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How well do state-of-the-art techniques measuring the vertical profile of tropospheric aerosol extinction compare?

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[1] The recent Department of Energy Atmospheric Radiation Measurement (ARM) Aerosol Intensive Operations Period (AIOP, May 2003) yielded one of the best measurement sets obtained to date to assess our ability to measure the vertical profile of ambient aerosol extinction $\sigma_{ep}(\lambda)$ in the lower troposphere. During one month, a heavily instrumented aircraft with well-characterized aerosol sampling ability carrying well-proven and new aerosol instrumentation devoted most of the 60 available flight hours to flying vertical profiles over the heavily instrumented ARM Southern Great Plains (SGP) Climate Research Facility (CRF). This allowed us to compare vertical extinction profiles obtained from six different instruments: airborne Sun photometer (AATS-14), airborne nephelometer/absorption photometer, airborne cavity ring-down system, ground-based Raman lidar, and two ground-based elastic backscatter lidars. We find the in situ measured $\sigma_{ep}(\lambda)$ to be lower than the AATS-14 derived values. Bias differences are 0.002–0.004 Km^{-1} equivalent to 13–17% in the visible, or 45% in the near-infrared. On the other hand, we find that with respect to AATS-14, the lidar $\sigma_{ep}(\lambda)$ are higher: Bias differences are 0.004 Km^{-1} (13%) and 0.007 Km^{-1} (24%) for the two elastic backscatter lidars (MPLNET and MPLARM, λ = 523 nm) and 0.029 Km^{-1} (54%) for the Raman lidar (λ = 355 nm). An unnoticed loss of sensitivity of the Raman lidar had occurred leading up to AIOP, and we expect better agreement from the recently restored system. Looking at the collective results from six field campaigns conducted since 1996, airborne in situ measurements of $\sigma_{ep}(\lambda)$ tend to be biased slightly low (17% at visible wavelengths) when compared to airborne Sun photometer $\sigma_{ep}(\lambda)$. On the other hand, $\sigma_{ep}(\lambda)$ values derived from lidars tend to have no or positive biases. From the bias differences we conclude that the typical systematic error associated with measuring the tropospheric vertical profile of the ambient aerosol extinction with current state-of-the-art instrumentation is 15–20% at visible wavelengths and potentially larger in the UV and near-infrared.

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1. Introduction

[2] A major uncertainty in predicting future changes to the Earth system in general, and its climate in particular, stems from the difficulty of modeling the effects of atmospheric aerosols. In fact, recent modeling studies debate to what extent controlling the emission of aerosol (i.e., reducing the emission of light-absorbing aerosol) into the Earth's atmosphere may be a feasible way to slow global warming [*Jacobson*, 2002; *Hansen et al.*, 2000; *Sato et al.*, 2003; *Penner et al.*, 2003; *Penner*, 2003]. The current low confidence in the estimates of aerosol induced perturbations of the Earth's radiation balance is caused by the highly nonuniform compositional, spatial and temporal distribution of tropospheric aerosols owing to their heterogeneous sources and short lifetimes.

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[3] Aerosols affect climate through a variety of pathways. These pathways include direct effects on the scattering and absorption of radiation, indirect effects caused by aerosol roles in cloud microphysics, and "semidirect" effects caused by aerosol modification of atmospheric heating, temperature profiles, convection, and large-scale horizontal transport [e.g., *Ackerman et al.*, 2000; *Chameides and Bergin*, 2002; *Lelieveld et al.*, 2002; *Menon et al.*, 2002]. Many of these pathways can affect precipitation, and thus aerosols are intimately linked to the hydrological cycle [e.g., *Ramanathan et al.*, 2001; *Rotstayn and Lohmann*, 2002].

[4] Monitoring the global distribution of aerosols requires the combination of continuous observations from satellites, networks of ground-based instruments, and dedicated field experiments [*Kaufman et al.*, 2002].

[5] The globally distributed Aerosol Robotic Network (AERONET) consisting of ~200 Sun-and sky-scanning ground-based automated radiometers provides column measurements of aerosol optical properties, with up to ten years of observations in some locations [*Holben et al.*, 2001]. These data are used extensively for the validation of satellite-derived aerosol properties [e.g., *Diner et al.*, 2001; *Torres et al.*, 2002; *Chu et al.*, 2003]. In situ measurements of aerosol optical properties and composition are made by numerous ground-based networks around the world [e.g., *Delene and Ogren*, 2002; *VanCuren*, 2003]. Ground-based lidar networks monitoring the vertical distribution of aerosols are also emerging [*Welton et al.*, 2001; *Ansmann et al.*, 2003]. The era of continuous satellite-based observation of the vertical distribution of tropospheric aerosols has begun very recently with the launch of the Geoscience Laser Altimeter System (GLAS) in January 2003 [*Spinhirne et al.*, 2005].

[6] Here, we assess the accuracy with which the vertical profile of aerosol extinction (a fundamental aerosol property) can currently be measured with state-of-the-art instrumentation. We cannot stress enough that for climate considerations it is the properties of the unaltered aerosol at its ambient concentration and thermodynamic state that are of interest. Hence the accuracy assessment presented here applies to the measurement of the vertical profile of ambient aerosol extinction. To arrive at this assessment we rely on comparisons of ambient aerosol extinction profiles obtained in coordinated field campaigns that include in situ and remote sensing measurements of aerosols aboard airborne platforms over surface-based lidars. We start with the results of a recent campaign, the Department of Energy Atmospheric Radiation Measurement (ARM) Aerosol Intensive Operations Period (AIOP, May 2003), and then consider these results in the context of findings from other field campaigns conducted since 1996.

[7] AIOP yielded one of the best suited measurement sets obtained to date to assess our ability to measure the vertical profile of ambient aerosol extinction. During one month, a heavily instrumented aircraft with well-characterized aerosol sampling ability carrying a combination of well-proven and new aerosol instrumentation, devoted most of the 60 available flight hours to flying vertical profiles over the heavily instrumented ARM Southern Great Plains (SGP) Climate Research Facility (CRF) [*Ackerman and Stokes*, 2003]. This allows us to compare vertical extinction profiles obtained from 6 different instruments: airborne Sun photometer, airborne nephelometer/absorption photometer, airborne cavity ring-down system, ground-based Raman lidar and 2 ground-based elastic backscatter lidars.

2. Measurements

2.1. Airborne Measurements

2.1.1. Twin Otter Aircraft

[8] The Twin Otter is operated by the Marina, California, based Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) [*Bluth et al.*, 1996; *Bane et al.*, 2004]. Between 6 and 29 May 2003, the Twin Otter performed 16 research flights out of Ponca City, Oklahoma, Airport. All flight patterns were anchored at the ARM SGP CRF (36.60°N, 97.48°W, 319 m), 32 km west of Ponca City. For the AIOP campaign the maximum flight altitude was 5.6 km. All in situ instrumentation aboard the Twin Otter discussed here sampled aerosol from a shrouded intake whose inlet passing efficiency was tested in airborne and wind tunnel experiments by *Hegg et al.* [2005]. They find no appreciable loss in efficiency for particles smaller than ~3.5 μm diameter at the typical Twin Otter velocity of 50 m s^{-1}. For larger particles, the efficiency decreases rapidly but levels off at an efficiency of slightly better than 0.6 for particles 5.5 μm diameter through the limit of their measurements at 9 μm.

2.1.2. Aerosol Extinction From Sun Photometry Aboard the Twin Otter

[9] The NASA Ames Airborne Tracking 14-channel Sun photometer (AATS-14) measures the transmission of the direct solar beam in 14 spectral channels (354 to 2139 nm). AATS-14 is an enhanced version of the AATS-6 instrument [*Matsumoto et al.*, 1987].

[10] The AATS-14 tracking head is mounted outside the aircraft skin to minimize blockage by aircraft structures and to avoid data contamination by aircraft window effects. The instrument locates and tracks the Sun without input from an operator and records data in a self-contained data system. Using aircraft-provided data on latitude, longitude and ambient static pressure, aerosol (or particulate) optical depth $\tau_p(\lambda)$ and columnar water vapor (CWV) are computed and displayed in real time.

[11] AATS-14 made its first science flights during the Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX) in July 1996 [*Russell et al.*, 1999a, 1999b]. Since then, AATS-14 has been operated on many aircraft in numerous aerosol oriented field experiments: ACE-2 [*Schmid et al.*, 2000], SAFARI 2000 [*Schmid et al.*, 2003a], ACE-Asia [*Schmid et al.*, 2003b], CLAMS [*Redemann et al.*, 2005], SOLVE-2 [*Livingston et al.*, 2005; *Russell et al.*, 2005]), and ADAM [*Bucholtz et al.*, 2003].

[12] During AIOP, AATS-14 operated successfully on all 16 Twin Otter research flights. Conditions in the boundary layer tended to be relatively turbulent, resulting in larger (compared to flights over the ocean surface) AATS-14 tracking errors. Measurements exceeding a tracking error of 1° were flagged as questionable data points and not used for this study. The tracking capabilities of AATS-14 under such bumpy conditions have recently been improved by changing settings in the tracking software. To avoid contamination of the AATS-14 entrance window, the tracking head was moved into its park position before flying through clouds.