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Ship-based aerosol optical depth measurements in the Atlantic Ocean: Comparison with satellite retrievals and GOCART model

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[1] Aerosol optical depth measurements were made in October–December 2004 onboard the R/V Akademik Sergey Vavilov. The cruise area included an Atlantic transect from North Sea to Cape Town and then a crossing in the South Atlantic to Argentina. In the open oceanic areas not influenced by continental sources aerosol optical depth values were close to background oceanic conditions ($\tau_a \sim 0.06$ – 0.08). Spectral dependence, especially in the high latitude Southern Atlantic, can be considered as quasi-neutral (Angstrom parameter α was less than 0.4). Back-trajectory analysis allowed statistical division of the aerosol optical parameters and showed similar properties for the North Atlantic polar marine, South Atlantic subtropical marine and South Atlantic polar marine air. Ship-borne aerosol optical depth comparisons to GOCART model and satellite retrievals revealed systematic biases. Satellite retrieved optical depths are generally higher by 0.02–0.07 (depending on the sensor), especially in low τ_a conditions. GOCART model simulated optical depths correlate well with the ship measurements and, despite overall bias and a notable disparity with the observations in a number of cases, about 30% agree within ± 0.01 . **Citation:** Smirnov, A., et al. (2006), Ship-based aerosol optical depth measurements in the Atlantic Ocean: Comparison with satellite retrievals and GOCART model, *Geophys. Res. Lett.*, 33, L14817, doi:10.1029/2006GL026051.

1. Introduction

[2] Atmospheric optical properties over the oceans were not well studied until the mid-sixties of the last century. Remarkable progress has been made since then in our understanding of aerosol generation, evolution, transport, the way aerosol particles act as cloud condensation nuclei, affect microphysics of clouds and their ability to precipitate.

Substantial radiative effects of sea-salt aerosol, better understanding of the climate change forcing by aerosols [Haywood et al. 1999; Kaufman et al., 2005], combined with very few systematic measurements over the oceans [Smirnov et al., 2002], especially in the South Ocean, create a demand for more data acquisition. Recently the Aerosol Robotic Network (AERONET) [Holben et al., 1998] established a few new island sites in the Southern Ocean, however, large areas south of 35° still have no coverage. Ship-based measurements can at least partly fill the gap which exists in our knowledge on the global aerosol distribution over the oceans.

[3] Ship-based measurements of columnar aerosol optical properties are extremely valuable for several important reasons. First, not all areas of the World Ocean can be studied from islands therefore ship-based measurements are the only source of data for such regions (e.g., areas south from the “roaring forties” in the South Atlantic). Second, it is not absolutely clear to what extent an island, acting as a local perturbation and/or source of aerosol, can alter aerosol optical depth and its spectral dependence. Finally, ship-based data can be advantageously used for validation of global aerosol transport model simulations and satellite retrievals (data on aerosol optical depth over the oceans were successfully employed in the regional [Ignatov et al., 1995] and in the global validation of two channel AVHRR aerosol optical thickness retrievals [Liu et al., 2004]). Certain steps in these directions have been recently made and hopefully will continue [Sakerin and Kabanov, 2002; Knobelspiesse et al., 2004].

[4] In the current paper we present some new results on aerosol optical depth measurements in the Atlantic (mainly in the Southern Atlantic) Ocean and compare ship-borne measurements to satellite retrievals from various sensors and to the global transport model GOCART.

2. Instrumentation and Data Collection

[5] Aerosol optical depth measurements were made in October–December 2004 onboard the R/V Akademik Sergey Vavilov. The cruise track included a transect in the Atlantic from the North Sea to Cape Town, South Africa and then a crossing in the South Atlantic to Ushuaia, Terra del Fuego, Argentina (Figure 1). The cruise track allowed sampling of several aerosol regimes over the Northern and Southern Atlantic. A hand-held sunphotometer (Microtops II) was used to acquire 314 series of measurements spanning 38 days.

[6] The Microtops II sun photometer is a handheld instrument specifically designed to measure columnar

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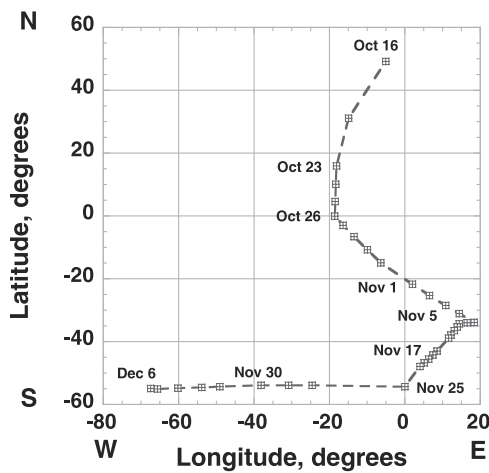


Figure 1. R/V Akademik Sergey Vavilov cruise track.

optical depth and water vapor content [Morys *et al.*, 2001]. Direct sun measurements are acquired in five spectral channels at 340, 440, 675, 870, and 940 nm. The instrument has built-in pressure and temperature sensors. To obtain the time of measurements and geographical position of the ship a GPS was connected to the sunphotometer. The instrument was calibrated at the NASA Goddard Space Flight Center against the AERONET reference CIMEL Sun/sky radiometer. The estimated uncertainty of the optical depth in each channel did not exceed plus or minus 0.02, which is slightly higher than the uncertainty of the AERONET field (not master) instruments, as shown by Eck *et al.* [1999]. Aerosol optical depth was retrieved by applying the AERONET processing algorithm (Version 2) to raw data.

[7] The measurements were carried out when the solar disk was free of clouds. The number of measurements averaged into one data point (a series) was not less than 5 during a three-minute period. The number of series during the day varied from 1 to 33. Arithmetic and geometric daily

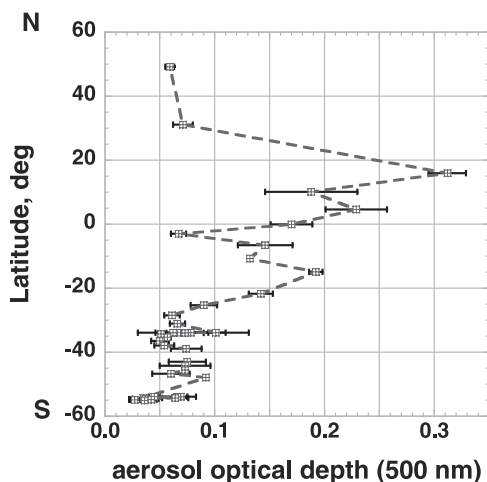


Figure 2. Latitudinal distribution of aerosol optical depth. The horizontal bars indicate plus or minus one standard deviation.

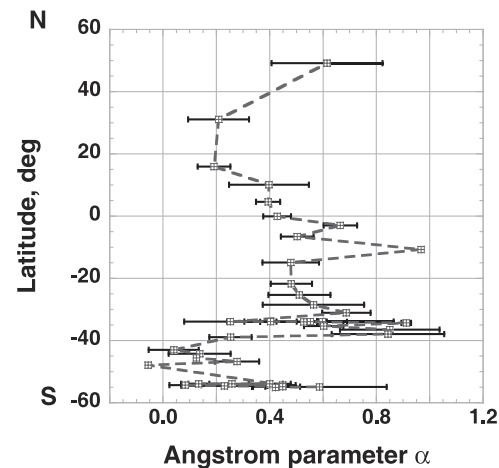


Figure 3. Latitudinal distribution of the Angstrom parameter. The horizontal bars indicate plus or minus one standard deviation.

averages of optical depth (compared to avoid sampling biases [O'Neill *et al.*, 2000]) agree within 0.005 or less.

3. Results

[8] Temporal and latitudinal distribution of the daily averaged aerosol optical depth at 500 nm and Angstrom parameter α (based on 3 wavelengths 440, 675 and 870 nm) are presented in Figures 2 and 3. In order to provide a common basis for comparison with previous results we calculated aerosol optical depth at 500 nm using log-linear interpolation between channels 440 and 675 nm.

[9] Aerosol optical depth values are close to the background oceanic conditions (0.06–0.08 at 500 nm [Holben *et al.*, 2001; Smirnov *et al.*, 2002]) in the open oceanic areas not influenced by continental sources or long-range aerosol transport. Spectral dependence $\tau_a(\lambda)$, characterized by the Angstrom parameter α , is close to neutral (α less than 0.6). South of the “roaring forties” instantaneous $\tau_a(500 \text{ nm})$ did not exceed 0.11, varying mainly within the same range (0.04–0.08) as in other remote oceanic areas, however predominance of smaller Angstrom parameters (0.0–0.40) is evident. The wind speed range for the area south of 40° latitude was 5–15 m/s during the measurement period. The most transparent conditions were encountered near coast of Argentina where measured aerosol optical depth was 0.04 or even less. Relatively turbid conditions (optical depth ~ 0.30 at 500 nm) in the tropical Atlantic were associated with Saharan dust transport. Continental (dust and possibly

Table 1. Mean Optical Characteristics of Various Air Mass Source Regions^a

Air Mass Source Region	τ_a	σ	α	σ_α	N
NA polar marine (30°–50° N)	0.07	0.01	0.41	0.29	2
African dust (0°–16° N)	0.23	0.06	0.35	0.11	4
Mod SA tropical marine (6°–21° S)	0.15	0.03	0.61	0.24	4
SA subtropical marine (25°–34° S)	0.08	0.02	0.51	0.14	7
SA polar marine (34°–55° S)	0.06	0.02	0.38	0.28	20

^a τ_a , average of aerosol optical depth at 500 nm; σ , standard deviation of the aerosol optical depth; α , average of the Angstrom parameter; σ_α , standard deviation of the Angstrom parameter; N, number of days.

Table 2. Regression Statistics of the GOCART and Satellite Retrieved τ_a , Versus Ship-Based Sunphotometer Measured τ_a , and Mean Absolute (SAT/Model-SP) Differences for Two Subsets of Data^a

Sensor	a	b	R	N	34°–55°S	50°N–34°S	N ₁ /N ₂
MISR ($\lambda = 558$ nm)	1.136	0.001	0.99	6	0.009	0.018 (0.016)	1/5
MODIS ($\lambda = 550$ nm)	0.688	0.062	0.85	29	0.049 (0.029)	0.034 (0.022)	13/16
AVHRR ($\lambda = 550$ nm) ^b	0.737	0.031	0.97	6	0.013 (0.008)	0.022 (0.006)	2/4
AVHRR ($\lambda = 630$ nm) ^c	0.834	0.052	0.93	32	0.046 (0.018)	0.036 (0.023)	20/12
GOCART ($\lambda = 500$ nm)	0.733	0.049	0.59	35	0.045 (0.042)	0.035 (0.029)	20/15

^a $\tau_a(\text{SAT}/\text{Model}) = a \cdot \tau_a(\text{SP}) + b$; R, correlation coefficient; N, number of points; standard deviations are shown in parentheses; N₁ and N₂, number of points in each subset.

^bMishchenko et al. [1999] retrieval methodology.

^cIgnatov et al. [2004] retrieval methodology.

smoke aerosol) influence also can be seen in the data acquired between 6° and 21° S.

[10] Aerosol optical depth did not vary significantly within most measurement days keeping the standard deviation (σ) of daily means rather low (Figure 2). Relatively larger σ 's of the α daily means (Figure 3), partly, are due to larger errors in the Angstrom parameter estimates in the transparent (low τ_a) atmospheres.

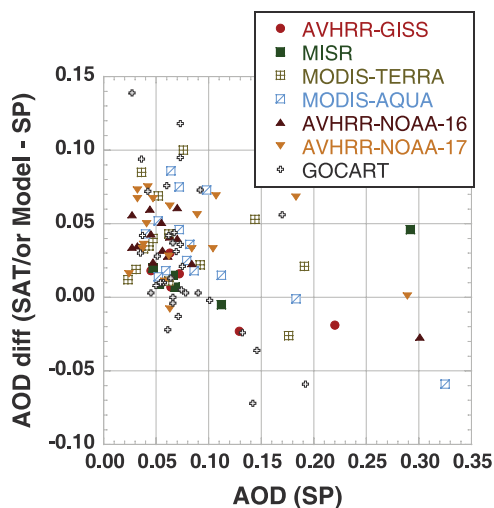
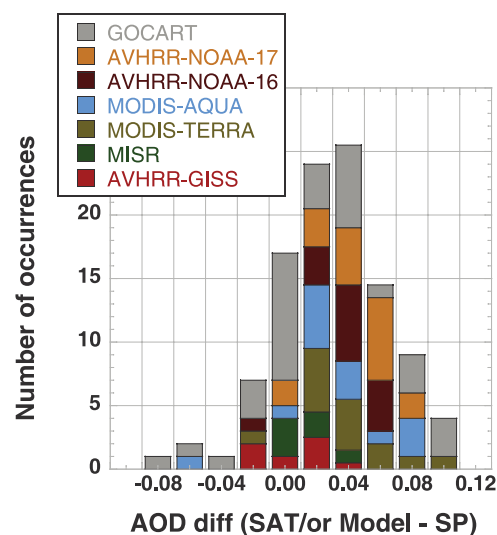
[11] Seven-day back-trajectory analysis [Schoeberl and Newman, 1995] afforded understanding of changes in atmospheric optical properties for various aerosol sources and allowed certain statistical latitudinal division of the aerosol optical parameters (Table 1). Statistical characteristics of aerosol optical depth and Angstrom parameter in the North Atlantic (NA) polar marine, South Atlantic (SA) subtropical marine, and South Atlantic polar marine are quite similar and agree very well with earlier studies by Volgin et al. [1988], Livingston et al. [2000], Voss et al. [2001], Smirnov et al. [2002], Knobelspiesse et al. [2004] and Quinn and Bates [2005]. Optical depth in the SA Tropical region (6°–21° S) was higher than during the Aerosols99 Experiment; however, Voss et al. [2001] pointed out a notable latitudinal variability of optical depth in this area.

[12] Aerosol optical depth can be retrieved from satellite data [e.g., Remer et al., 2005; Kahn et al., 2005; Mishchenko et al., 1999; Ignatov et al., 2004]. The ship-borne sunphotometer data set provided excellent opportunity for comparison.

Satellite retrievals were collocated with the ship position whenever possible, although in the conditions of the relatively stable optical properties during the day (small standard deviations of daily means) exact matching in space and time is less important. Sunphotometer measurements were spectrally adjusted using log-linear interpolation to the “validation” satellite wavelength.

[13] Table 2 presents regression statistics of the GOCART model [Chin et al., 2002] and satellite retrieved aerosol optical depths versus sunphotometer data. A positive intercept is evident for all sensors except for MISR. Table 2 shows that in the current study the performance of the MISR (algorithm version 15) was better comparing to reported by Kahn et al. [2005]; 62% of the retrievals from MODIS were inside predicted uncertainty as outlined by Remer et al. [2005]; the AVHRR-GISS retrieval methodology produced same slope and intercept as in the work by Liu et al. [2004]; and the operational AVHRR product yielded a less accurate result compared to Ignatov et al. [1995] (this may be partly due to the AVHRR operational calibration uncertainty). Mean absolute differences (SAT/Model-SP) are similar for two latitude bands presented in Table 2.

[14] In order to better visualize aerosol optical depth differences between satellite and sunphotometer retrievals we present them against ground-truth τ_a separately for the morning and afternoon satellites wherever possible (Figure 4). Figure 4 shows that satellite retrieved τ_a tend

**Figure 4.** Aerosol optical depth differences between various sensors and sunphotometer.**Figure 5.** Histogram of the AOD differences.

to overestimate optical depth especially when τ_a is small. MISR and AVHRR-GISS [Mishchenko et al., 1999] did slightly better than others; however, their number of match-up cases was limited.

[15] A stacked histogram of the τ_a differences (Figure 5) allows seeing the most frequent overall bias and the proportion of each category within each column. It is notable that despite the GOCART intercept and mean absolute (SAT/Model-SP) difference being near the high end of satellite results (Table 2) approximately 30% of the GOCART model simulations are within ± 0.01 of the sunphotometer measurements. The histogram of the τ_a differences not only has a peak at 0.04, but also is skewed toward positive satellite/model-sunphotometer differences.

4. Conclusions

[16] The principal conclusions from our work can be summarized as follows:

[17] 1. It was found that atmospheric aerosol optical parameters ($\tau_a(500\text{ nm}) \sim 0.04\text{--}0.08$ and $\alpha \sim 0.0\text{--}0.4$) in the Southern Atlantic between 34° S and 55° S are close to other remote oceanic areas (for example, high latitude Northern Atlantic, Southern and Tropical Pacific, and South Indian Ocean [Matsubara et al., 1983; Volgin et al., 1988; Smirnov et al., 2002, 2003; Wilson and Forgan, 2002; Shinzuka et al., 2004; Quinn and Bates, 2005]).

[18] 2. Almost 60% of satellite retrieved optical depths, although highly correlated with the sunphotometer measurements ($R = 0.85\text{--}0.99$), are generally higher by $0.02\text{--}0.07$, depending on sensor (see Figure 5). A wide range of factors can be responsible for that but we do not discuss them in the current study. The GOCART model calculated aerosol optical depths, on the other hand, are less correlated with sunphotometer measurements ($R = 0.59$), and, despite the overall bias, about 30% agree within ± 0.01 .

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References

- Chin, M., et al. (2002), Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and Sun photometer measurements, *J. Atmos. Sci.*, **59**, 461–483.
- Eck, T. F., et al. (1999), Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosol, *J. Geophys. Res.*, **104**, 31,333–31,350.
- Haywood, J. M., et al. (1999), Tropospheric aerosol climate forcing in clear-sky satellite observations over the oceans, *Science*, **283**, 1299–1303.
- Holben, B. N., et al. (1998), AERONET—A federated instrument network and data archive for aerosol characterization, *Remote Sens. Environ.*, **66**(1), 1–16.
- Holben, B. N., et al. (2001), An emerging ground based aerosol climatology: Aerosol optical depth from AERONET, *J. Geophys. Res.*, **106**, 12,067–12,097.
- Ignatov, A. M., et al. (1995), Validation of the NOAA/NESDIS satellite aerosol product over the North Atlantic in 1989, *J. Geophys. Res.*, **100**, 5123–5132.
- Ignatov, A., et al. (2004), Operational aerosol observations (AEROBS) from AVHRR/3 on board NOAA-KLM satellites, *J. Atmos. Oceanic Technol.*, **21**, 3–26.
- Kahn, R. A., et al. (2005), Multiangle Imaging Spectroradiometer (MISR) global aerosol optical depth validation based on 2 years of coincident Aerosol Robotic Network (AERONET) observations, *J. Geophys. Res.*, **110**, D10S04, doi:10.1029/2004JD004706.
- Kaufman, Y. J., et al. (2005), The effect of smoke, dust, and pollution aerosol on shallow cloud development over the Atlantic Ocean, *Proc. Natl. Acad. Sci. U.S.A.*, **102**, 11,207–11,212.
- Knobelspiesse, K. D., et al. (2004), Maritime aerosol optical thickness measured by handheld sunphotometers, *Remote Sens. Environ.*, **93**, 87–106.
- Liu, L., et al. (2004), Global validation of two-channel AVHRR aerosol optical thickness retrievals over the oceans, *J. Quant. Spectrosc. Radiat. Transfer*, **88**, 97–109.
- Livingston, J. M., et al. (2000), Shipboard sunphotometer measurements of aerosol optical depth spectra and columnar water vapor during ACE-2, and comparison with selected land, ship, aircraft, and satellite measurements, *Tellus, Ser. B*, **52**, 594–619.
- Matsubara, K., et al. (1983), Turbidity over the Indian Ocean, in *Proceedings of the Fifth Symposium on Polar Meteorology and Glaciology, Spec. Iss. Mem. Natl. Inst. Polar Res.*, **29**, 77–84.
- Mishchenko, M. I., et al. (1999), Aerosol retrievals over the ocean by use of channels 1 and 2 AVHRR data: Sensitivity analysis and preliminary results, *Appl. Opt.*, **38**, 7325–7341.
- Morys, M., et al. (2001), Design, calibration, and performance of MICRO-TOPS II handheld ozone monitor and Sun photometer, *J. Geophys. Res.*, **106**, 14,573–14,582.
- O'Neill, N. T., et al. (2000), The lognormal distribution as a reference for reporting aerosol optical depth statistics: Empirical tests using multi-year, multi-site AERONET sunphotometer data, *J. Geophys. Lett.*, **27**(20), 3333–3336.
- Quinn, P. K., and T. S. Bates (2005), Regional aerosol properties: Comparison of boundary layer measurements from ACE 1, ACE 2, Aerosols99, INDOEX, ACE Asia, TARFOX, and NEAQS, *J. Geophys. Res.*, **110**, D14202, doi:10.1029/2004JD004755.
- Remer, L. A., et al. (2005), The MODIS aerosol algorithm, products and validation, *J. Atmos. Sci.*, **62**, 947–973.
- Sakerin, S. M., and D. M. Kabanov (2002), Spatial inhomogeneities and the spectral behavior of atmospheric aerosol optical depth over the Atlantic Ocean, *J. Atmos. Sci.*, **59**, 484–500.
- Schoeberl, M. R., and P. A. Newman (1995), A multiple-level trajectory analysis of vortex filaments, *J. Geophys. Res.*, **100**, 25,801–25,815.
- Shinzuka, Y., et al. (2004), Sea-salt vertical profiles over the Southern and tropical Pacific oceans: Microphysics, optical properties, spatial variability, and variations with wind speed, *J. Geophys. Res.*, **109**, D24201, doi:10.1029/2004JD004975.
- Smirnov, A., et al. (2002), Optical properties of atmospheric aerosol in maritime environments, *J. Atmos. Sci.*, **59**, 501–523.
- Smirnov, A., et al. (2003), Effect of wind speed on columnar aerosol optical properties at Midway Island, *J. Geophys. Res.*, **108**(D24), 4802, doi:10.1029/2003JD003879.
- Volgin, V. M., et al. (1988), Optical depth of aerosol in typical sea areas, *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys., Engl. Transl.*, **24**, 772–777.
- Voss, K. J., et al. (2001), Aerosol optical depth measurements during the Aerosols99 experiment, *J. Geophys. Res.*, **106**, 20,811–20,819.
- Wilson, S. R., and B. W. Forgan (2002), Aerosol optical depth at Cape Grim, Tasmania, 1986–1999, *J. Geophys. Res.*, **107**(D8), 4068, doi:10.1029/2001JD000398.
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