

This work was written as part of one of the author's official duties as an Employee of the United States Government and is therefore a work of the United States Government. In accordance with 17 U.S.C. 105, no copyright protection is available for such works under U.S. Law.

Public Domain Mark 1.0

<https://creativecommons.org/publicdomain/mark/1.0/>

Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

**Please provide feedback**

Please support the ScholarWorks@UMBC repository by emailing [scholarworks-group@umbc.edu](mailto:scholarworks-group@umbc.edu) and telling us what having access to this work means to you and why it's important to you. Thank you.

# Will aerosol measurements from Terra and Aqua polar orbiting satellites represent the daily aerosol abundance and properties?

Yoram J. Kaufman and Brent N. Holben

NASA Goddard Space Flight Center, Greenbelt Maryland

Didier Tanré

Lab. d'Optique Atmos., CNRS, Univ. de Sciences et Techniques de Lille, Villeneuve d'Ascq, France

Ilya Slutsker, and Alexander Smirnov

Science Systems and Applications, Inc., Lanham, MD 20706

Thomas F. Eck

Raytheon ITSS and NASA GSFC, code 923, Greenbelt, Maryland 20771

**Abstract.** The Terra and Aqua missions will help quantify aerosol radiative forcing of climate by providing innovative measurements of the aerosol daily spatial distribution and identifying dust, smoke and regional pollution. However, these measurements are acquired at specific times of the day. To what extent can such measurements represent the daily average aerosol forcing of climate? We answer this question using 7 years of data from the Aerosol Robotic Network (AERONET) of 50-70 global ground-based instruments. AERONET measures the aerosol spectral optical thickness and the total precipitable water vapor every 15 minutes throughout the day. With a data set of 1/2 million measurements, AERONET demonstrates that Terra and Aqua aerosol measurements can represent the annual average value within 2% error. This excellent Terra representation of the daily average optical thickness is independent of the particle size or range of the optical thickness. This finding should facilitate ingest of satellite aerosol measurements in models that calculate radiative forcing and predict climate change.

## 1. Introduction

There are new developments in our ability to measure aerosol remotely and to assess aerosol radiative forcing of climate. We are moving away from a qualitative global description of the aerosol presence, which has been available for several years (Jankowiak and Tanré, 1992; Husar et al., 1997; Herman et al., 1997), to quantitative measurements of laboratory precision (Chu et al., 1998; Tanré et al., 1999). These measurements will not only tell us the aerosol loading or optical thickness (Tanré et al., 1997), but also the aerosol intrinsic optical properties and radiative forcing of climate (Kaufman et al., 1997a). The revolution will be accomplished by:

- Developing new satellite sensors (Kaufman et al., 1997b);

- Re-analyzing 20 year data records from operational sensors using new techniques (Higurashi and Nakajima, 1999; Mishchenko et al., 1999);
- Forming a federated network -- the Aerosol Robotic Network (AERONET) of instruments, for ground based remote sensing of aerosols and their properties (Holben et al., 1998); and
- Conducting intensive field campaigns to measure the aerosol physical and chemical properties and radiative forcing of climate (e.g. SCAR-B - Kaufman et al., 1998, INDOEX - Satheesh et al., 1999, ACE-2 - Raes et al., 2000).

Polar orbiting satellites are most suitable for remote sensing of aerosol. They provide good spatial and spectral resolution while maintaining global coverage (King et al., 1999). However, the data cannot provide the daily average values or the diurnal cycle, because the data are acquired at a fixed time of the day. Even geostationary satellites with frequent measurements during the day cannot give the full diurnal cycle over the ocean, since during half of the day the data are affected by glint reflection and cannot be analyzed for aerosol. The AERONET instruments supplement satellite records by measuring the diurnal cycle of aerosol in different locations with a wide variety of aerosol types. We use AERONET data from 50 to 70 stations dating from 1993 to evaluate the daily representation of aerosol by the Terra or Aqua measurements. All of the half a million measurements used in the evaluation are publicly available from the AERONET website: <http://aeronet.gsfc.nasa.gov:8080/>

## 2. Analysis

Two AERONET data sets are used in this analysis. The first is the full 1999 data set, which has the largest single year number of measurements (~200,000); however, part of the data does not have final calibration and therefore the data quality is uncertain. The second data set from 1993-1999, has full quality control (Holben et al., 2000) and includes also the part of 1999 data that were fully calibrated and verified. The analysis is focused on the 1993-1999 data set, which uses 400,000 multispectral measurements. The instrument sites, which are distributed over all continents and many oceanic islands, are chosen to represent

**Table 1:** Mean values of the AERONET measured optical thickness, Angstrom exponent and the total precipitable water vapor for 1999 and for the period 1993–1999 for five ranges of the Angstrom exponent,  $\alpha$ . Values are given for the time of day of the Terra observations (10:00–11:30 AM local time), the Aqua observations (12:30–14:00, and for the whole day.

TIME OF THE DAY	$\alpha > 1.8$		$0.7 < \alpha < 1.8$		$\alpha > 0.7$	
	1999	1993-9	1999	1993-9	1999	1993-9
<b>Aerosol optical thickness at 550 nm</b>						
Terra	0.212	<b>0.295</b>	0.156	<b>0.182</b>	0.314	<b>0.288</b>
Aqua	0.200	<b>0.299</b>	0.159	<b>0.184</b>	0.290	<b>0.286</b>
Daily	0.203	<b>0.299</b>	0.149	<b>0.185</b>	0.317	<b>0.286</b>
<b>Angstrom exponent (550–870 nm)</b>						
Terra	2.13	<b>2.15</b>	1.26	<b>1.29</b>	0.43	<b>0.39</b>
Aqua	2.11	<b>2.06</b>	1.26	<b>1.29</b>	0.42	<b>0.42</b>
Daily	2.07	<b>1.98</b>	1.28	<b>1.30</b>	0.44	<b>0.45</b>
<b>Total precipitable water vapor (cm)</b>						
Terra	1.84	<b>1.91</b>	1.91	<b>1.86</b>	2.31	<b>2.18</b>
Aqua	1.79	<b>1.95</b>	1.86	<b>1.89</b>	2.25	<b>2.19</b>
Daily	1.86	<b>1.92</b>	1.86	<b>1.87</b>	2.32	<b>2.16</b>

the regional aerosol loading. Although the monitoring sites are not equally distributed over the globe, we assume that this large data set can be used to judge the diurnal representation of the morning Terra or afternoon Aqua measurements. The stations were located mainly north of the Equator with some stations in South America, a biomass burning region, and Southern Africa. The durations of the measurements in each station are not equal. Note that the measurements require a cloud free view of the sun, which may bias towards less cloudy and drier conditions. Daily measurements of the optical thickness, Angstrom exponent, and total precipitable water vapor were made at 15 minutes intervals from the solar zenith angle of  $78^\circ$  in the morning to  $78^\circ$  in the evening. The measurements were used to calculate the daily ratios of the value during the Terra or Aqua orbit to the average daily value on the whole day. Cloud contamination effects were screened from these data using the methodology of Smirnov et al., (2000).

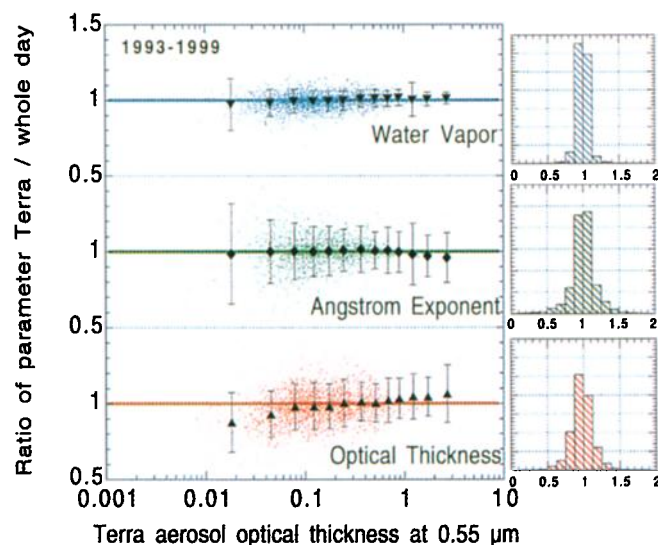
In each of the data sets, the data are averaged for the Terra (10:00–11:30) and Aqua (12:30–14:00) local time windows and for the whole day of measurements. Only data with at least 3 measurements per day in the Terra or Aqua window are kept. The daily average measurements are sorted as a function of the Angstrom exponent and separated into five groups. The Angstrom exponent,  $\alpha$ , is defined as:

$$\alpha = -\ln(\tau_{0.865}/\tau_{0.55})/\ln(0.865/0.55),$$

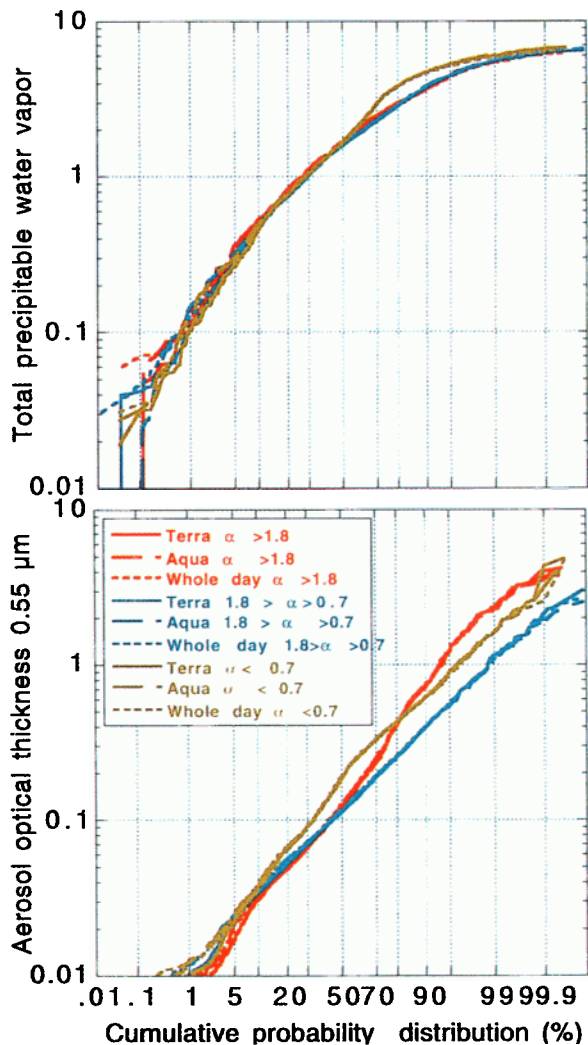
where  $\tau$  is the optical thickness for the 0.865 and 0.55  $\mu\text{m}$  channels. It is used as a rough measure of the aerosol type, in which large dust particles (super-micron radius) are dominant for  $\alpha < 0.7$  and those in which small pollution or smoke particles (sub-micron radius) are dominant for  $\alpha > 1.8$ . Between these two thresholds the aerosol is a mix of the two modes. The average values of the optical thickness ( $\tau_{0.550}$ ), the Angstrom exponent, and the total precipitable water vapor are given in Table 1 for the Terra and Aqua time frames and for the whole day. The optical thickness at 0.55  $\mu\text{m}$  is derived from the AERONET data by interpolating between the measurements at 0.44 and 0.66  $\mu\text{m}$ . Despite large variability in the aerosol properties in these three

data sets there is very small variation between the Terra time window, Aqua, or the whole day. For the 1993–1999 data set the average optical thickness was close to 0.30 for the defined aerosol modes ( $\alpha < 0.7$  or  $\alpha > 1.8$ ) and decreased to 0.18 for the mixed mode. The diurnal variation of the average values for this particular distribution of AERONET sampling sites is about 2%.

The rest of this paper focuses on the analysis of the Terra time window. In Fig. 1, scatter plots of the ratios of the Terra values to the whole day are plotted as a function of the optical thickness. All 3 scatter plots are centered at a ratio of  $1.0 \pm 0.03$ . The daily standard deviation in the optical thickness ratio is 0.1 to 0.2 for aerosol and 0.05–0.1 for water vapor. Therefore, in most of the cases the ratio of optical thickness or any of the other parameters during the Terra pass is similar to the daily average. Note that for the very small optical thickness,  $\tau$ , a calibration error of  $\Delta\tau = \pm 0.01$  to  $\pm 0.02$  generates a larger error in the diurnal cycle. Whether or not the aerosol and water vapor columns viewed by Terra and Aqua missions are representative of the daily average value may change with the aerosol type and meteorological conditions. In Fig. 2, we investigate this using cumulative histogram plots for the optical thickness and the total precipitable water vapor for the same three groups of Angstrom exponent. Each color in the figure corresponds to a given range of the Angstrom exponent. Cumulative histograms compare the value for a given fraction of occurrence of the aerosol optical thickness or precipitable water vapor. Except for the 0.1% of the data that represent the most hazy cases, there is no difference in the probability of occurrence of a given value of the optical thickness or total precipitable water vapor for the three daily intervals in any of the three groups of Angstrom exponent. This diurnal stability can be understood as the result of a lifetime of 5–10 days for the aerosol and water vapor air mass during the relatively cloud free conditions needed for the measurements, versus the few hours of daily stability. In order to find out whether the stability breaks down for individual



**Figure 1** Scatter plot (left) of the daily ratios of the measured optical thickness, Angstrom exponent and total precipitable water vapor, during the Terra period (10:00–11:30) to the daily average, plotted as a function of the optical thickness during the Terra period. The best quality data for 1993–1999 were used. The black symbols are the average value and standard deviations for sequential intervals of the optical thickness. On the right histograms of the ratios are shown from the same daily data.



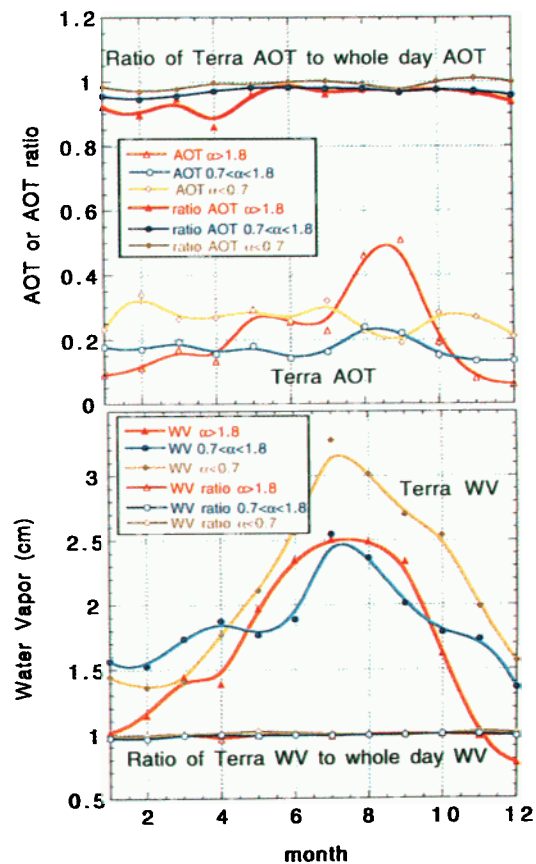
**Figure 2.** Cumulative histograms of the total precipitable water vapor (top) and of the aerosol optical thickness at  $0.55 \mu\text{m}$  (bottom) for three ranges of the Angstrom exponent,  $\alpha$ , indicating predominantly large particles - dust ( $\alpha < 0.7$ ), regional pollution or smoke ( $\alpha > 1.8$ ) and mixed cases in between. The histograms are given for the Terra period of observations (10:00–11:30 AM), Aqua (12:30–14:00) and for the whole day, for the datasets of 1993–1999.

sites, we averaged the data individually for 36 sites in the 1993–1999 data set. The maximum average diurnal variation for these sites is 11% for optical thickness, 20% for the Angstrom exponent and 6% for the water vapor. This means that for these sites the average optical thickness during the Terra pass is 11% different from the average over the whole day (e.g. for Barbados). While still very small, this variability is larger than the variability for the general climatology. Seasonal variation in aerosol properties can affect the diurnal variability. In Fig. 3 we show the monthly variation of the optical thickness and precipitable water vapor for the three ranges of the Angstrom exponent. The optical thickness increases in Aug.–Sept. due to biomass burning in the tropics and air pollution in the Northern Hemisphere. As shown in the figure, the ratio of the optical thickness or water vapor measured during the Terra time frame (10:00–11:30 AM) and during the whole day, is different from 1.0 by 5–10% for February to April. For example, during the 3 months burning season of

August–October, Mongu, Zambia shows a 15–20% diurnal range in the aerosol optical depth due in part to a diurnal cycle in the time of burning.

### 3. Conclusions

Three daily average values of the aerosol spectral optical thickness and total precipitable water vapor are derived from measurements made by 50–70 distributed ground-based AERONET sunphotometers. One daily average corresponds to the Terra satellite observations (10:00–11:30 AM local time), the second to the Aqua time (12:30–14:00), and the third to the whole day average. No systematic differences were detected between these three data sets, for either the optical thickness or the precipitable water vapor for the several ranges of the Angstrom exponent, which were used as a rough indication of the aerosol type. Daily ratios of the values during the Terra time to the whole day are centered on  $1.00 \pm 0.03$  with a standard deviation of 0.1 to 0.2, which decreases with the increase in the optical thickness. Diurnal variability of 5–10% is observed for Feb.–April.



**Figure 3.** Monthly variation of the optical thickness-AOT (top) and precipitable water vapor-WV (bottom) for three range of the Angstrom exponent,  $\alpha$ :  $\alpha < 0.7$  for predominantly dust conditions,  $0.7 < \alpha < 1.8$  for mixed continental conditions and  $\alpha > 1.8$  for aerosol dominated by urban pollution and smoke. The optical thickness picks in Aug.–Sept. due to biomass burning in the tropics and air pollution in the Northern Hemisphere. The 1993–1999 data set is used. The ratio of the AOT or WV measured during the Terra time frame (10:00–11:30 AM) and the whole day is also shown. The only significant seasonally of 5–15% is observed for the pollution aerosol.

Therefore, each polar orbiting satellite that measure aerosol should be able to represent the daily average impact of aerosol on climate, independent of morning or afternoon orbit. Note that any satellite with global coverage should have the same statistics of the aerosol load and properties. This allows the intercomparison of MODIS or MISR on Terra or Aqua with other instruments, such as AVHRR, TOMS, Polder, ATSR, GLI, as a cross check if the same aerosol climatology is obtained. The lack of sensitivity to the time of day of measurements is probably the result of the relatively long aerosol lifetime (several days), which reduces differences between mornings and afternoons. Also contributing to the low sensitivity is the close relationship of aerosol loading to the frequency of synoptic scale meteorological processes -- growing, scavenging, and advecting aerosols, which are largely independent of diurnal cycles. That diurnal variability can be more significant for short time scales and owing to proximity of diurnal source regions such as urban centers. However, in Goddard Space Flight Center in the vicinity of Washington DC, the average for the month of August during the Terra morning pass is smaller by only 5% than the whole month average. We also recognize that the cloud screened data are biased towards less cloudy and drier conditions. More humid conditions may enhance the diurnal cycle. The insignificant dependence of the time of data acquisition, as demonstrated in this paper, will facilitate the use of Terra and Aqua data in climate models.

**Acknowledgement.** We would like to acknowledge the scientists and technicians, who conducted the field measurements during the last 7 years, without whom this new view of aerosol would not be possible. We would also like to acknowledge data analysis by Shana Mattoo and valuable comments from Vanderlei Martins and Lorraine Remer.

## References

- Chu, A., Y. J. Kaufman, L. A. Remer, B. N. Holben, 1998: Remote sensing of smoke from MODIS Airborne Simulator During SCAR-B Experiment. *J. Geophys. Res.*, 103, 31,979-31,988.
- Herman, M., J. L. Deuzé, C. Devaux, et al., Remote sensing of aerosol over land surfaces including polarization and application to POLDER measurements, *J. Geophys. Res.*, 102, 17,039-17,050, 1997b.
- Higurashi, A. and T. Nakajima, 1999: Development of a two channel aerosol retrieval algorithm on global scale using NOAA AVHRR. *J. Atmos. Sci.*, 56, 924-941.
- Holben, B. N., T. F. Eck, I. Slutsker, D. Tanré, et al., AERONET-A federated instrument network and data archive for aerosol characterization, *Rem. Sens. Environ.*, 66, 1-16 (1998).
- Holben, B.N., D. Tanre, A. Smirnov, T.F. Eck et al., An emerging ground based aerosol climatology: Aerosol optical depth from AERONET, submitted to *J. Geoph. Res.*, 2000
- Husar, R. B. J. Prospero and L.L. Stowe, Patterns of tropospheric aerosols over the oceans, *J. Geophys. Res.* 102, 16,889 (1997).
- Jankowiak I. and D. Tanré, 1992: Climatology of Saharan dust events observed from Meteosat imagery over Atlantic Ocean. Method and preliminary results, *J. Clim.*, 5, 646-656.
- Kaufman, Y. J., D. Tanré, L. Remer, E. Vermote, et al., Remote Sensing of Tropospheric Aerosol from EOS-MODIS over the Land. *J. Geoph. Res.*, 102, 17051-17067, 1997a.
- Kaufman, Y. J., D. Tanré, H. R. Gordon, T. Nakajima, et al., 1997b: Passive Remote Sensing of Tropospheric Aerosol and Atmospheric Correction. *J. Geoph. Res.*, 102, 16815-16830.
- King, M. D., Y. J. Kaufman, D. Tanré, and T. Nakajima: Remote sensing of tropospheric aerosols from space: past, present and future. *Bull. of Meteor. Soc.* 80, 2229-2259, 1999.
- Mishchenko, M.I., I.V. Geogdzhayev, B. Cairns, et al., Aerosol retrievals over the ocean by use of channels 1 and 2 AVHRR data: sensitivity analysis and preliminary results, *Appl. Optics*, 38, 7325-7341, 1999.
- Raes, F., T. Bates, F. McGovern, and M. Van Liedekerke: ACE-2 general overview and main results, *Tellus*, 52B, 111-125.
- Satheesh, S.K., V. Ramanathan, L.J. Xu, et al., A model for the natural and anthropogenic aerosols over the tropical Indian Ocean derived from INDOEX data., *J. Geoph. Res.*, 104, 27421-27440, 1999.
- Smirnov, A., B.N.Holben, T.F.Eck, O.Dubovik, I.Slutsker, Cloud screening and quality control algorithms for the AERONET data base, *Remote Sensing of Environment*, 73, 337-349. 2000.
- Tanré, D., Y. J. Kaufman, M. Herman and S. Mattoo, Remote sensing of aerosol over oceans from EOS-MODIS. *J. Geophys. Research* , 102, 16971-16988, 1997.
- Tanré, D., L.R. Remer, Y.J. Kaufman, P.V. Hobbs, et al. 1999: Retrieval of Aerosol Optical Thickness and Size Distribution Over Ocean from the MODIS Airborne Simulator during Tarfox, *J. Geophys. Res.*, 104, 2261-2278.
- Yoram J. Kaufman, NASA/GSFC code 913, Greenbelt MD 20771 ([kaufman@climate.gsfc.nasa.gov](mailto:kaufman@climate.gsfc.nasa.gov)).
- Brent N. Holben, NASA/GSFC code 923, Greenbelt MD 20771.
- Didier Tanré, Lab. d'Optique Atmos., CNRS, Univ. de Sciences et Techniques de Lille, Villeneuve d'Ascq, France,
- Ilya Slutsker, and Alexander Smirnov, Science Systems and Applications, Inc., Lanham, MD 20706
- Tom F. Eck, Raytheon ITSS and NASA GSFC, code 923, Greenbelt, Maryland 20771

(Received June 28, 2000; revised September 5, 2000; accepted September 7, 2000)