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# Is the top of atmosphere dust net radiative effect different between Terra and Aqua?

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[1] We assess the difference in Top of Atmosphere (TOA) cloud-free Net Radiative Effect (NRE) of dust aerosols between the Terra and Aqua satellites using three years of collocated Moderate Resolution Imaging SpectroRadiometer (MODIS) and the Clouds and the Earth's Radiant Energy System (CERES) data over the Atlantic Ocean [0–30°N, 10–60°W]. The dust aerosol optical thickness at 0.55 $\mu$m ($\tau_{\rm dust}$) was first separated from the total aerosol column aerosol optical thickness ($\tau$) and our results indicate that the Terra minus Aqua difference for both $\tau$ and $\tau_{\rm dust}$ is approximately 10%, with Terra values generally being slightly higher. The resulting difference in TOA NRE from dust aerosols is less than 1 Wm$^{-2}$. The difference between Terra and Aqua NRE lies well within previously reported uncertainties indicating that data from either satellite can be used interchangeably if independent adjustments for diurnal effects and clear-sky sample biases are made.
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## 1. Introduction

[2] Satellite data has enabled significant progress in characterizing the Direct Radiative Effect (DRE) and Direct Climate Forcing (DCF) of aerosols [*Yu et al.*, 2006]. The radiative effect of 'natural aerosols' such dust and marine is called DRE, whereas DCF is the contribution from anthropogenic aerosols. However, most of these studies used Terra satellite data which is in a sun synchronous polar orbit with a descending equatorial crossing time of ~10:30 am. In these satellite-based studies, primarily over the global oceans, the common approach is to take the aerosol optical thickness retrievals from the Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and then assuming that this value is representative of the entire day, radiative transfer (RT) calculations are performed to compute diurnally averaged top of atmosphere (TOA) solar radiative fluxes. In these RT calculations the surface, atmospheric, and aerosol properties are usually assumed to be constant during the day and calculations are simply averaged over different solar zenith angles. For shortwave calculations, these approaches require wavelength dependent (usually between 0.2 to 4.5 $\mu$m) surface and aerosol properties such as surface albedo, aerosol optical thickness, single scattering albedo, and aerosol asymmetry parameter [e.g., *Remer and Kaufman*, 2005; *Bellouin et al.*, 2005]. Other studies utilize the Terra-MODIS aerosol optical thickness values and use broadband Clouds and the Earth's Radiant Energy System (CERES) measurements to infer TOA fluxes thereby bypassing RT calculations [e.g., *Zhang et al.*, 2005]. However, even these values are valid for only the satellite overpass time and approximations are required to convert these instantaneous values to diurnally averaged values. In the MODIS-CERES approach even if one MODIS pixel within the CERES footprint is cloud-contaminated, they are removed thereby creating sample biases that must be accounted for when reporting final results [*Loeb and Manalo-Smith*, 2005; *Zhang et al.*, 2005].

[3] Identical MODIS and CERES instruments also exist on the Aqua satellite which is also on a sun synchronous polar orbiting platform but with an ascending equatorial crossing time of ~1:30 p.m local time. Since Terra and Aqua have identical MODIS and CERES instruments, we can obtain the 'morning' and 'afternoon' aerosol optical thickness and the corresponding DRE of dust aerosols, thereby providing a pseudo measure of diurnal variability even though their overpass times are only 3 hours apart. Although geostationary satellites are best suited for capturing high temporal variations of aerosols and their properties, *current sensors* on these geostationary satellites, especially over the Western hemisphere, are not well suited for aerosol research due to the limited number of channels and the lack of visible channel calibration.

[4] Prior to the launch of the Terra and Aqua satellites, *Kaufman et al.* [2000] used Aerosol Robotic Network (AERONET) data from 50–70 locations to address the question of whether aerosol measurements from Terra and Aqua will represent the daily aerosol burden. They used AERONET aerosol optical thickness data and separated it into Terra (10:00–11:30 local time), Aqua (12:30–14:00) and the whole day average and concluded, that for climate applications, Terra and Aqua can independently represent the daily average to within 2% annual average error, although the diurnal variations could be significant near aerosol source regions. A later study by *Ignatov et al.* [2006] used actual Terra and Aqua data for a one week period in October 2002 and noted that the Aqua aerosol optical thickness were, on average, lower than the corresponding Terra values. Although the difference was small, it proved statistically significant and no single cause could be isolated. In a comprehensive study, *Ichoku et al.* [2005] examined the Aqua-Terra aerosol optical thickness differences between June 2002–December 2003 and report that over the mid-Atlantic Ocean [0–30°N, 15°W–50°W] the average difference was 0.004. They further concluded that although there are differences between Terra and Aqua aerosol optical thickness values over the global oceans,

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**Table 1.** Dust Aerosol Optical Thickness and Direct Radiative Effect (in $Wm^{-2}$) for Aerosols From Terra and Aqua

| | Terra | Aqua |
|---|---|---|
| | *Total Aerosol* | |
| CERES AOT | 0.24 | 0.22 |
| MODIS AOT | 0.30 | 0.30 |
| SW $F_{clr}$ | 76.3 | 75.8 |
| LW $F_{clr}$ | 287.7 | 291.1 |
| Cloud fraction | 0.60 | 0.61 |
| | *Dust Aerosol* | |
| CERES $AOT_{DUST}$ | 0.16 | 0.15 |
| MODIS $AOT_{DUST}$ | 0.24 | 0.23 |
| Instantaneous SWRE | −12.74 | −11.72 |
| Adjusted SWRE | −7.77 | −7.73 |
| Instantaneous LWRE | 1.52 | 1.07 |
| Adjusted LWRE | 0.93 | 0.74 |
| Net radiative effect | −6.87 | −6.99 |

Note that the dust NRE statistics are calculated only where dust aerosols exist, which accounts for approximately 50% of the total sample.

there is no consistent morning to afternoon increase or decrease in aerosol loading. In this paper, we take this comparison a step further and use combined MODIS and CERES data (CERES-SSF) to examine the differences between top of atmosphere DRE independently derived from Aqua and Terra observations. We not only examine the Terra-Aqua differences in total aerosol DRE but how the dust aerosol optical thickness and the DRE differ between the two satellites.

[5] To accomplish this task, we use nine months of CERES-SSF data from the Terra and Aqua satellites between 2003 to 2005 for the months of June, July, and August over the tropical Atlantic Ocean [0–30°N, 10–60°W]. The total column AOT ($\tau$) is separated into the dust component ($\tau_{dust}$) based on an algorithm developed by *Kaufman et al.* [2005], which are then used to calculate the DRE of dust for both satellites. Now that both Terra and Aqua have been in orbit simultaneously for several years, we will reexamine the *Kaufman et al.* [2005] assumption that Terra and Aqua $\tau$ (and thereby DRE) data can be used interchangeably, or whether a significant bias exists from one satellite or the other.

## 2. Data and Methods

[6] The data and methods used here are similar to those described by *Christopher and Jones* [2007] in their calculation of the DRE of dust aerosols in the tropical Atlantic. That study used the MODIS and CERES merged data set (CERES-SSF) to determine the net radiative effect (NRE) that is a sum of the shortwave DRE (SWRE) and the longwave DRE (LWRE). Data from the tropical Atlantic domain were used since they were readily available from the previous research, and since $\tau_{dust}$ during June–August is some of the highest on the globe [*Prospero et al.*, 2002]. Since the Aqua satellite was launched much later than Terra (2002 vs. 1999), only continuous June, July, and August data exist for both satellites between 2003 and 2005. The total DRE is derived by subtracting CERES TOA cloud-free fluxes from clear sky values ($F_{clr}$) that are cloud *and* aerosol free [*Zhang et al.*, 2005].

[7] The $\tau_{dust}$ is derived using the method explained by *Kaufman et al.* [2005] and implemented in a slightly modified form as outlined by *Christopher and Jones* [2007]. This method derives $\tau_{dust}$ using a mathematical relationship that incorporates observed and assumed fine mode fraction for each aerosol type. The dust DRE is then calculated by taking the ratio of $\tau_{dust}$ to $\tau$ and multiplying it by the total DRE on a pixel-by-pixel basis. The Terra/Aqua $\tau$ and DRE are obtained only during the time of the satellite overpass and these values are converted to daily averages based on methods outlined in *Remer and Kaufman* [2005]. The CERES pixel size is much larger than the MODIS and since only CERES cloud-free pixels are used in the analysis, the $\tau$ values obtained from the CERES footprint will always be smaller than the MODIS resulting in sample biases. We correct for this sample bias based on methods outlined by *Zhang et al.* [2005] and *Christopher and Jones* [2007]. To maintain the independence of the two data sets, the bias adjustments are calculated separately for each using corresponding Terra or Aqua daily averaged $\tau$ values.

## 3. Results

[8] On average, Aqua derived CERES-SSF $\tau$ were between 5 and 10% less than Terra derived values over the same spatial and temporal domain (Table 1). The largest difference occurs where $0.35 < \tau < 0.50$ (Figure 1a). In this $\tau$ range, the normalized probability of $\tau$ occurrence is consistently less for Aqua $\tau$ when compared to Terra. The low values that are present in Aqua $\tau$ are also present for each individual year in addition to the three-year average. Despite the overall low values, Terra and Aqua $\tau$ do remain highly correlated with a linear correlation coefficient of 0.72. The $\tau_{dust}$ variability increases slightly when comparing Terra and Aqua values resulting in correlation of only 0.62. However the Aqua $\tau_{dust}$ does remain slightly less than its Terra counterpart (Table 1).

[9] Interestingly, Terra and Aqua daily averaged total MODIS $\tau$ are quite similar with no significant differences present with data from either sensor (Table 1). The $\tau_{dust}$ derived from Aqua and Terra is also very highly correlated. Note that the daily averaged MODIS $\tau$ is a completely independent dataset, with a separate spatial and temporal data distribution when compared to the CERES-SSF data. As a result, the bias adjustment required for Aqua was greater than the corresponding Terra value (0.053 vs. 0.043).

[10] Aqua's later overpass time results in higher clear sky outgoing LW flux due to generally higher ocean surface temperatures in the afternoon hours (Table 1). Only minor differences exist between Terra and Aqua SW $F_{clr}$ values. Cloud cover, defined using the CERES cloud fraction, is generally similar for both satellites with Aqua having a slightly higher average cloud fraction (Table 1). This may be due an increased likelihood of clouds in the afternoon hours corresponding to the Aqua overpass time, but the magnitude of this difference is only 1%.

[11] The Aqua-Terra CERES-SSF $\tau$ further manifests itself by reducing Aqua dust NRE compared to Terra (Table 1 and Figure 1b). The instantaneous Terra SWRE was $-12.7$ $Wm^{-2}$ while Aqua SWRE was only $-11.7$ $Wm^{-2}$, a difference of approximately 15%. This is slightly greater than the Terra-Aqua $\tau$ difference of ~10 %. The SWRE over this domain has a large spatial variability (±10 $Wm^{-2}$), which is substantially greater than the

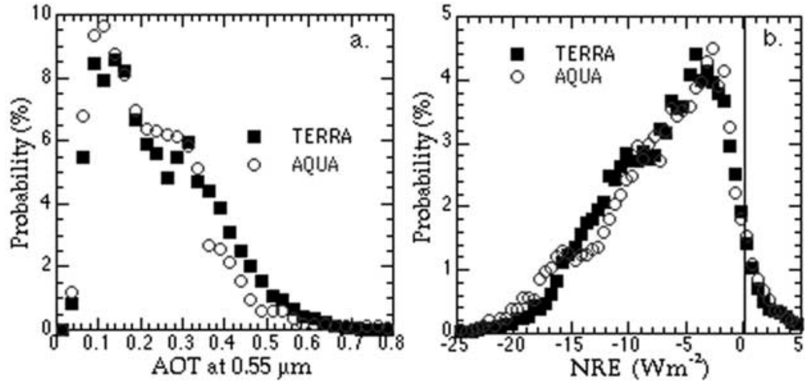


**Figure 1.** Probability density functions of (a) Terra minus Aqua total aerosol optical thickness ($\tau$) from CERES-SSF data and (b) diurnal and sample-bias adjusted Net Radiative Effect. The AOT and NRE data are binned in 0.025 and 0.5 bins respectively.

1 Wm$^{-2}$ difference observed between the overall Terra and Aqua averages. To examine the spatial distribution differences between Terra and Aqua we examined the NRE (Figure 2) where absolute Aqua NRE is subtracted from absolute Terra NRE. Regions where Terra NRE is greater have a positive difference while regions were Aqua is greater have a negative difference. Figure 2 indicates that the variation between Terra and Aqua NRE has a more or less random distribution. These variations correspond well to the spatial variation of Terra-Aqua $\tau$ difference (not shown). These differences do *not* correspond to the spatial variation of Terra-Aqua cloud fraction difference, which indicates that the diurnal change in cloud cover is not directly affecting AOT or NRE observations.

[12] The larger dust bias adjustment for Aqua data results in the final dust NRE for Terra and Aqua being essentially equal at $-6.9$ Wm$^{-2}$ despite the instantaneous NRE from Aqua being 1 Wm$^{-2}$ less than obtained from Terra measurements (Table 1). Despite the lower average $\tau$ and instantaneous NRE reported by the Aqua data, the $\tau_{\text{dust}}$ versus SWRE (dust) relationship is essentially identical for both satellites (Figure 3). The slope (usually labeled as the Radiative Efficiency) of the best-fit lines between Aqua and Terra data vary by less than 5 %, substantially less than the >10 % variation in Terra and Aqua regional SWRE. The adjusted radiative efficiency (Adjusted SWRE/CERES $\tau_{\text{dust}}$) for Terra and Aqua are $-48.6$ and $-51.5$ Wm$^{-2}$/$\tau_{\text{dust}}$ respectively.

## 4. Discussion and Conclusions

[13] The overriding conclusion of this study is that measurable spatial differences *do* exist between Terra and Aqua observed $\tau$ and DRE characteristics over the tropical Atlantic during June–August when dust concentrations are

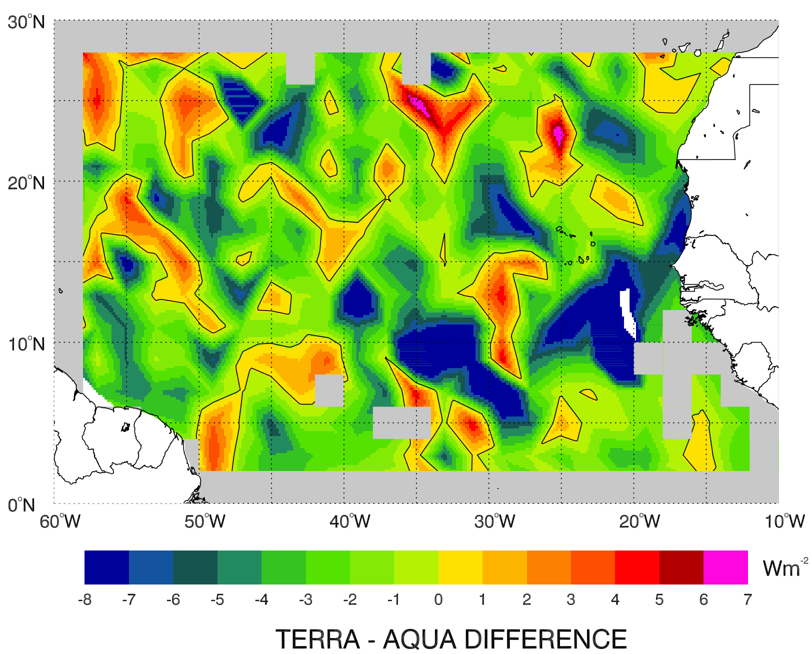


**Figure 2.** Difference in gridded dust Net Radiative Effect between Terra and Aqua over the tropical Atlantic. Warm colors (red-pink) indicate that the magnitude of Terra NRE is greater while cold colors (green-blue) indicate regions where Aqua NRE is greater. Black lines indicate the location of zero difference contours.

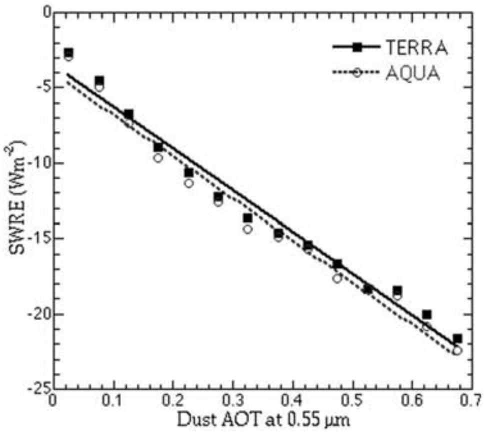


**Figure 3.** Shortwave Radiative Efficiency (SWRE) of dust aerosols shown as the relationship between CERES dust SWRE and MODIS-derived dust AOT.

the largest. However, when averaged over the area of study and over the study period, the Aqua CERES-SSF $\tau$ and corresponding instantaneous dust NRE are approximately 10% less than their Terra counterparts. This difference was not apparent when comparing the independent MODIS daily averaged $\tau$ products. As a result, the bias adjustment for Terra and Aqua differ, given an almost identical $-6.9$ Wm$^{-2}$ adjusted NRE for both satellites. It is possible that since Aqua's overpass occurs later in the afternoon during a time that is climatologically associated with greater cloud cover, additional pixels are removed as a result of cloud contamination when deriving Aqua CERES-SSF $\tau$. *Ignatov et al.* [2006] note that a systematic decrease in marine aerosol concentrations may occur from morning to afternoon, but that this is unlikely. *Smirnov et al.* [2002] reported a small decrease in $\tau$ between 7 and 17 UTC measured from an AERONET station on Cape Verde. However, Terra and Aqua $\tau$ in the Cape Verde region, which occur at approximately 11 and 15 UTC, show only a very small difference (0.355 vs. 0.347). Given the magnitude of this difference and taking general uncertainty of $\tau$ measurements into account, this difference cannot be considered significant.

[14] The lack of any measurable difference in MODIS $\tau$ between Terra and Aqua indicates the difference observed with the CERES-SSF products are not a reflection of a significant change in aerosol concentration or their scattering properties between Terra and Aqua overpass times. The lack of correlation with Terra-Aqua cloud fraction difference indicates that Terra-Aqua AOT/NRE differences are not a product of change in cloud cover from morning to afternoon.

[15] This work also highlights the importance of sample bias adjustment when deriving the radiative effects of aerosols. Either narrow-band to broadband regression relationships [*Loeb and Manalo-Smith*, 2005] or radiative efficiency methods [*Zhang et al.*, 2005; *Christopher and Jones*, 2007] must be used to account for the sample biases. Without this adjustment, the reported NRE would be too low as a result of the clear-sky bias apparent when using the CERES-SSF data. Assuming that appropriate bias adjustment is applied, the difference in Aqua and Terra dust NRE is less than 5%. This difference is more or less randomly distributed and is well within the uncertainties reported by other studies [e.g., *Zhang et al.*, 2005].

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## References

Bellouin, N., O. Boucher, J. Haywood, and M. S. Reddy (2005), Global estimate of aerosol direct radiative forcing from satellite measurements, *Nature*, *438*, 1138–1141, doi:10.1038/nature04348.

Christopher, S. A., and T. Jones (2007), Satellite-based assessment of cloud-free net radiative effect of dust aerosols over the Atlantic Ocean, *Geophys. Res. Lett.*, *34*, L02810, doi:10.1029/2006GL027783.

Ichoku, C., L. A. Remer, and T. F. Eck (2005), Quantitative evaluation and intercomparison of morning and afternoon Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol measurements from Terra and Aqua, *J. Geophys. Res.*, *110*, D10S03, doi:10.1029/2004JD004987.

Ignatov, A., P. Minnis, W. F. Miller, B. A. Wielicki, and L. Remer (2006), Consistency of global MODIS aerosol optical depths over ocean on Terra and Aqua CERES SSF data sets, *J. Geophys. Res.*, *111*, D14202, doi:10.1029/2005JD006645.

Kaufman, Y. J., B. N. Holben, D. Tanré, I. Slutsker, A. Smirnov, and T. F. Eck (2000), Will aerosol measurements from Terra and Aqua polar orbiting satellites represent the daily aerosol abundance and properties?, *Geophys. Res. Lett.*, *27*(23), 3861–3864.

Kaufman, Y. J., I. Koren, L. A. Remer, D. Tanre, P. Ginoux, and S. Fan (2005), Dust transport and deposition observed from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) spacecraft over the Atlantic Ocean, *J. Geophys. Res.*, *110*, D10S12, doi:10.1029/2003JD004436.

Loeb, N. G., and N. Manalo-Smith (2005), Top-of-atmosphere direct radiative effect of aerosols over global oceans from merged CERES and MODIS observations, *J. Clim.*, *18*, 3506–3526.

Prospero, J. M., P. Ginoux, O. Torres, and S. Nicholson (2002), Environmental characterization of global sources of atmospheric soil dust derived from NIMBUS-7 TOMS absorbing aerosol product, *Rev. Geophys.*, *40*(1), 1002, doi:10.1029/2000RG000095.

Remer, L. A., and Y. J. Kaufman (2005), Aerosol effect on the distribution of solar radiation over the clear-sky global oceans derived from four years of MODIS retrievals, *Atmos. Chem. Phys. Disc.*, *5*, 5007–5038.

Smirnov, A., B. N. Holben, T. F. Eck, I. Slutsker, B. Chatenet, and R. T. Pinker (2002), Diurnal variability of aerosol optical depth observed at AERONET (Aerosol Robotic Network) sites, *Geophys. Res. Lett.*, *29*(23), 2115, doi:10.1029/2002GL016305.

Yu, H., et al. (2006), A review of measurement-based assessment of aerosol direct radiative effect and forcing, *Atmos. Chem. Phys.*, *6*, 613–666.

Zhang, J., S. A. Christopher, L. A. Remer, and Y. J. Kaufman (2005), Shortwave aerosol radiative forcing over cloud-free oceans from Terra: 2. Seasonal and global distributions, *J. Geophys. Res.*, *110*, D10S24, doi:10.1029/2004JD005009.

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