparent reflectances averaged over areas covered by Asian dusts and by thin cirrus clouds; and (d) the channel ratio image (1.38 μm/1.24 μm) to demonstrate the separation between cirrus-pixels from dust-pixels. The symbols in (c) represent actual data points, while the connecting lines serve as guides to human eyes.

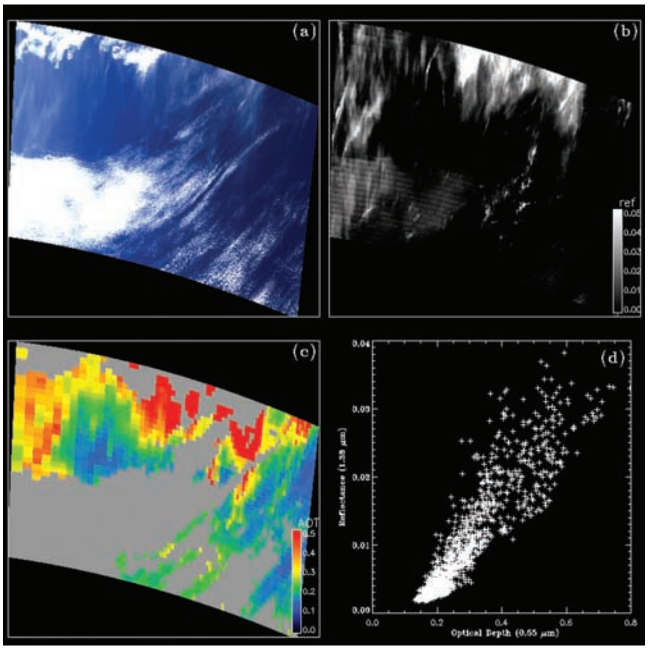

Figure 1. (a) a color image (red: 0.66-μm channel; green: 0.55-μm channel; blue: 0.47 μm channel) processed from the MODIS data acquired over ocean areas near Hawaii on February 14, 2001 at UTC 21:20; (b) the 1.38-μm channel image over the same areas; (c) the retrieved aerosol optical depth (0.55 μm) image; and (d) a scatter plot between the 1.38-μm apparent reflectances and the retrieved optical depths.

[7] The channel ratio method (1.38-μm/1.24-μm) has been tested with many sets of MODIS data acquired in different geographical regions around the world. Figure 3 shows the channel ratios as a function of apparent reflectance at 0.66 μm for areas covered by thin cirrus clouds, dusts, smoke particles, and clear ocean. In general, areas with thin cirrus clouds have ratio values of 0.3 or greater. As a result, we have selected a threshold value of 0.3 for improving the screening of thin cirrus clouds.

[8] The technique has recently been implemented into the operational version of the MODIS aerosol algorithm for cirrus screening. Figure 4 shows an example of comparisons between aerosol optical depths retrieved with two versions of the aerosol algorithms - with and without the new cirrus screening module. Fig. 4a shows a color image (red: 0.66-μm channel; green: 0.55-μm channel; blue: 0.47 μm channel) of a MODIS scene. The data were collected over the northeastern part of the United States and the Atlantic

Ocean at UTC 15:35 on May 5, 2001. Figure 4b shows the 1.38-μm image for the scene. There are thin cirrus clouds in the upper portions of the image. Figure 4c shows the image of aerosol optical depths at 0.55 μm derived with the earlier version of the operational aerosol algorithm. The thin cirrus clouds in the upper right portions of the image are incorrectly treated as aerosols during the retrievals. Figure 4d shows the optical depth image obtained with the recent version of the aerosol algorithm, which includes the cirrus screening module and other improvements for aerosol retrievals over land surfaces. The upper right portions are successfully masked out and no aerosol retrievals were made over these areas.

3. Discussion

[9] While searching for an improved cirrus screening algorithm, we tested other cloud masking techniques. For example, brightness temperature (BT) differences between two IR emission channels (8.6 and 11 μm) have been proposed for daytime and nighttime detection of dust layers [*Wald et al.*, 1998]. We tried this technique and other BT difference techniques, and were less successful in objectively separating thin cirrus clouds from dust layers with these techniques. By examining Figure 2c, it can be seen that large contrast also exists between the 1.64- and 1.38-μm channels for cirrus and dust covered areas. In principle, the ratio of 1.64-μm/1.38-μm is also very useful for the screening of thin cirrus clouds. We did not select this ratio for cirrus screening. One reason is that the apparent reflectances of the 1.64-μm channel depends on the size and shapes of ice particles within cirrus clouds. The other reason is that the MODIS instrument on the Aqua Spacecraft has several non-functional detectors for the 1.64-μm channel. The 1.64-μm/1.38-μm channel ratio cannot be used for operational processing of the MODIS data acquired from the Aqua Spacecraft platform.

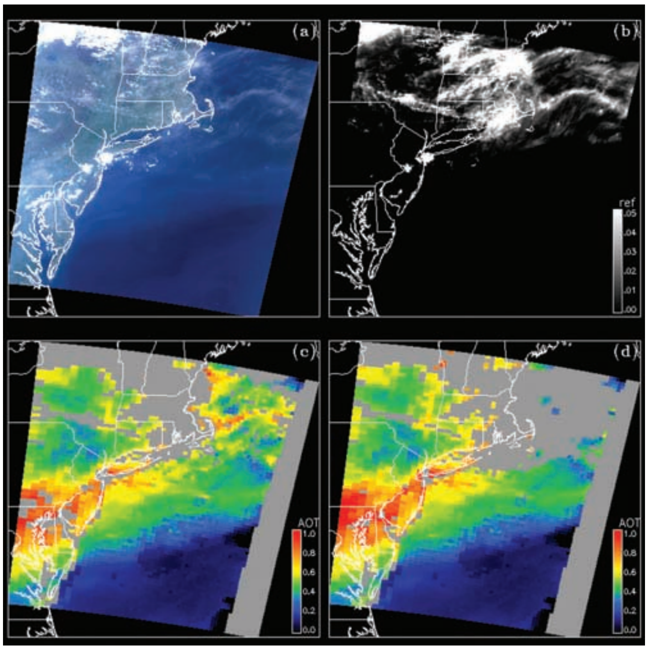

Figure 4. (a) a color image (red: 0.66-μm channel; green: 0.55-μm channel; blue: 0.47 μm channel) processed from the MODIS data acquired over the northeastern part of the United States and the Atlantic Ocean at UTC 15:35 on May 5, 2001; (b) the 1.38-μm channel image over the same areas; (c) the aerosol optical depth (0.55 μm) image retrieved with an earlier version of MODIS aerosol algorithm; and (d) the same as (c) but obtained with the current version of the aerosol algorithm, which includes the cirrus screening module and other improvements for aerosol retrievals over land.

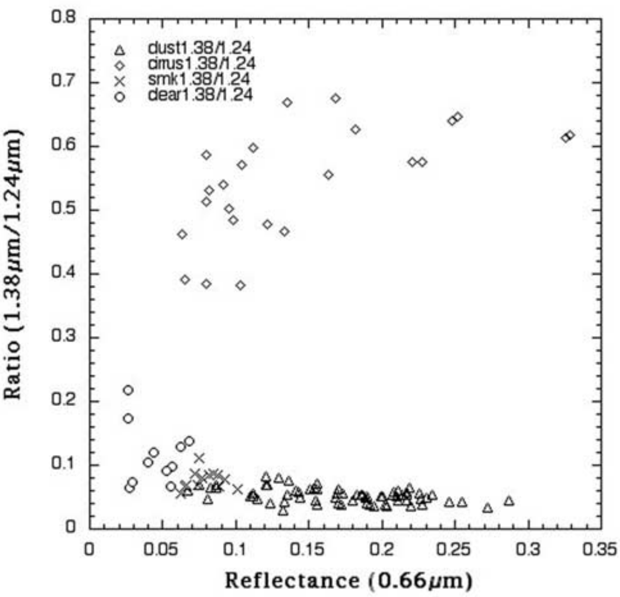

Figure 3. Channel ratios (1.38 μm / 1.24 μm) as a function of apparent reflectances at 0.66 μm obtained from MODIS data acquired over areas covered by thin cirrus clouds, dusts, smoke, and clear ocean.

4. Summary

[10] Through analysis of MODIS data, we have found that the 1.38-μm/1.24-μm channel ratio is very effective in separating the upper level cirrus clouds from the lower level dusts/aerosols. The technique has just been incorporated into the operational MODIS aerosol algorithms for improved aerosol retrievals.

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References

Chu, D. A., Y. J. Kaufman, C. Ichoku, L. A. Remer, D. Tanré, and B. N. Holben, Validation of MODIS aerosol optical depth retrieval over land, *Geophys. Res. Lett*, *29*(2), 1–4MOD 2, 2002.

Gao, B.-C., A. F. H. Goetz, and W. J. Wiscombe, Cirrus cloud detection from airborne imaging spectrometer data using the 1.38 μm water vapor band, *Geophys. Res. Lett.*, *20*, 301–304, 1993.

Gao, B. C., and Y. J. Kaufman, Selection of the 1.375-μm MODIS channel for remote sensing of cirrus clouds and stratospheric aerosols from space, *J. Atmos. Sci.*, *52*, 4231–4237, 1995.

Gordon, H. R., and M. Wang, Retrieval of water-leaving radiance and aerosol optical thickness over ocean with SeaWiFS: A preliminary algorithm, *Appl. Opt.*, *33*, 443–452, 1994.

Gordon, H. R., Atmospheric correction of ocean color imagery in the Earth Observing System era, *J. Geophys. Res.*, *102*, 17,081–17,106, 1997.

Kaufman, Y. J., Remote sensing of the direct and indirect aerosol forcing, in R. J. Charlson & J. Heintzenberg (Eds.), *Aerosol forcing of climate* (298–332), England: Wiley, 1995.

Kaufman, Y. J., D. Tanré, L. Remer, E. F. Vermote, D. A. Chu, and B. N. Holben, Operational remote sensing of tropospheric aerosol over the land from EOS-MODIS, *J. Geophys. Res.*, *102*, 17,051–17,068, 1997.

King, M. D., Y. J. Kaufman, D. Tanré, and T. Nakajima, Remote sensing of tropospheric aerosols from space: past, present and future, *Bull. Meteor. Soc.*, *80*, 2229–2259, 1999.

King, M. D., Y. J. Kaufman, W. P. Menzel, and D. Tanre, Remote sensing of cloud, aerosol and water vapor properties from the Moderate Resolution Imaging Spectrometer (MODIS), *IEEE Trans. Geosci. Remote Sens.*, *30*, 2–27, 1992.

Martins, J. V., D. Tanré, L. A. Remer, Y. J. Kaufman, S. Mattoo, and R. Levy, MODIS cloud screening for remote sensing of aerosol over oceans using spatial variability, *Geophys. Res. Lett,*, *29*(12), 1–4, MOD 4, 2002.

Remer, L. A., D. Tanré, Y. J. Kaufman, C. Ichoku, S. Mattoo, R. Levy, D. A. Chu, B. N. Holben, J. V. Martins, R. R. Li, and Z. Ahmad, Validation of MODIS aerosol retrieval over ocean, *Geophys. Res. Lett*, *29*(12), 1–4, MOD 3, 2002.

Smirnov, A., B. N. Holben, Y. J. Kaufman, O. Dubovik, T. F. Eck, I. Slutsker, C. Pietras, and R. N. Halthore, Optical properties of atmospheric aerosol in maritime environments, *J. Atmos. Sci*, *59*, 501–523, 2002.

Tanre, D., Y. J. Kaufman, M. Herman, and S. Mattoo, Remote sensing of aerosol properties over oceans using the MODIS/EOS spectral radiances, *J. Geophys. Res.*, *102*, 16,971–16,988, 1997.

Salomonson, V. V., W. L. Barnes, P. W. Maymon, H. E. Montgomery, and H. Ostrow, MODIS: advanced facility instrument for studies of the earth as a system, *IEEE Trans. Geosci. Remote Sens.*, *27*, 145–153, 1989.

Wald, A. E., Y. J. Kaufman, D. Tanré, and B. C. Gao, Daytime and nighttime detection of mineral dust over desert using infrared spectral contrast, *J. Geophys. Res.*, *103*, 32,307–32,313, 1998.

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