An analysis of potential cloud artifacts in MODIS over ocean aerosol optical thickness products

Jianglong Zhang and Jeffery S. Reid
Marine Meteorology Division, Naval Research Laboratory, Monterey, California, USA

Brent N. Holben
NASA Goddard Space Flight Center Data Center, Greenbelt, Maryland, USA

Received 18 April 2005; revised 31 May 2005; accepted 22 June 2005; published 5 August 2005.

[1] Using spatially and temporally collocated MODerate Resolution Imaging Spectroradiometer (MODIS) products and data from seven AErosol RObotic NETwork (AERONET) sun-photometer sites, we explored the relationship between MODIS aerosol optical depth and cloud fraction over remote oceans that have been recently reported in the literature. We show that artifacts such as cloud contamination or adjacency effect contribute to the majority of the relationship in clean marine conditions. This cloud fraction effect could result in a 10–20% overestimation in monthly mean aerosol optical depth or aerosol direct forcing values that are derived using MODIS aerosol products over cloud free oceans. It may also explain some of the high optical depth values derived in the mid-latitude southern oceans. We also suggest that covariances of meteorological phenomenon such as wind or humidity in cloudy regions while logical might only account for a minor portion of the ensemble relationship. **Citation:** Zhang, J., J. S. Reid, and B. N. Holben (2005), An analysis of potential cloud artifacts in MODIS over ocean aerosol optical thickness products, *Geophys. Res. Lett.*, *32*, L15803, doi:10.1029/2005GL023254.

1. Introduction

[2] The operational MODIS (MODerate Resolution Imaging Spectroradiometer) level II aerosol product (MOD04 for Terra, MYD04 for Aqua), provides daily estimation of aerosol optical properties over the globe and has become a mainstay of aerosol/climate research [*Kaufman et al.*, 2002]. At a spatial resolution of 10 km, MOD04/MYD04 contains the spectral aerosol optical depth (τ_λ), the fraction of fine mode to total aerosol optical depth (η), and other related aerosol optical properties [*Remer et al.*, 2005]. The MODIS τ_λ product has been examined through various studies, with estimated uncertainty levels of $0.05 \pm 0.20\ \tau_\lambda$, and $0.03 \pm 0.05\ \tau_\lambda$ [*Remer et al.*, 2005] over land and ocean, respectively.

[3] Over oceans, the MODIS cloud clearing is first performed at a 500 m spatial resolution. The best (e.g. cloud and glint free) pixels are chosen and are averaged, and aerosol retrieval is made for a 10 km resolution to improve the signal to noise ratio [*Remer et al.*, 2005]. In order to screen out cloudy pixels, the MODIS aerosol-retrieving algorithm uses a 3 × 3 standard deviation (STD) test [*Martins et al.*, 2002]. If the STD of reflectance (0.55 μm at a spatial resolution of 500 m) of a 3 × 3 box is greater than 0.0025, that center pixel of the box is identified as cloudy. In addition, the 1.38 μm channel and other IR channels are used to detect "homogenous thin cirrus and high cloud." This 3 × 3-STD cloud detection scheme is different from the standard MODIS cloud-masking product (MOD35) that uses as many as 14 of 36 channels and has extensive spectral checks [*Ackerman et al.*, 1998]. The MOD35 product is clear sky conservative (i.e., error towards more clouds), and therefore, thick aerosol features could be misidentified as clouds [*Martins et al.*, 2002]. To mitigate this misclassification, the MODIS 3 × 3-STD test is currently implemented operationally in the MODIS MOD04 and MYD04 aerosol-retrieving algorithm. The cloud fraction we mentioned hereafter refers to this MODIS 3 × 3-STD algorithm.

[4] Recently, *Loeb and Manalo-Smith* [2005] showed an interesting correlation where MODIS τ_λ increases with increasing cloud fraction. A similar relationship is also found using Advanced Very High Resolution Radiometer (AVHRR) data [*Loeb and Manalo-Smith*, 2005]. As discussed by *Loeb and Manalo-Smith* [2005], the relationship of τ_λ vs. cloud fraction could be explained as either the result of real physical phenomenology (e.g. variations in winds and relative humidity/hygroscopicity that correlate with clouds) or as artifacts due to cloud contaminations (e.g. sub-pixel size clouds). The τ_λ and cloud fraction relationship could also be due to transport covariance where large scale aerosol advection is associated with fronts and waves [*Reid et al.*, 2004], or adjacency effects where cloud free pixels are brightened by reflected light off of nearby clouds [e.g., *Wen et al.*, 2001]. This problem is important because if due to artifact, it could significantly bias a great deal of over water τ_λ data and consequently confound remote sensing studies of aerosol direct and indirect climate forcing. Conversely, if this correlation is real, it could have an important impact on interpretation of aerosol climate forcing studies. Using MODIS aerosol products and AErosol RObotic NETwork (AERONET) sun-photometer data, we reproduced the correlation and tested the potential reasons for its existence. Here we are concerned with only the clean marine boundary layer to isolate the cloud artifact contribution to this relationship, and leave the issue of transport covariance to a future publication.

2. Methods and Results

[5] An example of the global ocean MODIS τ_λ – cloud fraction relationship is shown in Figure 1 for the month of Sep. 2004 for MOD04 and MYD04 data. The MOD04/MYD04 data over oceans contains τ_λ at seven wavelengths (0.47, 0.55, 0.67, 0.87, 1.2, 1.6 and 2.1 μm) and "cloud fraction" of a given 10 km granule. Note that although mostly representing clouds, the parameter "cloud fraction" reported in MOD04/MYD04 is the fraction of pixels not used in the retrieval and includes those pixels discarded due

0094-8276/05/2005GL023254$05.00

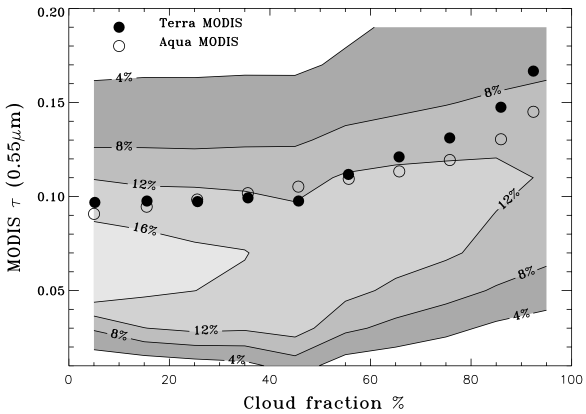

Figure 1. MODIS τ vs. cloud fraction for September 2004 for MOD04 and MYD04. The shaded area showed the data density distributions that are normalized at every 10% cloud fraction.

to clouds, glint, sediments and suspicious radiances. Data was selected from remote oceans (140°–180°W, 0°–90°S) to avoid major aerosol episodes originated from continental inland, and was averaged for every 10% cloud fraction. As shown in Figure 1 the purported bin averaged MOD04 (solid dots) τ at 0.55 µm ($\tau_{0.55\mu m}$) is increasing as cloud fraction increases. From cloud fractions of 1% to 80%, the averaged $\tau_{0.55\mu m}$ increases from 0.095 to 0.135 (or ~40%). The slope of $\tau_{0.55\mu m}$ vs. cloud fraction becomes steeper for cloud fractions larger than 80% so that a 10% change in cloud fraction introduces a 0.02 change in $\tau_{0.55\mu m}$. The change of $\tau_{0.55\mu m}$ as the function of cloud fraction is larger than the reported 0.03 ± 0.05 τ_λ uncertainty of the product by *Remer et al.* [2005]. The shaded areas in Figure 1 showed the data density distribution computed for every 10% change in cloud fraction with a step of 0.02 changes in $\tau_{0.55\mu m}$. The data density distribution showed a similar pattern throughout the MODIS τ_λ – Cloud fraction population indicating that the relationship is a systematic phenomenon rather than being caused by few outlying points. Also shown in Figure 1 are bin averaged $\tau_{0.55\mu m}$ from Aqua MYD04 data (open circles), and a similar but less steep slope is also observed. To simplify discussions, in the remainder of the sections, our studies focused on using data from Terra MODIS (MOD04).

[6] Figure 2a is a true color image that shows examples of both cloud fields and clear regions from the remote ocean 16:15 UTC, Feb., 20, 2005 granule. This is to minimize possible aerosol contaminations originating from continents. Figures 2b and 2c shows the MOD04 τ at 0.55 µm ($\tau_{0.55\mu m}$) and the MODIS brightness temperature (BT) from the 12 µm channel, respectively. Indicated in Figure 2a and 2b, larger $\tau_{0.55\mu m}$ values of up to 0.2 and higher are found over cloud edges while the $\tau_{0.55\mu m}$ values are less than 0.1 for the cloud free oceans. Clearly, whether physical or not, this effect is relegated strictly to the region around cloud edges. Notice the BT values of cloud free oceans are on the order of 275–277 K (above freezing), while most cloud pixels have BT values below the freezing point. Especially, a layer of thin cloud was observed at the left bottom part of the image that has the averaged BT value of around 270 K with the minimum BT of less than 260 K (likely above any aerosol layers in this remote region). The cloud free $\tau_{0.55\mu m}$ values are less than 0.1 one granule away from the boundary (10 km); within the cloudy regions $\tau_{0.55\mu m}$ values could be 0.2 or higher (indicated by the circles). The sharp increase of more than 100% (from <0.1 to ≥0.2) in $\tau_{0.55\mu m}$ values for two adjacent granules with cold clouds (i.e., non-boundary layer) is less likely to be explained by wind speed (i.e., salt production) or hydroscopic growth.

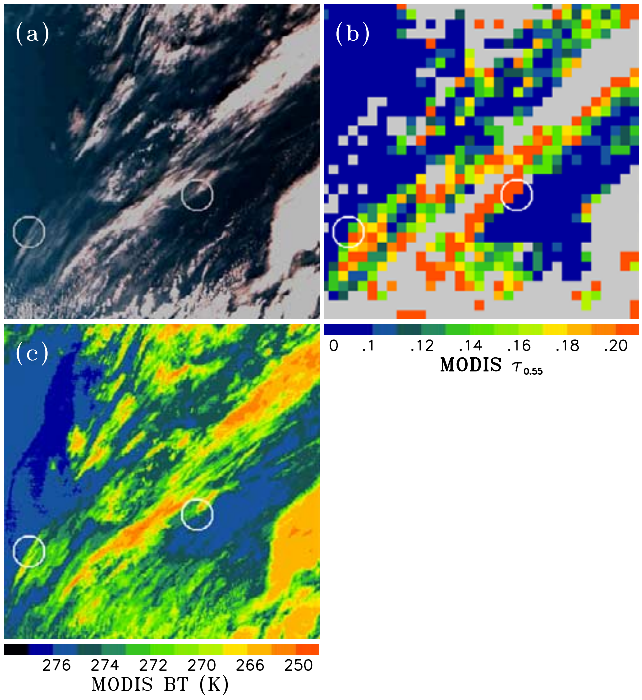

Figure 2. (a) A three-band overlay of the 1-km MODIS visible image; (b) the 10-km MOD04 aerosol optical depth at 0.55 µm ($\tau_{0.55\mu m}$); and (c) the 1-km MODIS brightness temperature (BT) from 12 µm channel. White circles showed regions around cloud edges with large $\tau_{0.55\mu m}$ variations.

3. Implications

[13] We examined the correlation between MODIS τ_λ and cloud fraction that has been reported by a recent paper [*Loeb and Manalo-Smith*, 2005]. Our study suggest that much of this relationship is a systematic phenomenon, and conclude that 60%–90% of the relationship is introduced by artifacts such as cloud contamination and cloud brightening effects. Using the frequency distribution of MOD04 cloud fraction averaged from one month of MOD04 data (Sep. 2004) and following the methodology of *Zhang et al.* [2005], we estimated that the monthly averaged $\tau_{0.55\mu m}$ value is overestimated by 10–20% due to these artifacts. This overestimation will further introduce a 10–20% overestimation in the cloud free aerosol direct forcing value over oceans that are estimated using MOD04 data [e.g., *Loeb and Manalo-Smith*, 2005; *Zhang et al.*, 2005]. Additionally, these artifacts in aerosol retrievals may partially explain the high τ_λ cases observed around the southern hemisphere mid-latitude oceans (i.e., roaring 40's) in MOD04/MYD04 aerosol product [e.g., *Remer et al.*, 2005].

[14] This study also indicates that about 10–40% of the increase could not be explained by the artificial effects and might be caused by monthly variations in the MODIS τ and cloud fraction relationship. This leaves 10–40% of the correlation in clean marine conditions to be from possible physical phenomenon such as humidity as suggested by [*Loeb and Manalo-Smith*, 2005]. Clearly there is a need to examine this further.