Comparison of Three Years of Terra and Aqua MODIS Aerosol Optical Thickness Over the Global Oceans

Lorraine A. Remer, Yoram J. Kaufman, and Richard G. Kleidman

***Abstract*—Far from land-based sources, long-term statistics of aerosol optical thickness (AOT) over the oceans is expected to have a negligible diurnal signal. Therefore, comparing large-scale regional and global mean AOT derived independently from Terra and Aqua Moderate Resolution Imaging Spectroradiometer data will provide a measure of the precision of the overall product. Three years of overlapping records of quality and pixel-weighted level-3 statistics were analyzed. These data show that the instruments' measurement of the long-term global annual mean agree to within 1% or 0.0014-in optical thickness with an rms difference of 0.004, which is calculated from global monthly means. Two-thirds of the regions have long-term annual regional means that agree to within 2.5%. The highest regional difference is 5%, which is found over the southern circumpolar ocean. Other aerosol parameters such as particle size will show larger differences. Datasets that are not quality and pixel weighted may also show larger differences.**

***Index Terms*—Aerosols, aerosol optical thickness (AOT), Aqua, Moderate Resolution Imaging Spectroradiometer (MODIS), remote sensing, satellite, Terra, time series.**

I. Introduction

EACH day, NASA's twin Moderate Resolution Imaging Spectroradiometers (MODIS) aboard the Terra and Aqua satellites observe the Earth independently. From these observations, the MODIS science team derives aerosol optical thickness (AOT), which is a measure of the total column aerosol loading in the atmosphere [11]. The two MODIS instruments and the aerosol algorithms applied to the MODIS-measured radiances are designed to be identical. In the absence of a diurnal process that would influence aerosol properties, we would expect the long-term statistics derived from Terra and Aqua MODIS aerosol products to be the same.

Locally, diurnal patterns in aerosol parameters exist, but these patterns should be absent in long-term statistics over the ocean. Aerosol emissions over the land may have a strong diurnal signal, e.g.; emissions from biomass burning [10]. However, over open oceans far from sources, we expect a negligible diurnal signal in total column aerosol amounts [13], and for global average, we expect less than 2% difference between the measurements made at Terra or Aqua observation times and the true daily average [8]. Therefore, differences between Terra and Aqua in long-term statistics of MODIS aerosol products represent the precision of deriving these products, rather than revealing a true diurnal signal.

By precision, we mean the ability of two independent instruments of the same design to produce the same results for the same quantity. In terms of MODIS aerosol products, precision is a function of both the instrument characteristics and the sensitivity of the retrieval algorithms to these characteristics.

Instrument calibration will affect MODIS precision, as was demonstrated previously with twin Advanced Very High Resolution Radiometer (AVHRR) sensors [6]. The radiometric calibration of the reflective channels on both the Terra and Aqua MODIS instruments characterized to 2%. However, despite measuring within specifications, the two instruments are different. For example, Terra has 11 noisy and one inoperable detector (out of a possible 490), while Aqua's channels are all good, except the 1.6-μm channel that has many dead detectors [1], [15]. These differences and others can affect the aerosol inversion.

The different equatorial crossing times of the two satellites, with Terra crossing at 10:30 local time and Aqua at 13:30 local time, may also introduce differences in the retrieved aerosol products. This would be due to different viewing geometries returning different distributions of scattering angles. If the two scattering angle distributions are sufficiently different, systematic differences arising from errors in the assumed phase function can propagate into the retrieved products.

II. Background

Several prior comparisons of Terra and Aqua MODIS AOT show small differences between the two satellites. Ichoku *et al.* [4] suggest that, over the oceans, the mean Aqua AOT at 0.55 μm (τ_{550}) is 7%–19% higher than the same from Terra, depending on the Angstrom exponent. For a low Angstrom exponent, Aqua AOT is 0.25, while Terra is only 0.21. For a moderate AOT, Aqua is 0.16 and Terra is 0.15. Kaufman *et al.* [9] find the opposite. They show Terra values are 2%–17% higher than Aqua, depending on the optical-thickness bin. In the highest AOT bin, Aqua AOT is 0.55, while Terra is 0.59. In another AOT bin, the values are much closer, with the Aqua AOT $= 0.107$, while Terra AOT $= 0.109$. The Ichoku *et al.* [4] study is based on a three-year dataset (2000–2003) of Terra and Aqua points collocated in space and time with Aerosol Robotic Network (AERONET)

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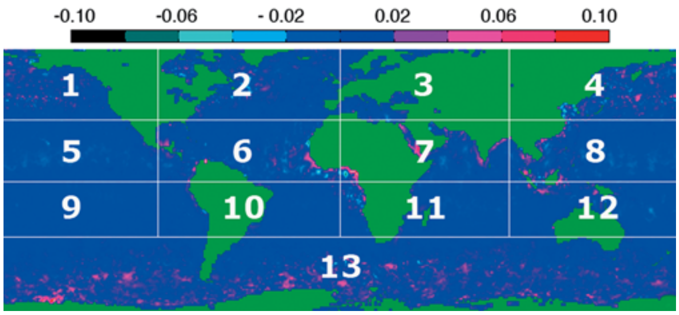

Fig. 1. Definition of the 13 regions superimposed on a background representing the difference in AOT, as derived from Terra MODIS and Aqua MODIS for a three-year mean dataset (October 2002–October 2005). Positive values indicate that Terra is higher. The larger differences along the continental boundaries may represent true diurnal signals due to land–sea breeze circulations or other continental effects.

observations [3], but not collocated with each other. In their study, Terra and Aqua observations do not need to be made on the same day or even in the same month. In fact, the Terra dataset includes data from 2000 to mid-2002 that occurred prior to Aqua's launch. Kaufman *et al.* [9] base their study on one year of data (2002–2003), which are also collocated in space with AERONET sites. However, they compare monthly mean values, requiring at least five days of observations from each satellite to be included in the study. The five days do not have to be the same ones, but at least data from the same months and years are analyzed together. Ignatov *et al.* [7] analyze only nine days of global data, but agree with Kaufman *et al.* [9] that Terra's global mean τ is higher than Aqua's by 7% (0.009 in optical-thickness units). In these previous studies, comparisons between platforms were either spatially limited to a few dozen AERONET locations [4], [9] or temporally limited to a nine-day period [7]. In this letter, we will explore the long-term, global, and broad regional differences between the Terra and Aqua MODIS-derived AOT.

III. Data

We use the MODIS Collection 004 level-3 daily 1° data (MOD08_D3 and MYD08_D3) to derive monthly mean values of the quality-weighted AOT over the oceans at 0.55 μm for the globe and for 13 broad regions defined in Fig. 1. The monthly mean values are weighted by the number of pixels in the 1° box, so that the final monthly mean value represents the true mean of the globe or region as if the mean had been calculated using the retrieved product at its native resolution ($\sim$ 10 km). Observations do not need to be collocated in time, and in any particular square, retrievals are not necessarily from the same day; but broad spatial and temporal averaging domains should mitigate inconsistencies.

In Fig. 1, we see that the differences in the AOT between the two satellites are very small over open ocean. Near continental boundaries and in the southern ocean (region 13) the differences increase. Rather than speculating on the cause of these differences, either a true diurnal signal or artificially introduced by instrument and retrieval, we proceed to quantify their effect on long-term statistics.

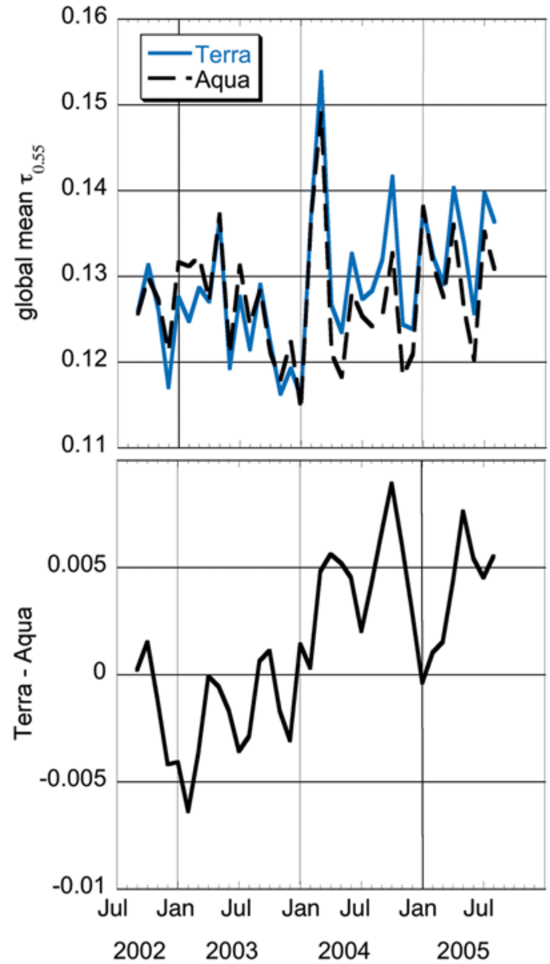

Fig. 2. Time series of global monthly mean AOT ($\tau_{0.55}$) over the oceans from the Terra and Aqua MODIS sensors for a 36-month period (top). The bottom panel shows the monthly differences between the two sensors.

IV. Results

Fig. 2 shows the time series of Terra and Aqua global mean AOT, with the difference between the two curves plotted below. Clearly, Terra and Aqua are reporting the same quantity with nearly the same magnitude and tracking together through monthly and annual variations. Aqua begins slightly higher than Terra, disagreeing with the more limited datasets of both Kaufman *et al.* [9] and Ignatov *et al.* [7] constructed during this early period. Later, there is a reversal, and Terra is slightly higher than Aqua. Note that this trend and reversal are in part due to a slight algorithm change implemented in January 2004 that was applied to the entire Aqua time series by reprocessing, but only to Terra's processing from that point forward. The algorithm change will affect the retrieval of size parameters more severely, but we also see it here as noticeable, yet less than 0.01 increase in retrieved Terra AOT. We use the difference between the Terra and Aqua results to give us the precision of determining the global AOT from MODIS. Over the entire time series, the average precision is 1% or 0.0014 optical thickness. The rms difference between the two sensors based on the individual monthly means is 0.004 in optical thickness.

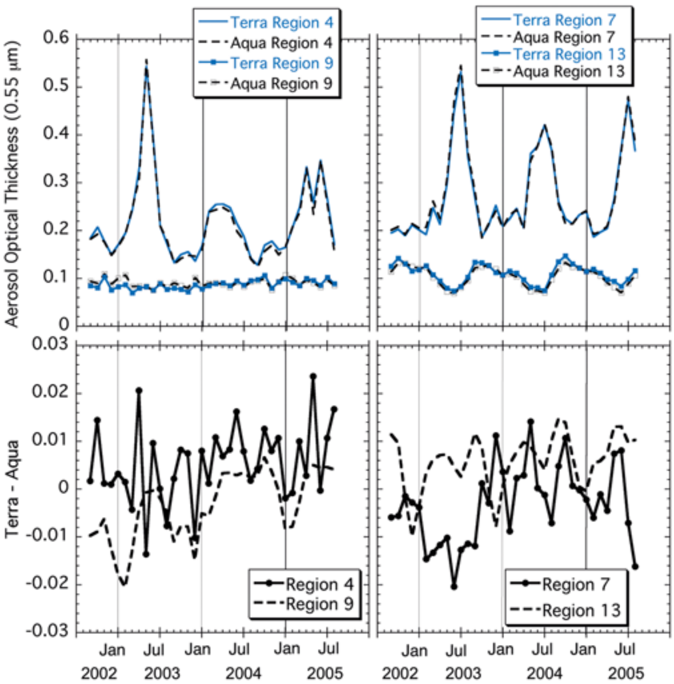

Fig. 3. Time series of regional monthly mean AOT ($\tau_{0.55}$) over the oceans from the Terra and Aqua MODIS sensors for four selected regions defined in Fig. 1. The bottom panels show the monthly differences between the two sensors. Region 4 is the northwest Pacific off the coast of Asia that is affected by pollution, desert dust, and biomass burning, depending on the season. Region 7 is located over the Arabian Sea and has summer dust and winter pollution with the highest overall AOT of any region. Region 9 is the most pristine region and is located over the eastern tropical Pacific. Region 13 is the southern circumpolar ocean.

Time series and difference plots for 4 of the 13 regions defined in Fig. 1 are shown in Fig. 3. Even though the differences between Terra and Aqua results are larger than in the global average, we still see the two instruments producing results that track together over the course of the time series. The midlatitude regions, both Northern and Southern Hemispheres, show Terra biased higher than Aqua (including regions 4 and 13 shown in the figure). Region 13, which is the southern circumpolar ocean, shows the highest positive bias for Terra of 5% (0.0058 in optical-thickness units). The tropical regions of both hemispheres show the overall negative bias with Terra less than Aqua. Region 9, which is the pristine southern tropical Pacific, shows the highest negative bias for Terra of 4% (0.0034 in optical-thickness units). Two-thirds of the regional monthly mean differences are less than 2.5% or 0.007 optical thickness. The largest rms difference between the two sensors for any of the regions, which is based on individual monthly means, is 0.009.

Fig. 4 shows the relationship of the Aqua monthly regional mean AOT as a function of the corresponding Terra value. The 36 months for each of the 13 individual regions are plotted. The good agreement between Terra and Aqua seen in the time series is reflected here by the tight regression ($R = 0.995$) and nearly unit slope ($\text{slope} = 0.996$).

V. Discussion

This analysis of long-term statistics of AOT derived from MODIS on the Terra and Aqua satellites demonstrates the ex-

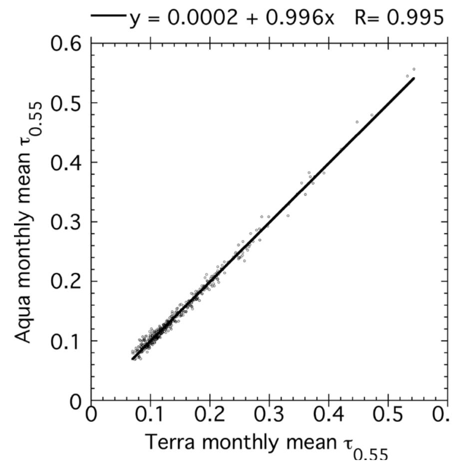

Fig. 4. Scatterplot of monthly regional mean AOT at 0.55 μm from Aqua MODIS against the same from Terra MODIS. The regression equation and correlation coefficient are given above. Thirteen regions and 36 months of data yield 468 points in the plot.

cellent agreement between the two instruments. The remaining small differences between the platforms suggest a precision in the MODIS determination of long-term global-mean AOT of 1% or 0.0014 optical thickness. Determination of long-term regional-mean AOT is almost as precise (2.5%), with the exception of a few regions noted in the text where the difference is 5%. Terra is higher than Aqua in midlatitude regions and lower than Aqua in the tropics. These estimates of precision should be taken as conservative because some differences may be attributable to true diurnal differences in the aerosol.

The differences calculated here from global data are smaller than the numbers calculated over coastal AERONET sites [4], [9], which may experience greater diurnal effects because of the proximity to land. The long-term differences calculated here are also less than those calculated from the short-term global study [7]. Short-term differences between Terra and Aqua will be larger than the longer term statistics reported here. A random sampling of ten days suggests that daily differences of global means will be 5%–8%, corresponding to the 7% of [7].

Averages of a month or longer allow MODIS to view a location with a broad distribution of viewing geometry and scattering angles [12]. Despite differences in viewing geometry introduced by the different equator crossing times, the broad monthly distributions overlap sufficiently to mitigate differences arising from errors in the assumed phase function. Using the Remer and Kaufman [12] estimate of AOT errors as a function of the scattering angle, we find that the global annual mean error introduced by different equator crossing times is 0.18%, significantly less than the 1% precision calculated here. Even in regions dominated by desert dust (i.e., region 6 in northern summer) where nonsphericity introduces geometry-dependent errors, little difference between Terra and Aqua is evident in the monthly mean AOT.

The MODIS aerosol algorithm produces two major products in the over-ocean retrieval. One is the optical thickness, which is analyzed here. The other is a measure of the aerosol particle size (i.e., Angstrom exponent or fine-mode fraction). A good cross-platform agreement in optical thickness does not guarantee good agreement in aerosol-size parameter. Satellite-derived aerosol-size parameters are especially sensitive to small perturbations in sensor spectral calibration [5]. We expect to find more uncertainty in general and less agreement across platforms in the analysis of the size parameter [14].

Precision is not the same as accuracy. A measurement system can make very precise measurements that are inaccurate. Accuracy of the MODIS determination of AOT should be determined from careful collocation of individual observations with reliable ground-based measurements [11]. Such validation exercises using only Terra data show that the uncertainty of MODIS retrievals of optical thickness over oceans is $\Delta\tau = \pm 0.03 \pm 0.05\tau$. The precision determined from the differences between Terra and Aqua satellites easily falls within the bounds of the expected error. The excellent agreement in the results of the two independent satellite instruments, each with their own orbit and calibration issues, adds overall confidence to the climate-scale MODIS product.

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