Snow and Ice Mask for the MODIS Aerosol Products

Rong-Rong Li, Lorraine Remer, Yoram J. Kaufman, Shana Mattoo, Bo-Cai Gao, and Eric Vermote

***Abstract*—Atmospheric products have been derived operationally from multichannel imaging data collected with the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua spacecrafts. Preliminary validations of the products were previously reported. Through analysis of more extensive time-series of MODIS aerosol products (Collection 4), we have found that the aerosol products over land areas are slightly contaminated by snow and ice during the springtime snow-melting season. We have developed an empirical technique using MODIS near-infrared channels centered near 0.86 and 1.24 μm and a thermal emission channel near 11 μm to mask out these snow-contaminated pixels over land. Improved aerosol retrievals over land have been obtained. Sample results from application of the technique to MODIS data acquired over North America, northern Europe, and northeastern Asia are presented. The technique has been implemented into the MODIS Collection 5 operational algorithm for retrieving aerosols over land from MODIS data.**

***Index Terms*—Aerosol, ice, Moderate Resolution Imaging Spectroradiometer (MODIS), snow.**

I. Introduction

AEROSOL particles suspended in the air can affect climate directly by interacting with solar and terrestrial radiation and indirectly by their effect on cloud microphysics, albedo, and precipitation [1], [2]. In order to understand globally the impact of aerosols on climate, the aerosol characteristics, such as composition, size distribution, and total contents, need to be determined on the global scale. Satellite remote sensing of aerosols can greatly help in achieving this objective. Information on aerosol optical depths over ocean have been derived from imaging data measured with heritage satellite instruments, such as the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (AVHRR), Geostationary Operational Environment Satellites (GOES), and the European meteorological satellites (METEOSAT). These instruments typically have only one or two channels for aerosol retrievals.

The Moderate Resolution Imaging Spectroradiometer (MODIS) instruments onboard the Terra and Aqua spacecrafts with 36 narrow channels covering a wide spectral range between 0.4 and 14 μm are designed for global remote sensing of the land, ocean, and atmosphere [3], [4]. The increased number of channels and spectral information allow the simultaneous retrieval of aerosol optical depth over land [5] and ocean [6] with some information on the particle size distributions. Over land, the main difficulty for aerosol retrievals is to separate the satellite measured apparent reflectance [5] into two components, i.e., the atmospheric component and the land surface component. The difficulty is overcome by estimating surface reflectances of visible channels for dark targets, such as the areas covered by the low reflecting soils and green vegetation, from the 2.13-μm channel data based on correlations in reflectances among these channels [7]. The atmospheric components for the visible channels centered near 0.47 and 0.66 μm for the dark pixels are obtained by subtracting the estimated visible channel surface reflectances from the measured total apparent reflectances. After the isolation of atmospheric contributions, the Level 2 aerosol products with a grid spacing of 10 km $\times$ 10 km over the dark land surfaces are derived. The bright land surfaces, such as the Sahara deserts, and snow and ice-covered surfaces, are mostly excluded during the retrieval process. The Level 2 aerosol products over both the land and ocean are aggregated to produce the Level 3 global aerosol products with a $1^\circ \times 1^\circ$ latitude–longitude grid on daily, eight-day, and monthly-mean basis.

The initial aerosol products derived from the Terra MODIS data and the preliminary evaluations on the products were previously reported in a series of papers [8]–[11]. These first results suggested that the MODIS retrievals were falling within prelaunch estimates of uncertainty. No major flaws were found over different geographical regions based on the analysis of about one year of the Terra MODIS aerosol products.

At present, more than four years of Terra MODIS aerosol products and two years of Aqua MODIS aerosol products are publicly available. Through analysis of the more extensive time series of MODIS aerosol products [12], we have found that, over certain geographic regions, especially during the springtime snow-melting season, the MODIS aerosol optical depths are consistently overestimated due to snow contamination. Through analysis of MODIS data, we have developed an empirical technique using the near-infrared channels centered near 0.86 and 1.24 μm and an 11-μm emission channel to mask out these snow-contaminated pixels. Improved aerosol retrievals have been obtained. Sample results from application

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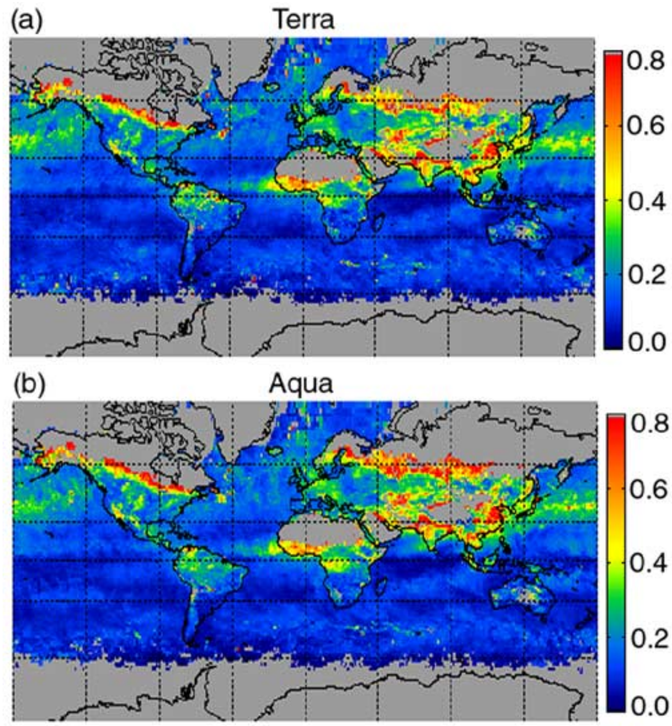


Fig. 1. Sample level 3 monthly-mean global aerosol optical depth images retrieved from (a) the Terra and (b) Aqua MODIS datasets for April 2004.

of the technique to MODIS data acquired over North America, northern Europe, and northeastern Asia are presented.

II. Background

MODIS instruments onboard National Aeronautics and Space Administration's Terra and Aqua satellites have been acquiring data since February 2000 and May 2002 respectively and global aerosol products have been routinely produced. Fig. 1(a) and (b) shows sample Level 3 monthly-mean global aerosol optical depth images retrieved from the Terra and Aqua MODIS datasets for April 2004. The major spatial patterns in the two images are approximately the same. Both images show obviously the large aerosol optical depths over the India Subcontinent due to air pollution for the month. The images also show large aerosol optical depths over the Atlantic Ocean west of the African Continent. The large aerosol optical depths are due to dust transported from the northern African deserts. The two examples demonstrate the success in aerosol retrievals over the two geographic regions using the operational MODIS aerosol algorithms.

However, at the high-latitude regions ($> 45°$N) in North America, northern Europe, and northern Asia where aerosol retrievals were made, large aerosol optical depths (> 0.5) are observed in the Fig. 1 images. Because there were no known aerosol sources at the high latitudes and over an extended longitude range, the large aerosol optical depths were suspected to be due to snow or ice contamination.

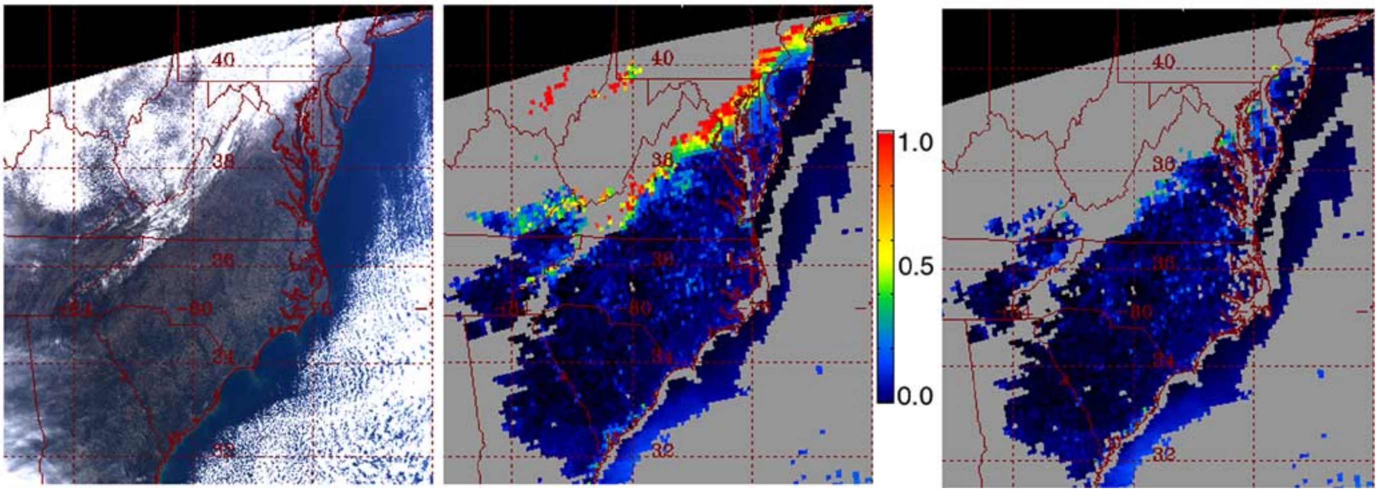
In order to demonstrate clearly the snow contamination in the MODIS aerosol products over land, we show a true-color Aqua MODIS image (red: 0.66-μm channel; green: 0.55-μm channel; and blue: 0.47-μm channel) obtained over North America at 18:25 UTC on February 8, 2004 in Fig. 2(a). The snow or ice covered areas in the upper portion are white. The clear land areas not covered by snow in the scene have a dark brown color. Fig. 2(b) shows the aerosol optical depth image for the scene, which was processed from the aerosol product retrieved with an operational version (Collection 4) of MODIS aerosol algorithm. In order to exclude snow-contaminated pixels from being used for aerosol retrievals, the aerosol algorithm used the standard snow mask (MOD35) built into the MODIS cloud mask [13]. This snow mask is generated with various tests, including a threshold for values of the normalized snow and ice index (NDSI) data [14]. By comparing Fig. 2(b) with Fig. 2(a), it is seen that most of the snow-covered areas were successfully masked out for aerosol retrievals. However, over the snow/nonsnow boundary areas, enhanced aerosol optical depths are observed because of residual snow contamination. In order to improve the operational MODIS aerosol products, we need to develop a technique to mask out the residual snow-contaminated pixels.

III. Method

Over the past decade or so, various algorithms have been developed for remote sensing of snow cover, including mapping of subpixel snow areas, using multichannel satellite imaging data, such as those from Landsat and MODIS, and hyperspectral imaging data, such as the data from the Airborne Visible Infrared Imaging Spectrometer (AVIRIS) [15]. The algorithms include, but are not limited to, the work of Hall *et al.* [16], Vermote *et al.* [17], Salomonson and Appel [18], Nolin *et al.* [19], Kaufman *et al.* [20], and Vikhamar and Solberg [21]. The algorithms are mainly designed for mapping snow-covered areas and for hydrological applications, which do not fully satisfy our needs of masking out snow-contaminated pixels for aerosol retrievals.

The land version of the MODIS aerosol algorithm retrieves aerosols over dark surfaces [5]. Basically, it assumes that the aerosol contributions to satellite measured radiance at 2.13 μm in reflectance units, or the apparent reflectance $\rho^*_{2.13}$, is negligible except for dust. It assumes the surface reflectance for the dark target for the 0.66-μm channel to be approximately equal to half of $\rho^*_{2.13}$, and for the 0.47-μm channel to be about one quarter of $\rho^*_{2.13}$ [7]. Such assumptions are valid for dark soil surfaces and areas covered by green vegetation. The atmospheric contributions to the 0.47- and 0.66-μm channel for the dark pixels are obtained by subtracting the estimated visible channel surface reflectances from the MODIS-measured total apparent reflectances respectively for each of the two channels.

The spectral dependence of snow reflectances are very different from that of vegetation and soils. Fig. 3 shows examples of reflectance spectra of snow, green vegetation, dry vegetation, and soils. The positions and widths of seven MODIS channels are also illustrated in this figure as thick horizontal bars. The reflectance of snow near 2.13 μm is quite small (typically less than 0.05), while the snow reflectances in the visible spectral regions are typically greater than about 0.7. If a MODIS vegetation pixel is contaminated by 5% of snow, the apparent reflectance for the



(a) (b) (c)

Fig. 2. (a) Aqua MODIS image over North America on February 8, 2004. (b) The derived aerosol optical depth image using the operational MODIS aerosol algorithm. (c) The aerosol optical depth image with additional snow masking.

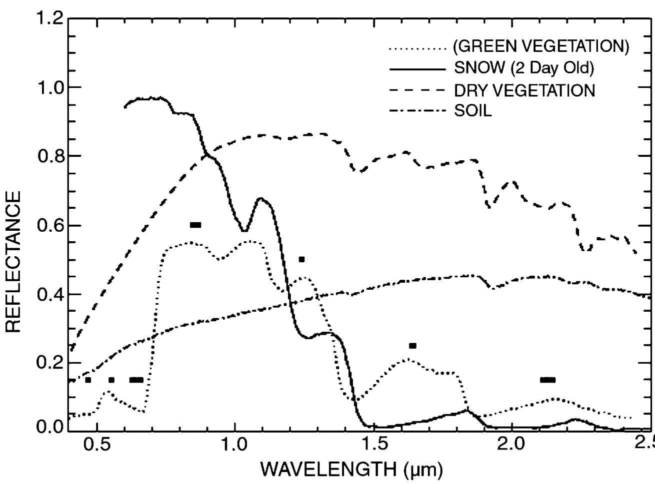


Fig. 3. Sample reflectance spectra of snow, green vegetation, dry vegetation, and soil.

2.13-μm channel would remain about the same, while the apparent reflectances for the 0.47- and 0.66-μm channel would increase by about 0.035 in reflectance unit. The error in retrieved aerosol optical depth would be approximately 0.35 if the snow-contaminated MODIS pixel were not masked out during aerosol retrievals. Therefore, accurate retrieval of aerosols from MODIS data requires dedicated masking of snow-contaminated pixels.

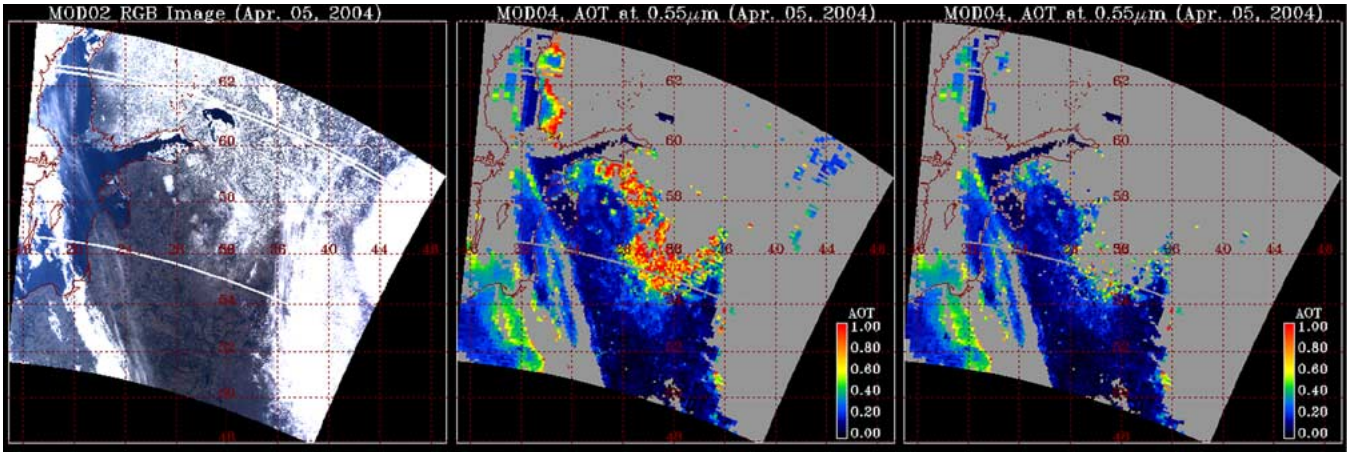
Through analysis of MODIS data, we have developed an empirical technique for masking out the residual snow-contaminated pixels near the snow/nonsnow boundary areas, such as the "red" pixels in Fig. 2(b). The development is based on the spectral properties of snow, vegetation, and soil. As seen from Fig. 3, snow reflectance decreases rapidly with increasing wavelength in the 0.8–1.3 μm wavelength range due to strong ice absorption features centered near 1.05 and 1.24 μm. The reflectance of green vegetation decreases slightly with increasing wavelength due to weak liquid water absorption bands centered near 0.96 and 1.18 μm. The reflectances of soil and dry vegetation typically increase with wavelength in the same spectral region. In view of these spectral differences, we decided to use the normalized difference ratio, which is defined as

$$R = \frac{[\rho^{\star}_{0.86} - \rho^{\star}_{1.24}]}{[\rho^{\star}_{0.86} + \rho^{\star}_{1.24}]} \tag{1}$$

for identifying snow-contaminated pixels. This ratio was previously used for remote sensing of liquid water content of vegetation canopies from AVIRIS data [22]. The apparent reflectance (ρ^*) of a given channel in (1) is calculated from the MODIS L1B radiance according to the definition ρ^* is equal to $\pi L/(\mu_0 E_0)$, where L is the radiance of the channel, μ_0 the cosine of solar zenith angle, and E_0 the extraterrestrial solar irradiance.

The shapes of the four reflectance spectra in the 0.8–1.3 μm wavelength interval in Fig. 3 are very different. The normalized difference ratios, R, for snow, green vegetation, dry vegetation, and soil are 0.53, 0.10, -0.05, and -0.09, respectively. During the development of snow masking technique, we initially selected a ratio threshold R_{th} of 0.2. Pixels with the ratio values greater than R_{th} were assumed to be snow-contaminated. Such selection allowed the masking of most snow-contaminated pixels at high latitudes (>45). However, the selection failed during tests with MODIS data acquired over other geographical regions. It often incorrectly masked out certain vegetated areas in midlatitudes and tropical regions. The multiple scattering of solar radiation at 1.24 μm within these vegetation canopies enhanced liquid water absorption near 1.24 μm (see the green vegetation reflectance spectrum in Fig. 3), and caused the ratio values to be greater than 0.2.

In order to correctly mask out the snow-contaminated pixels and to avoid the incorrect masking of vegetated pixels, we decided to use an additional 11-μm thermal emission channel. After experimenting with different combinations of the ratio threshold (R_{th}) and the 11-μm channel brightness temperature threshold (T_{th}), we selected one set of threshold values, $R_{\text{th}} > 0.05$ and $T_{\text{th}} < 285$ K, for masking out the residual snow-contaminated pixels, such as those "red" pixels in Fig. 2(b). The cloud and cloud-shadow pixels over land should be masked out before using this additional snow-mask algorithm.



(a) (b) (c)

Fig. 4. (a) Terra MODIS image over northern Europe on April 5, 2004. (b) The derived aerosol optical depth image using the operational MODIS aerosol algorithm. (c) The aerosol optical depth image with improved snow masking.

IV. Sample Results

Many tests have been made for masking the residual snow-contaminated pixels with global MODIS data. The results show the algorithm works properly over different geographical regions. Sample results on the application of the technique to MODIS data acquired over North America, northern Europe, and northeastern Asia are described below.

A. North America

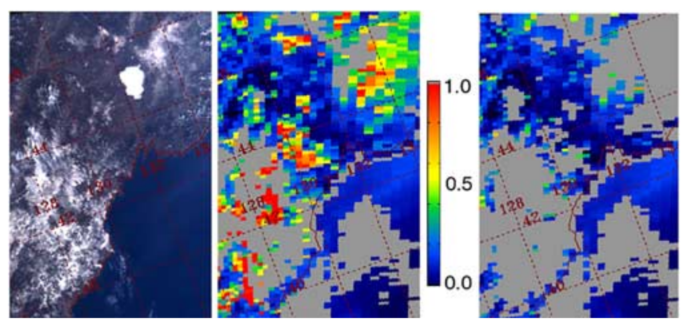
The Aqua MODIS data acquired over North America at 18:25 UTC February 8, 2004 has been used in Section II to illustrate the effect of snow-contamination on aerosol retrievals. Fig. 2(a) shows a true-color image for the MODIS scene. Fig. 2(b) shows the aerosol optical depth image with applications of the standard snow and cloud masks. By comparing Fig. 2(b) with Fig. 2(a), it can be seen that over the snow/nonsnow boundary areas, the aerosol optical depths are unreasonably large due to subpixel snow contamination. Fig. 2(c) shows the image of aerosol optical depths retrieved from the MODIS data with our additional snow mask. The boundary areas with large optical depths in Fig. 2(b) are successfully eliminated out in Fig. 2(c).

B. Northern Europe

Fig. 4(a) shows a true-color Terra MODIS image obtained over northern Europe at 09:20 UTC on April 5, 2004. The snow-covered areas appear white. The clear land areas not covered by snow appear dark brown, while the clear water surfaces appear dark blue. Fig. 4(b) shows the aerosol optical depth image with the use of the standard MODIS snow and cloud masks, Many "red" pixels (due to residual snow contamination) with optical depths greater than about 0.8 are present. Fig. 4(c) is the aerosol optical depth image retrieved from the same scene, but with the additional application of our snow mask. The "red" pixels with large optical depths in Fig. 4(b) are mostly masked out in Fig. 4(c).

C. Northeastern Asia

Fig. 5(a) shows another true-color Terra MODIS image obtained over northeastern Asia at 02:50 UTC on April 5, 2004.



(a) (b) (c)

Fig. 5. (a) Terra MODIS image over northeastern Asia on April 5, 2004. (b) The derived aerosol optical depth image using the operational MODIS aerosol algorithm. (c) The aerosol optical depth image with improved snow masking.

Fig. 5(b) shows the image of aerosol optical depths retrieved using the standard MODIS snow and cloud masks. "Red" pixels with unusually large optical depths are seen. Fig. 5(c) shows the image of aerosol optical depths retrieved by adding our snow mask. Again, "red" pixels with large optical depths in Fig. 5(b) are successfully removed in Fig. 5(c).

V. Discussion and Summary

Through analysis of several years of MODIS aerosol products, we found that the aerosol products over land areas were slightly contaminated by snow and ice, particularly during the snow-melting season over the snow/nonsnow boundary areas. We have developed an empirical technique using MODIS near-infrared channels centered near 0.86 and 1.24 and an 11-μm thermal emission channel to mask out these snow-contaminated pixels. Improved aerosol retrievals have been obtained from both the Terra and Aqua MODIS datasets. The technique has been implemented into the recently updated Collection 5 version of the MODIS operational algorithm for retrieving aerosols over land. It is expected that improved aerosol climatology, particularly over high-latitude regions, will be obtained from MODIS data.

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