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Diurnal variability of aerosol optical depth observed at AERONET (Aerosol Robotic Network) sites

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Received 18 September 2002; revised 27 October 2002; accepted 28 October 2002; published 10 December 2002.

[1] Diurnal variability of aerosol optical depth is important for various applications, including satellite aerosol data validation, radiative forcing computations, studies of aerosol interaction with humidity and clouds, and also public health. Aerosol optical depth measurements acquired through the ground-based Aerosol Robotic Network are analyzed. Analysis of the diurnal cycle over major urban/industrial areas within the network showed a prevailing pattern of the optical depth increase by 10–40% during the day at most sites. Diurnal variability range is <10% over various sites where dust aerosol is a major contributor to optical depth. Sites in southern Africa influenced by distant sources of biomass burning aerosol show no diurnal cycle, while the presence of local sources causes a diurnal trend with a maximum aerosol loading observed in the afternoon hours. Over oceans, because of the very low optical depth, even 20% departure from the daily average is practically within the measurement uncertainty.

INDEX TERMS: 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 0360 Atmospheric Composition and Structure: Transmission and scattering of radiation; 1640 Global Change: Remote sensing. **Citation:** Smirnov, A., B. N. Holben, T. F. Eck, I. Slutsker, B. Chatenet, and R. T. Pinker, Diurnal variability of aerosol optical depth observed at AERONET (Aerosol Robotic Network) sites, *Geophys. Res. Lett.*, 29(23), 2115, doi:10.1029/2002GL016305, 2002.

1. Introduction

[2] Aerosols frequently exhibit widely varying optical properties over time due to diffusion and aging processes such as coagulation, humidification, scavenging by precipitation and gas to particle phase conversion. These combined with varying source strengths and advection by local to synoptic meteorological processes create a dynamic atmospheric constituent for effects on climate, environment and public health. In particular, diurnal effects are largely unknown and little studied due to the paucity of data although several exceptions are noted [Kaufman *et al.*,

2000; Panchenko *et al.*, 1999; Pinker *et al.*, 1994; Peterson *et al.*, 1981; Barteneva *et al.*, 1967].

[3] The TRIANA satellite [Valero *et al.*, 1999] will provide the first good opportunity to assess systematic diurnal aerosol dynamics with the same solar zenith angle as ground based sun photometry such as the Aerosol Robotic Network (AERONET) stations provide [Holben *et al.* 1998]. Thus, the need to validate TRIANA diurnal retrievals will eventually lead to a synergistic global assessment between ground and satellite systems.

[4] Long-term exposure to aerosols is being shown to be critically important to public health, for lung cancer and cardiopulmonary mortality and respiratory diseases [Pope *et al.*, 2002]. However, little data exist that potentially could assess the impact of diurnal exposure.

[5] Multi-site multi-year aerosol optical depth data from AERONET provides a unique opportunity now for a comprehensive analysis of diurnal aerosol variations according to aerosol types and landscapes.

2. Analysis and Results

[6] AERONET is a federated international network of sun/sky radiometers dating back to 1993. AERONET maintains more than 180 automatic instruments (sun/sky radiometers) worldwide [Holben *et al.*, 1998; Holben *et al.*, 2001]. A series of papers describe the instrument, corresponding measurement sequences, accuracy and cloud screening procedure [Holben *et al.*, 1998; Eck *et al.*, 1999; Smirnov *et al.*, 2000; Holben *et al.*, 2001].

[7] All individual observations for a day are expressed as a percentage departure from the daily mean. Computed percentages were averaged hourly (0300–0400 GMT, 0400–0500 GMT etc.) for each measurement period. The sampling procedure, which is similar to one used by Peterson *et al.* [1981], renders systematic diurnal trends more evident. We present diurnal variability of aerosol optical depth at a wavelength 500 nm, unless otherwise noted.

[8] Five specific land sites with a multi-year record are described representing regionally distributed aerosol types (urban, dust, dust and smoke, smoke, and background) and multiple sites are analyzed for urban, dust, biomass burning and marine aerosols.

[9] Goddard Space Flight Center is situated in suburban Washington, D.C. Local emissions are dominated by automobiles, rather than by heavy industry. Aerosol optical depth (τ_a) diurnal variations for GSFC computed on a yearly basis are shown in Figure 1a. Each hourly average consists of at least three thousand individual observations. There is a clear diurnal τ_a cycle during the 1993–2001 period. The diurnal variability of optical depth ranges from ~8% in 1998 to 26% in 1997. Local pollutants along with

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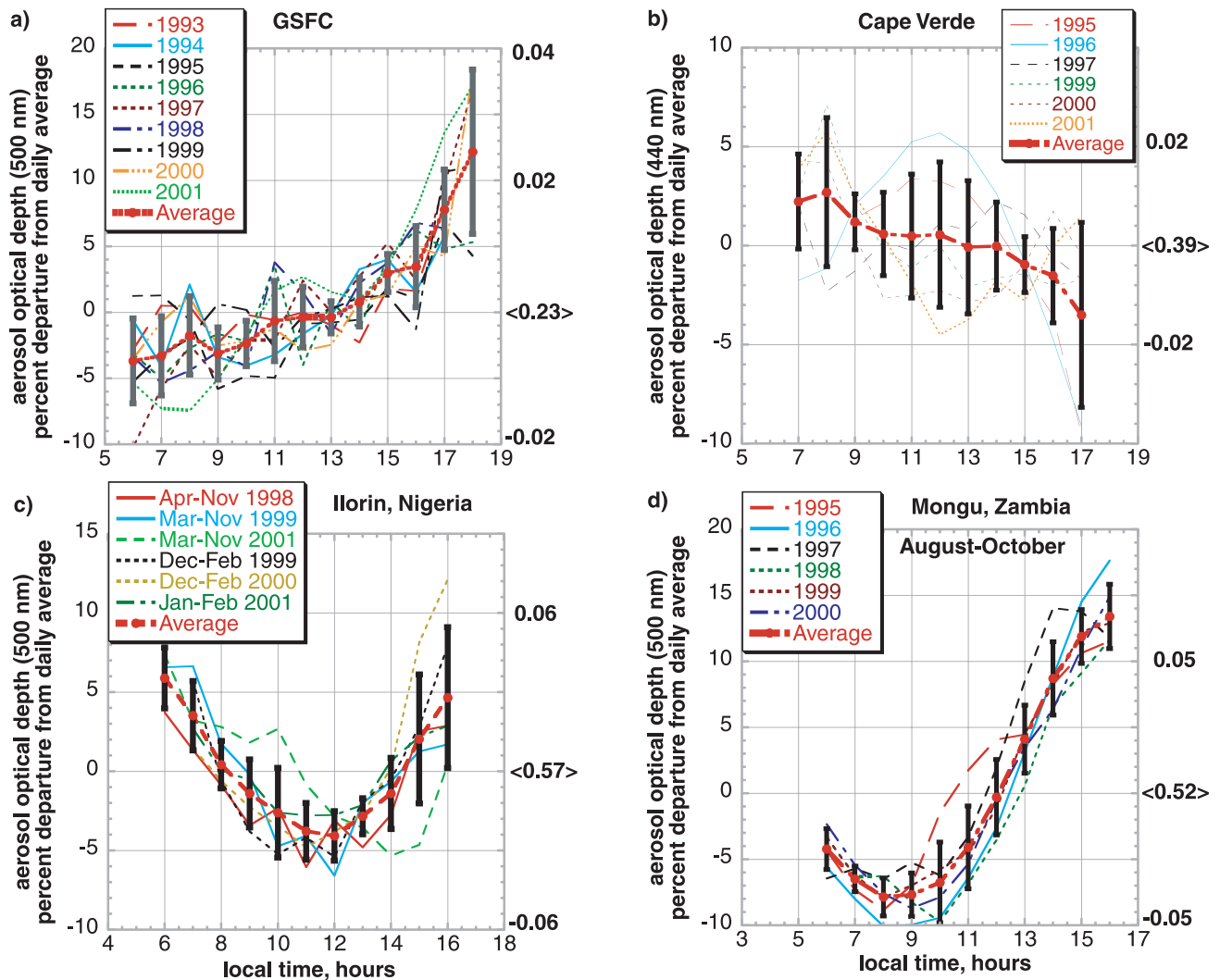


Figure 1. Diurnal variability of aerosol optical depth computed hourly as percent departure from daily average for Goddard Space Flight Center (a), Cape Verde (b), Ilorin, Nigeria (c), Mongu, Zambia (d). Average aerosol optical depth is given on right hand axis.

atmospheric convection likely played a major role in the slight diurnal increase of the optical depth. The diurnal pattern is consistent each year. The average diurnal increase of 16% corresponds to a 0.04 change in aerosol optical depth (yearly average $\tau_a(500 \text{ nm}) = 0.23$). However during the summer season the atmosphere is less stable, optical depth is higher and the same percent departure from the daily average yields a 0.07 increase in $\tau_a(500 \text{ nm})$. In summer the diurnal trend appears “noisier” because fewer measurements points are acquired in the afternoon due to cloud formation. However, a general trend of increasing aerosol optical depth in the afternoon is clear.

[10] Sal Island, Cape Verde, is located $\sim 500 \text{ km}$ west of the African coast in the outflow area of Saharan dust. High aerosol loading is evident all year round [Holben *et al.*, 2001] and dust is the major contributor [Chiapello *et al.*, 1999]. Diurnal variations of optical depth, although not similar in all the years, are practically insignificant (plus or minus only several percent from daily averages). Average diurnal variations of about $\pm 3\%$ from the mean (Figure 1b) correspond to ~ 0.02 change in $\tau_a(440 \text{ nm})$. The general

trend shows optical depth decreasing slightly in the afternoon. No definite cycle has been found when May–September (higher τ_a) and October–April (lower τ_a) seasons were considered separately.

[11] A multi-year data record from Ilorin, Nigeria represents a mixture of dust and smoke aerosol during the “dry” season (December–February) and predominantly dust aerosol from March through November (“wet” season). Midday minimum of aerosol optical depth contributes to a 10% *am* and *pm* peak during both the dry and wet seasons (Figure 1c). This remarkable consistency in different years and seasons is independent of the instrument and calibration history, and therefore depicts the actual conditions at the site, however the reason for this diurnal trend is unknown.

[12] Figure 1d illustrates a significant diurnal cycle for smoke aerosol during the burning season (from August through October) in the southern African site of Mongu, Zambia. Because local sources (satellite detected fire counts) peak at mid afternoon, aerosol optical depth increases throughout the day. This trend is consistent and repeatable. The average optical depth increase can be 0.10 or higher. Eck

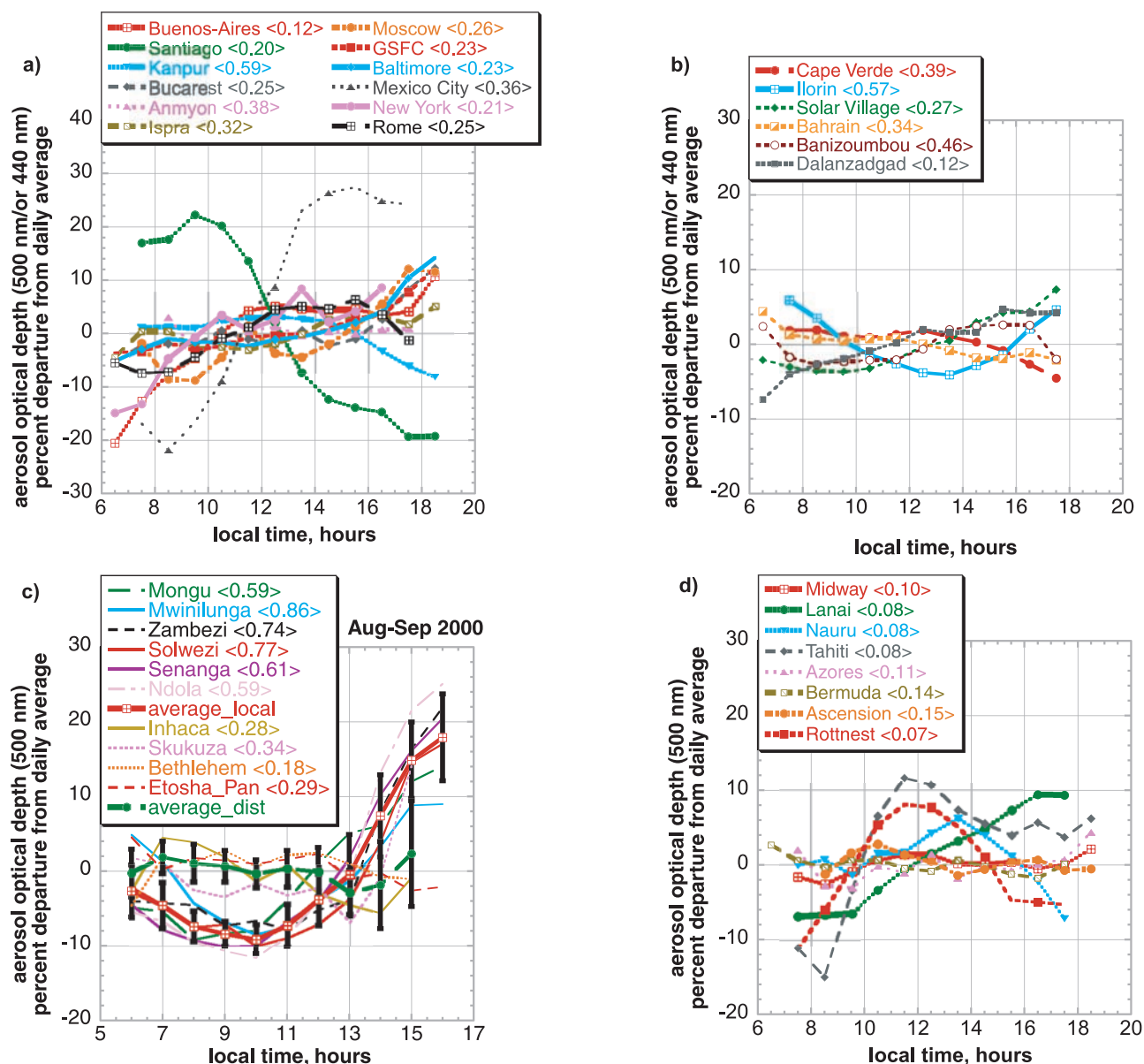


Figure 2. Diurnal variability of aerosol optical depth for various aerosol types: urban/industrial (a), dust (b), biomass burning in southern Africa (c), maritime (d). Average optical depths are listed next to the site names.

et al. [2002] noted that the diurnal cycle in aerosol loading is caused by a cycle not only in the number of fires, but possibly also their increasing intensity in the afternoon hours, owing to the higher air temperature, lower relative humidity and higher wind speeds at mid-day and later.

[13] A variable multi-year pattern is observed in Sevillaeta, New Mexico. This background site is located at the elevation of ~ 1500 m above sea level and is not influenced by local anthropogenic aerosol sources. Even in a year with $\sim 15\%$ range the magnitude of τ_a diurnal range is only ~ 0.01 . Therefore there is no obvious average diurnal cycle in Sevillaeta, which is in full agreement with the more general results presented by Kaufman *et al.* [2000].

[14] We start our multiple site consideration with the analysis of the diurnal cycle over major urban/industrial areas within the network.

[15] Mexico City is one of the most polluted metropolises in the world due to local industrial sources and

automobile emissions. Diurnal variability of aerosol optical depth is significant, annually repeatable, and on average is about 50% (Figure 2a). Late afternoon north-easterly flow ventilates the Mexico City basin by lofting the air from the valley into southwesterly flow above the mountaintop level [Bossert, 1997]. Measurements over Santiago, Chile also indicate a large diurnal cycle of $\sim 40\%$, however, optical depth decreases during the day. Trier and Horvath [1993] reported the same pattern and magnitude of diurnal variation in horizontal transmission over Santiago, Gramsch *et al.* [2000] observed similar trend of the absorption coefficient. Traffic causes the morning peak, and an evening breeze that runs from west to east brings in clean air in the afternoon [Gramsch *et al.*, 2000].

[16] The majority of sites influenced by local urban/industrial sources exhibit similar diurnal variability. Optical depth steadily increases throughout the day and reaches

maximum in the afternoon. This increase is less than 10% in Ispra, Italy between 10% and 15% in Rome, Bucarest, and GSFC, and ~20% or more in Baltimore, New York City, Buenos-Aires, and Moscow. The trend is less important for Buenos-Aires because average optical depth at 500 nm is only 0.12.

[17] Kanpur is located in one of North India's major industrial and population centers and is also influenced by desert dust from arid regions immediately to the west. Aerosol optical depth diurnal variability is about 10% (yearly average $\tau_a(500 \text{ nm}) = 0.59$), being constant during the morning and midday and decreasing in the late afternoon hours.

[18] There are virtually no changes (less than 5% overall) in the diurnal dependence over Anmyon, Korea. This site is influenced by pollution and dust sources in China and therefore the aerosol is transported a significant distance from the sources.

[19] Figure 2b illustrates the diurnal cycle over various sites where dust aerosol is a major contributor to optical depth. Diurnal variations are different for all sites, although they typically lie within the 10% range. Two sites (Solar Village, Saudi Arabia and Dalanzadgad, Mongolia) located relatively close to source regions exhibit a diurnal trend with the minimum τ_a in the morning and maximum in the afternoon.

[20] A number of instruments deployed during the SAFARI 2000 campaign allowed analysis of the biomass burning aerosol diurnal variability. Sites influenced by distant sources show no diurnal cycle [Eck et al., 2002]; on the other hand, sites in Zambia near local burning showed a distinct trend of aerosol optical depth (Figure 2c).

[21] Over oceans, a "classical" diurnal pattern (see, e.g. [Barteneva et al., 1967; Peterson et al., 1981] with a slow increase to maximal turbidity around midday is apparent only for Rottneest Island (20 km from the coast of western Australia). Figure 2d also shows a pronounced increase of τ_a around midday for Tahiti with a slow decrease in the afternoon. The diurnal trend over Lanai is not significant in terms of optical depth (less than 20% change corresponds to $\Delta\tau_a \sim 0.015$). Elsewhere at AERONET oceanic sites there is only a relatively weak diurnal variability (Figure 2d).

3. Conclusions

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

1. Analysis of the diurnal cycle over most major urban/industrial areas within the network showed a prevailing trend of the optical depth increase by 10–40%, depending on the site, during the day.

2. We could not generalize a diurnal trend for the dust aerosol, however, for all the sites considered it does not exceed $\pm 5\%$ from the mean.

3. Local sources of aerosols from biomass burning in Zambia caused a ~20% diurnal increase in optical depth, while sites distant from sources show no diurnal cycle.

4. Over oceans, diurnal variations of aerosol optical depth are mainly insignificant, taking into account the low values of $\tau_a(500 \text{ nm})$.

[23] **Acknowledgments.** The authors thank Dr. Michael King of the EOS Project Science Office for his support of AERONET. The authors would like to thank Yoram Kaufman and Paul Ginoux for fruitful discussions of certain issues. Our thanks are extended to the individual principal investigators and site managers who have maintained an active interest in the AERONET project and resulted in long-term observations. We also thank two anonymous reviewers for useful comments.

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