How well can aerosol measurements from the Terra morning polar orbiting satellite represent the daily aerosol abundance and properties?

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Abstract

The Terra mission, launched at the dawn of 1999, and Aqua mission to be launched soon, will possess innovative measurements of the aerosol daily spatial distribution, distinguish between dust, smoke and regional pollution and measure aerosol radiative forcing of climate. Their polar orbit gives daily global coverage, however measurements are acquired at specific time of the day. To what degree can present measurements from Terra taken between 10:00 and 11:30 AM local time, represent the daily average aerosol forcing of climate? Here we answer this question using 7 years of data from the distributed ground based 50-70 instrument Aerosol Robotic Network (AERONET). This AERONET half a million measurement data set shows that Terra aerosol measurements represent the daily average values within 5%. The excellent representation is found for large dust particles or small aerosol particles from fires or regional pollution and for any range of the optical thickness, a measure of the amount of aerosol in the atmosphere.

Introduction

Remote sensing of aerosol and aerosol radiative forcing of climate is being revolutionized as we write these lines. We are moving away from a qualitative global description of the aerosol presence, available now for several years (Jankowiak and Tanré 1992; Husar et al., 1997; Herman et al., 1997a), 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:

- Designing and using new satellite sensors (Kaufman et al., 1997b),
- Re-analyzing 20 year data records from operational sensors using new techniques (Nakajima and Higurashi, 1998; 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. recently 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. Because these polar platforms are sun-synchronous, the data are unable to provide the daily average values or the diurnal cycle. Even geostationary satellites, with frequent measurements during the day, cannot give the full diurnal cycle over the ocean, since around half of the day, the data are with glint reflection and cannot be analyzed for aerosol. The AERONET instruments measure the diurnal cycle of aerosol in different locations with wide variety of aerosol types thus supplementing the satellite record. We use AERONET data from 50-70 stations dating from 1993 to evaluate the daily representation of aerosol by the Terra 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/

Analysis

Two AERONET data sets were used. The full 1999 data set has the largest single year number of measurements (~200,000) but part of the data does not have final calibration and therefore the quality is expected to be lower than the second data set of full quality control (Holben et al., 2000) from 1993-1999. The 1993-1999 data set uses 400,000 multispectral measurements. The instrument sites, distributed over all continents and many oceanic islands, are chosen to be representative of regional aerosol loading. Although the monitoring sites are not statistically representing all geographic locations or aerosol regimes, we assume that this large data set can be used to judge the diurnal representation of the morning Terra measurements. We should also note that the measurements require a cloud free view of the sun which may bias towards less cloudy and drier conditions.

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 window are kept. The daily average measurements are sorted as a function of the Angstrom exponent, α, and separated into five groups. The Angstrom exponent, α, is defined as:

$$\alpha = -\ln(\tau_{865}/\tau_{550})/\ln(865/550),$$

where τ is the optical thickness for the 865 and 550 nm channels. It is used as a rough measure of the aerosol type, with large dust particles (super-micron radius) being dominant for $\alpha<0.5$ and small pollution or smoke particles (sub-micron radius) for $\alpha>1.5$. 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 550 nm, is derived from the AERONET data by interpolating between the measurements at 440 and 660 nm. Despite large variability among these five data sets, there is a very small variation between the Terra acquisition, to Aqua and the whole day, usually of 0-7%. The average optical thickness was 0.15-0.30 for the groups with $\alpha>0.5$ and increased to 0.35-0.40 for $\alpha<0.5$ indicating the difference between dusty ($\alpha<0.5$) and non-dusty ($\alpha>0.5$) conditions for this particular distribution of AERONET sampling sites.

Daily measurements of the optical thickness, Angstrom exponent and total precipitable water vapor were made at 15 minutes intervals from solar zenith angle of 78° in the morning to 78° in the evening. The measurements were used to calculate the daily ratios of the value during the Terra orbit to the average value on the whole day. Cloud contamination effects were screened from these data by the methodology of Smirnov et al., (2000). Scatter plots of the ratios are plotted as a function of the optical thickness in Fig. 1. All 3 scatter plots are centered at ratio of 1.0±0.03, with a slight variation with the optical thickness of the optical thickness ratio and standard deviation of 0.1 to 0.20 for aerosol and 0.05-0.1 for water vapor. Note that for very small optical thickness, τ, the calibration error of $\Delta\tau=\pm0.01$ to ±0.02 generates a larger error in the diurnal cycle of the optical thickness and Angstrom exponent than for high τ. Therefore in most of the cases the ratio of optical thickness or any of the other parameter during the Terra pass is similar to the daily average. The representation of the aerosol and water vapor by Terra and Aqua missions may change with the aerosol type and meteorological conditions. We investigate it in Fig. 2 using cumulative histogram plots for the optical thickness and the total precipitable water vapor for two groups of Angstrom exponent: $\alpha>1.0$ and $\alpha<1.0$. 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 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 or for the two 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. We were curious to see if the stability breaks down for individual sites, and averaged the data individually for 36 sites in the 1993-1999 data set. The maximum average daily variation for these sites is 11% for optical thickness, 20% for the Angstrom exponent and 6% for the water vapor. This variability is larger than for the general climatology but still very small. However we note that seasonality can occur in the diurnal variability. In Fig. 3: we show the monthly variation of the optical thickness and precipitable water vapor for three range of the Angstrom exponent. The optical thickness picks in Aug.-Sept. due to biomass burning in the tropics and air pollution in the Northern Hemisphere. The ratio of the AOT or WV measured during the Terra time frame (10:00-11:30 AM) and the whole day shown in the figure, is only significant seasonally for the pollution aerosol (5-15%). For example, Mongu, Zambia during the 3 month burning season of August-October shows a 15-20% diurnal range in the aerosol optical depth due in part to a diurnal cycle in the time of burning.

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), second to the Aqua time (12:30-14:00) and third to the whole day average. No systematic differences were detected between these three data sets, for the optical thickness or the precipitable water vapor, for several ranges of the Angstrom exponent, used as a rough indication of the aerosol type. Daily ratios of the values during the Terra time to the whole day are centered around 1.00±0.05 with standard deviation of 0.1 to 0.2 decreasing with an increase in the optical thickness. Diurnal variability of 5-10% is observed for Feb.-April. Therefore each satellite in a polar orbit 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 intercomparison of MODIS or MISR on Terra or Aqua, with other instruments, 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 (a few days) aerosol lifetime, that diminishes differences between mornings and afternoons. 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 are also contributing to the small sensitivity. We fully recognize that for short time scales and owing to proximity of diurnal source regions such as urban centers, that diurnal variability likely is locally significant.

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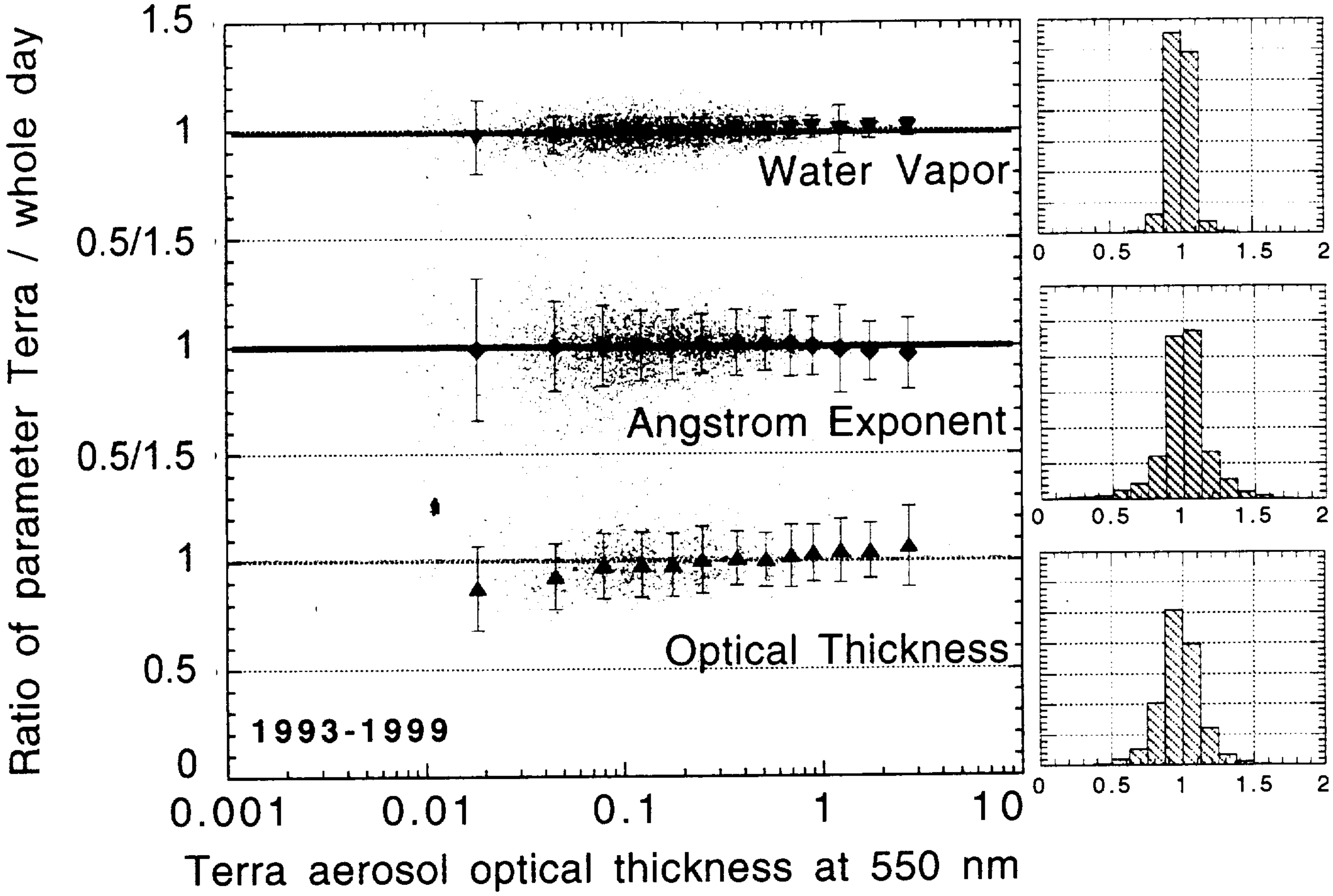
Fig. 1: Scatter plot (left) of the daily ratios of the measured optical thickness, Angstrom exponent and total precipitable water vapor, during the Terra period (10:00-11:30) to the daily average, plotted as a function of the optical thickness during the Terra period. The best quality data for 1993-1999 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.

Fig. 2: Cumulative histograms of the aerosol optical thickness at 550 nm (left) and of the total precipitable water vapor (right) for two ranges of the Angstrom exponent, α, indicating cases dominated by large particle - dust ($\alpha<1.0$) and regional pollution or smoke ($\alpha>1.0$). The histograms are given for the Terra period of observations, Aqua and for the whole day, for the datasets of 1993-1999.

Fig. 3: Monthly variation of the optical thickness-AOT (top) and precipitable water vapor-WV (bottom) for three range of the Angstrom exponent, α: α< 0.7 for predominantly dust conditions, 0.7<α<1.8 for mixed continental conditions and α>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.

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, α. 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. For the 1993-1999 data set, the average opitcal thickness is 0.23 for the Terra, Aqua and whole day periods. The mean Angstrom exponent is 1.25±0.01 for these periods, and the total precipitable water vapor is 1.95±0.02 cm.

TIME OF THE DAY	α > 2		1.5< α <2		1.0< α <1.5		0.5< α <1.0		α <0.5	
	1999	1993-9	**1999**	1993-9	**1999**	1993-9	**1999**	1993-9	**1999**	1993-9
Aerosol optical thickness at 550 nm										
Terra 10:00-11:30	**0.17**	0.24	**0.20**	0.28	**0.14**	0.16	**0.19**	0.15	**0.38**	0.35
Aqua 12:30-14:00	**0.18**	0.24	**0.19**	0.28	**0.15**	0.16	**0.19**	0.15	**0.34**	0.35
Whole day	**0.17**	0.24	**0.19**	0.29	**0.14**	0.16	**0.18**	0.15	**0.40**	0.35
Angstrom exponent (550-870 nm)										
Terra 10:00-11:30	**2.32**	2.39	**1.74**	1.73	**1.26**	1.26	**0.76**	0.76	**0.28**	0.28
Aqua 12:30-14:00	**2.29**	2.25	**1.70**	1.71	**1.26**	1.26	**0.76**	0.78	**0.29**	0.32
Whole day	**2.27**	2.11	**1.74**	1.69	**1.26**	1.28	**0.75**	0.82	**0.31**	0.35
Total precipitable water vapor (cm)										
Terra 10:00-11:30	**1.69**	1.84	**1.93**	2.01	**1.86**	1.83	**2.10**	1.79	**2.38**	2.33
Aqua 12:30-14:00	**1.69**	1.87	**1.88**	2.04	**1.83**	1.85	**2.00**	1.80	**2.32**	2.33
Whole day	**1.75**	1.85	**1.89**	2.02	**1.76**	1.84	**2.11**	1.78	**2.43**	2.30



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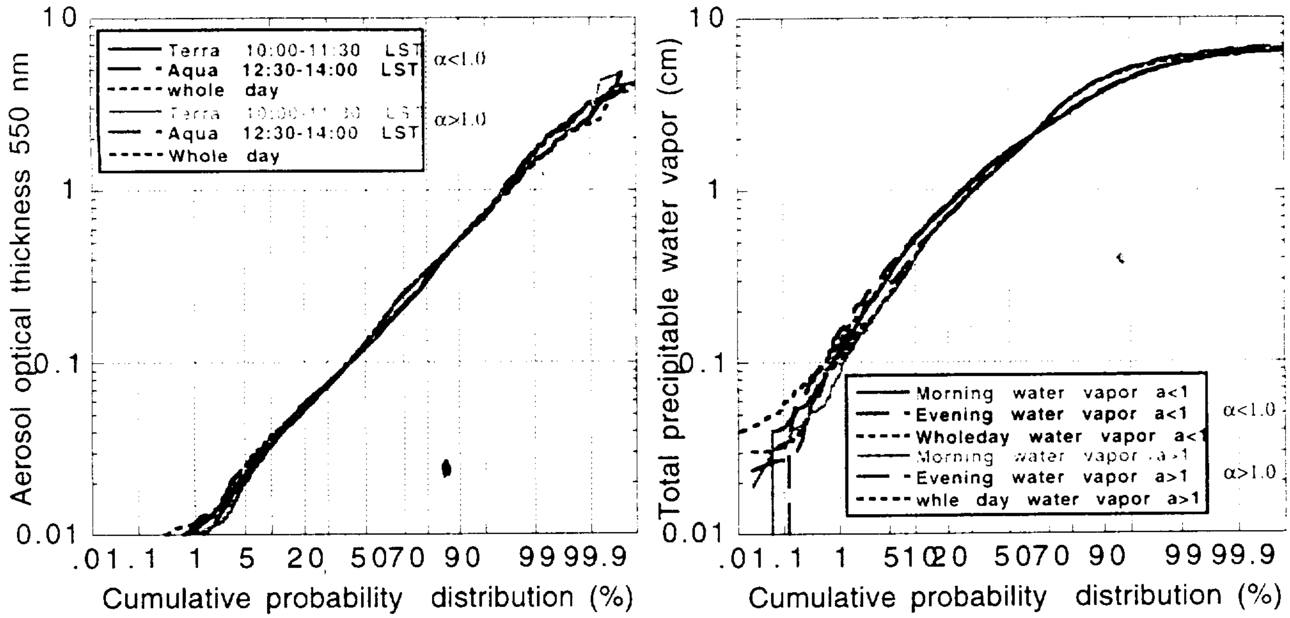

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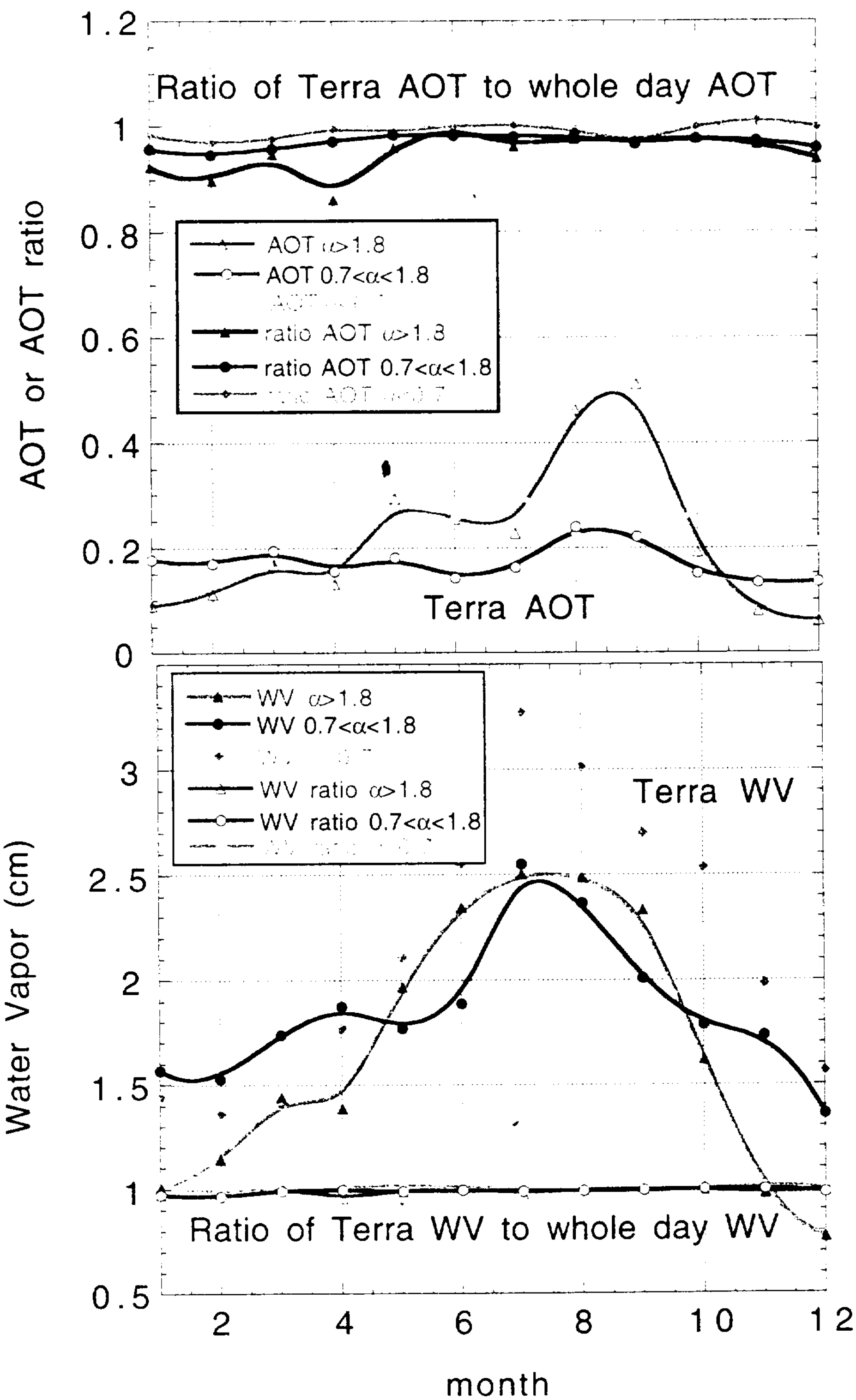

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