Measurement and Modeling of Vertically Resolved Aerosol Optical Properties and Radiative Fluxes Over the ARM SGP Site During the May 2003 Aerosol IOP

B. Schmid and J. Redemann
Bay Area Environmental Research Institute
National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California

W. P. Arnott
Desert Research Institute
Reno, Nevada

A. Bucholtz and J. Reid
Naval Research Laboratory
Monterey, California

P. Colarco
Earth System Science Interdisciplinary Center
University of Maryland
College Park, Maryland

D. Covert and R. Elleman
University of Washington
Seattle, Washington

J. Eilers, P. Pilewskie, and A. Strawa
National Aeronautics and Space Administration
Ames, Research Center
Moffett Field, California

R. A. Ferrare
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

B. N. Holben and E. J. Welton
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland

H. H. Jonsson
Center for Interdisciplinary Remotely-Piloted
Aircraft Studies
Naval Postgraduate School
Monterey, California

K. Ricci
National Aeronautics and Space Administration
Los Gatos Research
Ames Research Center
Moffett Field, California

J. Seinfeld
Div. of Engineering and Applied Sciences
California Institute of Technology
Pasadena, California

D. D. Turner
Pacific Northwest National Laboratory
Richland, Washington

J. Wang
Brookhaven National Laboratory
Upton, New York

Introduction

We present airborne results obtained during the May 2003 aerosol intensive operational period (AIOP) aboard the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter aircraft. The Twin Otter performed 16 research flights over the heavily instrumented Southern Great Plains (SGP) site. The aircraft carried instrumentation to perform in situ measurements of aerosol absorption, scattering, extinction and particle size. These instruments included such novel techniques as the photoacoustic and cavity ring-down methods for measuring absorption (675 nm) and extinction (675 and 1550 nm), respectively, and a new multiwavelength, filter-based absorption photometer (PSAP, λ = 467, 530, 660 nm). A newly developed instrument measured cloud condensation nucleus (CCN) concentrations at two supersaturation levels. Aerosol optical depth (AOD) and extinction (354-2139 nm) were measured with the National Aeronautics and Space Administration (NASA) Ames airborne tracking 14-channel sunphotometer (AATS-14). Furthermore, up- and downwelling solar (broadband and spectral) and infrared radiation were measured using seven individual radiometers. Three up-looking radiometers were mounted on a newly developed stabilized platform, keeping the instruments level up to aircraft pitch and roll angles of ~10°. This resulted in unprecedented continuous vertical profiles of radiative fluxes.

Vertically resolved aerosol optical properties were also measured with three ground-based lidar systems. We use a trajectory model and a three-dimensional aerosol transport and microphysics model to explore the long-range transport and evolution of smoke aerosols originating in Siberia and observed over SGP on May 25-28, 2003.

Selected Results

Aerosol Optical Depth Comparisons

During most of the flights the Twin Otter flew at least one low-altitude leg (300 ft above ground) near the SGP central facility. This allowed comparing AODs from the airborne sunphotometer (AATS-14) and ground-based sunphotometers such as the AERONET instruments. The comparison resulting from 18 low-altitude fly-bys is shown in Figure 1 for four different wavelengths. The Aerosol Robotic Network (AERONET) data used are Level 1.5 data from the Cimel instrument associated with the SMART trailer. We will repeat the comparison with Level 2 data (final calibration applied) which have become available recently. We are pleased with the level of agreement as it is similar to what we found from low altitude fly-bys in previous campaigns (Livingston et al. 2003, Schmid et al. 2003a, Redemann et al. 2004). AODs obtained with an AATS and an AERONET instrument operating on the ground side-by-side in previous IOPs were found to agree within 0.02 root mean square (Schmid et al. 1999).

Water Vapor Comparisons

AATS-14 uses the 0.94-µm H_2O-absorption band to derive the columnar water vapor (CWV) above the airplane (Schmid et al. 2001). Measuring CWV at two different altitudes allows determination of layer water vapor. Differentiating a vertical profile of CWV allows derivation of water vapor density ρ_w (see Schmid et al. 2000). ρ_w is also derived aboard the Twin Otter using measurements of static temperature, dew point temperature, and static pressure. Layer water vapor can be obtained from the in situ measurements by integrating ρ_w. During AIOP we found 35 vertical profiles that allow a comparison of ρ_w and layer water vapor as retrieved from in-situ and AATS-14 measurements. The results are shown as scatter plots in Figure 2.

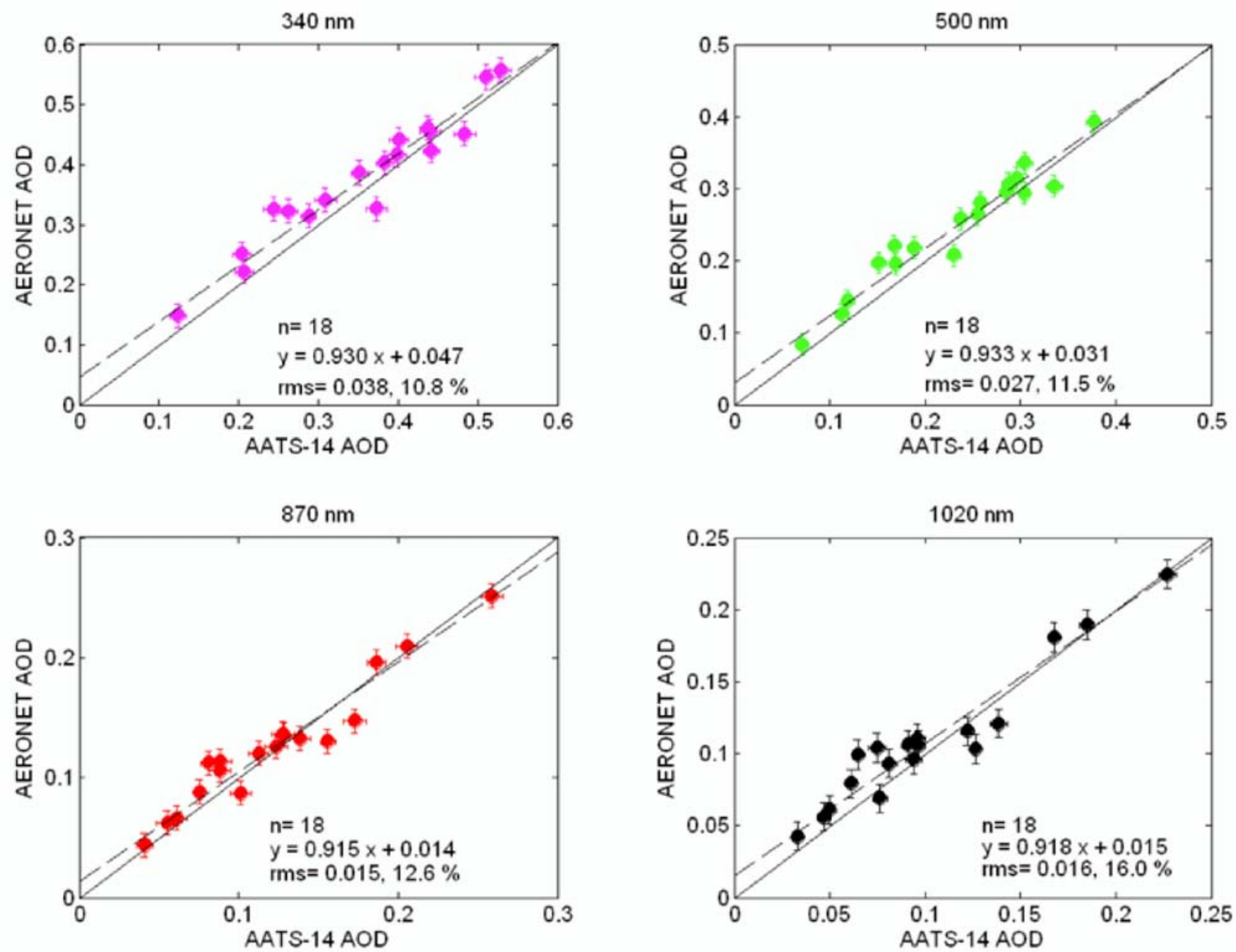

Figure 1. Comparing airborne AATS-14 and ground-based AERONET AODs at four wavelengths during 18 low-altitude fly-bys.

Aerosol Extinction Closure

In analogy to deriving ρ_w from airborne CWV measurements in profiles, AATS-14 data can be used to derive AOD of a layer or aerosol extinction by differentiating AOD vertical profiles (see Schmid et al. 2000). The same quantities can be derived from in-situ measurements aboard the aircraft. This over-determined data set allows addressing the question: "Can in situ measurements of aerosol properties account for the solar beam attenuation (extinction) by an aerosol layer or column?" Such closure studies reveal important insights about airborne aerosol sampling because inlet effects (e.g., loss or enhancement of large particles, shrinkage by evaporation of water, organics, or nitrates) and filter effects are avoided when using the AATS-14 data.

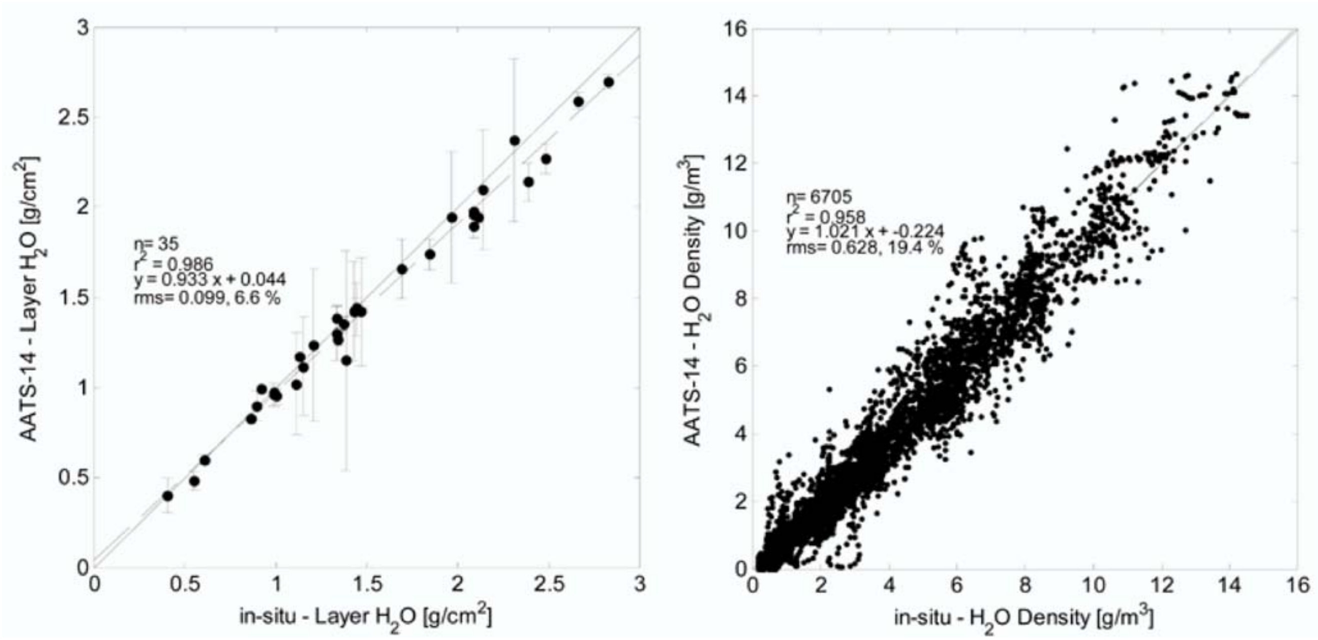

Figure 2. Comparisons of layer water vapor (left) and water vapor density (right) from EdgeTech chilled mirror in situ sensor and AATS-14 for 35 vertical profiles.

AATS data have contributed to numerous "closure" studies in field campaigns such as TARFOX, ACE-2, SAFARI 2000, ACE-Asia, CLAMS, and ARM AIOP (Hegg et al. 1997, Hartley et al. 2000, Collins et al. 2000, Schmid et al. 2000 and 2003b, Wang et al. 2002, Magi et al. 2003 and 2004, Redemann et al. 2000 and 2003).

During the May 2003 AIOP, comparisons between in-situ and AATS-14 layer AOD (and extinction) was possible for 26 vertical profiles. In situ extinction is computed as the sum of scattering (from humidified nephelometry) and absorption (PSAP instrument). In situ extinction is further derived using Cadenza (a cavity ring-down instrument; Strawa et al. 2003) again applying the humidification corrections measured with separate nephelometers. The layer AOD comparisons are shown in Figure 3. Based on the slope of the regression line (linear bisector) we find the layer AOD (λ = 675 nm) from Neph+PSAP and Cadenza to be lower than the AATS-14 values by 17% and 13%, respectively. The agreement between Cadenza and AATS-14 in the 26 vertical profiles studied here seems to be somewhat better overall than the agreement between Neph+PSAP and AATS-14. Comparisons between the SGP Raman lidar (RL) and AATS-14 have been presented by Ferrare et al. (2004). The RL suffered from degraded performance during the AIOP and the RL extinction values appear biased high (33%) versus AATS-14. We are currently extending the comparison to include two micropulse lidars (MPL) that were operated at SGP during AIOP, the NASA Micropulse Lidar Network (MPLNET) MPL and the ARM CART MPL.

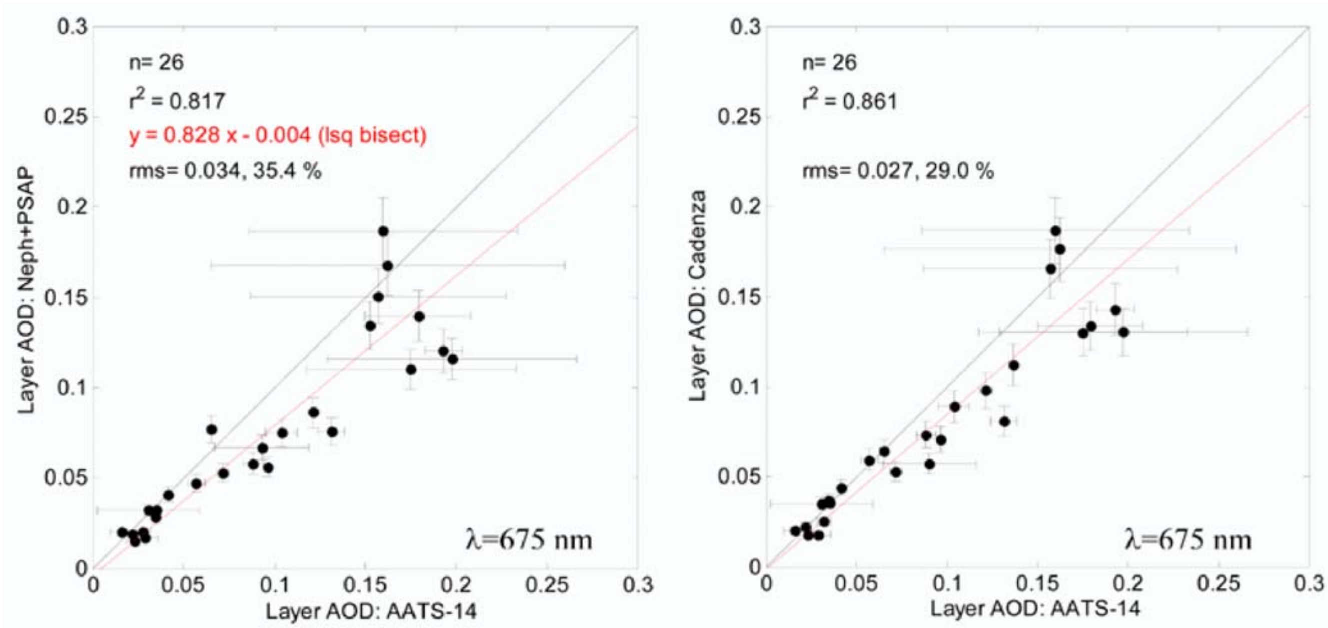

Figure 3. Left: Comparison of layer AOD from AATS-14 and Nephelometer+PSAP (corrected to ambient conditions). Right: Comparison of layer AOD from AATS-14 and Cadenza (cavity ring-down instrument, corrected to ambient conditions).

Elevated Smoke Layers from Siberia

In the period May 25-28, 2003, we observed elevated thin aerosol layers (most prominent at 3-4 km a.s.l) with extinction coefficients in the order of ~200 Mm^{-1} significantly exceeding the extinction values in the boundary layer. A picture taken from the cockpit of the Twin Otter on May 27, 2003, shows such an elevated layer (Figure 4). Aerosol transport modeling and satellite imagery confirmed that the smoke originated from Siberian fires. Using the MATCH/CARMA model (Colarco et al. 2004) we "predicted" the aerosol extinction profile at SGP. As shown in Figure 5, the model has difficulties reproducing the observed thin elevated layers.

Aerosol Absorption Comparisons

On the Twin Otter in-situ aerosol absorption measurements were made using three different techniques: Filter-based (PSAP), photoacoustic (PA), and difference between extinction and scattering (Cadenza). Detailed comparisons between the three datasets are currently being carried out (Strawa et al. 2004). Figure 6 shows a comparison between PSAP and PA for the flight conducted on May 27. The largest absorption values correspond to the Siberian smoke layers (see Figure 5), which we traversed several times during the flight.

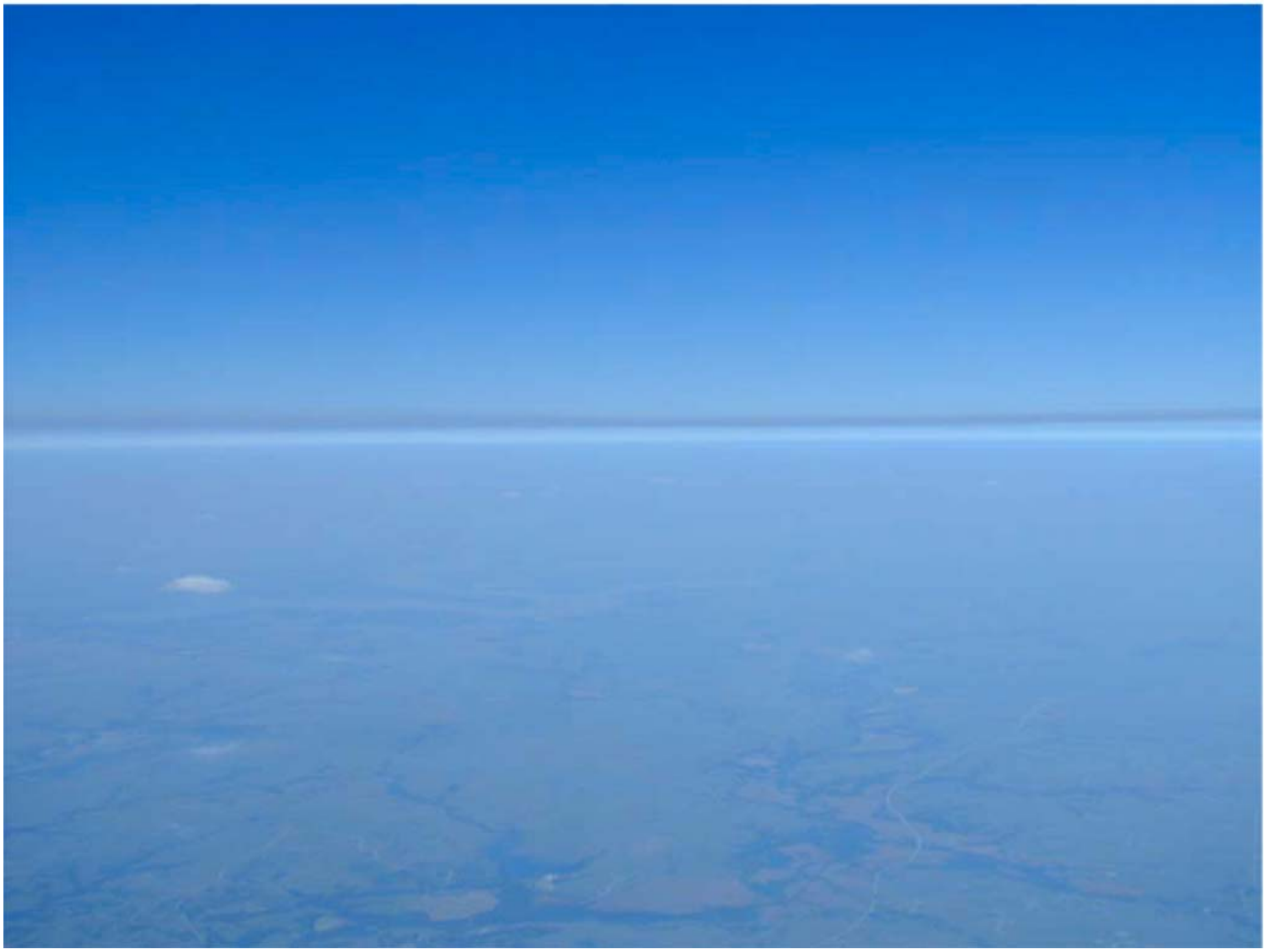

Figure 4. Picture of elevated aerosol layer over SGP taken from Twin Otter cockpit by pilot Roy Woods, May 27, 2003.

Concluding Remarks

Here we have only presented a very small subset of the AIOP results. A more comprehensive presentation of the results will appear in journal publications that are currently in preparation for an AIOP special issue.

ACP scientists and investigators, CIRPAS Twin Otter and Cessna pilots, crew, and support personnel, SGP site personnel, ARM infrastructure support, weather forecaster, and support from Greenwood aviation at the Ponca City airport. We thank ARM for their support of this IOP.

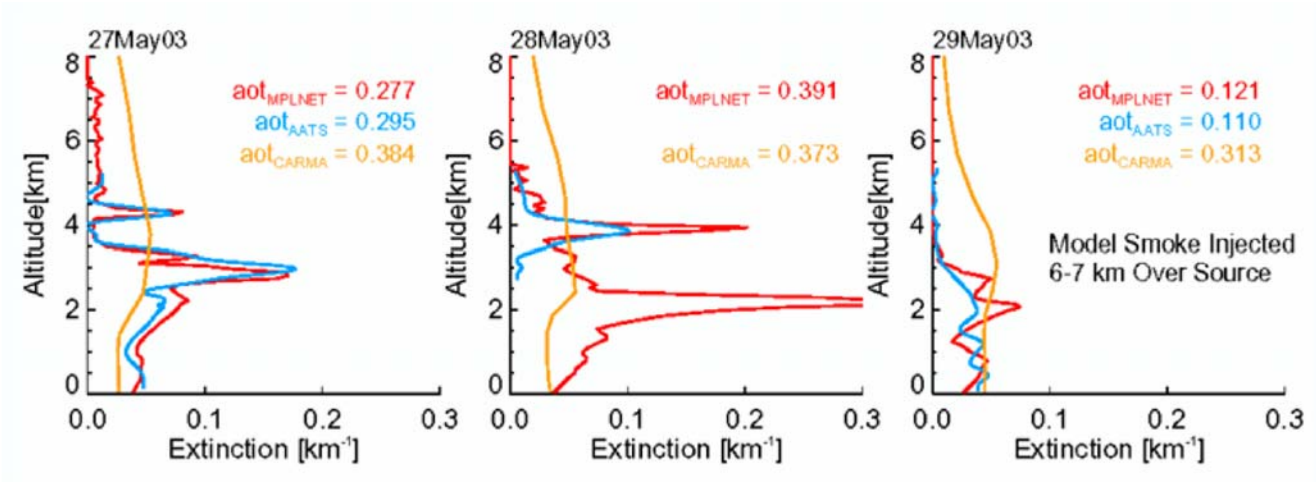

Figure 5. Aerosol extinction vertical profile over the SGP site measured by airborne sunphotometry (blue), ground-based MPLNET (red), and modeled with the MATCH/CARMA aerosol transport/process model (yellow).

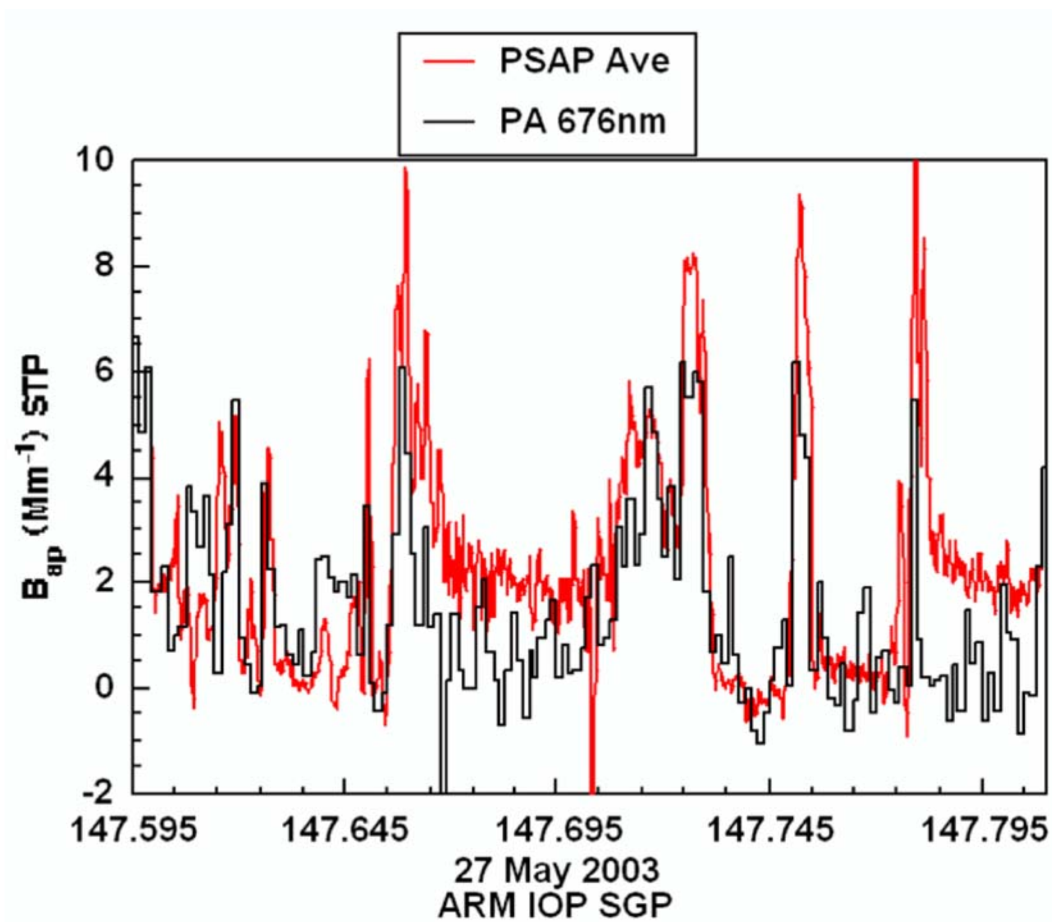

Figure 6. Comparison of aerosol absorption coefficient from photoacoustic (PA) and filter based PSAP instrument aboard the Twin Otter during a flight conducted on May 27.

Corresponding Author

B. Schmid, bschmid@mail.arc.nasa.gov, (650) 604-5933

References

Colarco, P. R., M. r. Schoeberl, B. G. Doddridge, L. T. Marufu, O. Torres, and E. J. Welton, 2004: Transport of smoke from Canadian forest fires to the surface near Washington, D.C.: Injection height, entrainment, and optical properties. *J. Geophys. Res*., **109**(D6), D06203, doi: 10.1029/2003JD004248.

Collins, D. R., H. H. Jonsson, J. H. Seinfeld, R.C. Flagan, S. Gassó, D. A. Hegg, B. Schmid, P. B. Russell, J. M. Livingston, E. Öström, K. J. Noone, L. M. Russell, and J. P. Putaud, 2000. In situ aerosol size distributions and clear column radiative closure during ACE-2. *Tellus*, **B 52**, 498–525.

Ferrare R., D. Turner, M. Clayton, B. Schmid, J. Redemann, D. Covert, R. Elleman, E.J. Welton, V. Brackett, J. Ogren, E. Andrews, and J.E.M. Goldsmith, 2004: SGP CART Raman lidar measurements during the May 2003 aerosol IOP. This Proceedings.

Hartley, W. S., P. V. Hobbs, J. L. Ross, P. B. Russell, and J. M. Livingston, 2000: Properties of aerosols aloft relevant to direct radiative forcing off the mid-Atlantic coast of the United States. *J. Geophys. Res*., **105**, 9859–9886.

Hegg, D. A., J. Livingston, P. V. Hobbs, T. Novakov, and P. B. Russell, 1997: Chemical apportionment of aerosol column optical depth off the mid-Atlantic coast of the United States. *J. Geophys. Res*., **102**, 25,293–25,303.

Livingston J. M., P. B. Russell, J. S. Reid, J. Redemann, B. Schmid, D. A. Allen, O. Torres, R. C. Levy, L. A. Remer, B. N. Holben, A. Smirnov, O. Dubovik, E. J. Welton, J. R. Campbell, J. Wang, and S. A. Christopher, 2003: Airborne sunphotometer measurements of aerosol optical depth and columnar water vapor during the Puerto Rico Dust Experiment, and comparison with land, aircraft, and satellite measurements. *J. Geophys. Res*., **108**(D19), 8588, doi:10.1029/2002JD002520.

Magi, B. I., P. V. Hobbs, B. Schmid, and J. Redemann, 2003: Vertical profiles of light scattering, light absorption, and single scattering albedo during the dry, biomass burning season in southern Africa and comparisons of in situ and remote sensing measurements of aerosol optical depths. *J. Geophys. Res*., **108** (D13), 8504, doi:10.1029/2002JD002361.

Magi B. I., P. V. Hobbs, T. W. Kirchstetter, T. Novakov, D. A. Hegg, S. Gao, J. Redemann, and B. Schmid, 2004: Aerosol properties and chemical apportionment of aerosol optical depth at locations off the United States east coast in July and August 2001. *J. Atmos. Sci*., in press.

Redemann, J., R. P. Turco, K. N. Liou, P. B. Russell, R. W. Bergstrom, B. Schmid, J. M. Livingston, P. V. Hobbs, W. S. Hartley, S. Ismail, R. A Ferrare, and E. V. Browell, 2000: Retrieving the Vertical structure of the effective aerosol complex index of refraction from a combination of aerosol in situ and remote sensing measurements during TARFOX. *J. Geophys. Res*., **105**(D8), 9949–9970.

Redemann, J., S. J. Masonis, B. Schmid, T. L. Anderson, P. B. Russell, J. M. Livingston, O. Dubovik, and A. D. Clarke, 2003: Clear-column closure studies of aerosols and water vapor aboard the NCAR C-130 during ACE-Asia, 2001. *J. Geophys. Res*., **108**(D23), 8655, doi:10.1029/2003JD003442.

Redemann J., B. Schmid, J. A. Eilers, R. Kahn, R. C. Levy, P. B. Russell, J. M. Livingston, P. V. Hobbs, W. L. Smith Jr., and B. N. Holben, 2004: Suborbital measurements of spectral aerosol optical depth and its variability at sub-satellite-grid scales in support of CLAMS, 2001. *J. Atmos. Sci*., accepted.

Schmid B., J. Michalsky, R. Halthore, M. Beauharnois, L. Harrison, J. Livingston, P. Russell, B. Holben, T. Eck, and A. Smirnov, 1999: Comparison of aerosol optical depth from four solar radiometers during the fall 1997 ARM intensive observation period. *Geophys. Res. Lett*., **26**(17), 2725-2728.

Schmid, B., J. M. Livingston, P. B. Russell, P. A. Durkee, H. H. Jonsson, D. R. Collins, R. C. Flagan, J. H. Seinfeld, S. Gassó, D. A. Hegg, E. Öström, K. J. Noone, E. J. Welton, K. J. Voss, H. R. Gordon, P. Formenti, and M. O. Andreae, 2000: Clear sky closure studies of lower tropospheric aerosol and water vapor during ACE 2 using airborne sunphotometer, airborne in-situ, space-borne, and ground-based measurements. *Tellus*, **B 52**, 568–593.

Schmid B., J. J. Michalsky, D. W. Slater, J. C. Barnard, R. N. Halthore, J. C. Liljegren, B. N. Holben, T. F. Eck, J. M. Livingston, P. B. Russell, T. Ingold, and I. Slutsker, 2001: Comparison of columnar water-vapor measurements from solar transmittance methods. *Applied Optics*, **40:**12, 1886–1896.

Schmid B., J. Redemann, P. B. Russell, P. V. Hobbs, D. L. Hlavka, M. J. McGill, B. N. Holben, E. J. Welton, J. R. Campbell, O. Torres, R. A. Kahn, D. J. Diner, M. C. Helmlinger, D. A. Chu, C. Robles Gonzalez, and G. de Leeuw, 2003a: Coordinated airborne, spaceborne, and ground-based measurements of massive, thick aerosol layers during the dry season in southern Africa. *J. Geophys. Res*, **108**(D13), 8496, doi:10.1029/2002JD002297.

Schmid B., D. A. Hegg, J. Wang, D. Bates, J. Redemann, P. B. Russell, J. M. Livingston, H. H. Jonsson, E. J. Welton, J. H. Seinfeld, R. C. Flagan, D. S. Covert, O. Dubovik, and A. Jefferson 2003b: Column closure studies of lower tropospheric aerosol and water vapor during ACE-Asia using airborne sunphotometer, airborne in-situ, and ship-based lidar measurements. *J. Geophys. Res*., **108**(D23), 8656, doi:10.1029/2002JD003361.

Strawa, A. W., R. Castaneda, T. Owano, D. S. Baer, and B. A. Paldus, 2003: The measurement of aerosol optical properties using continuous wave cavity ring-down techniques. *J. Atmos. Oceanic Tech*., **20**, 454–465.

Strawa A. W., A. G. Hallar, R. Castaneda, K. Ricci, R. Provencal, A. Bucholtz, B. Schmid, D. Covert, R. Elleman, and W. P. Arnott, 2004: Cavity ring down measurement of aerosol scattering, extinction, and absorption during DOE aerosol intensive operating period. This Proceedings.

Wang J., R. C. Flagan, J. H. Seinfeld, H. H. Jonsson, D. R. Collins, P. B. Russell, B. Schmid, J. Redemann, J. M. Livingston, S .Gao, D. A. Hegg, E. J. Welton, and D. Bates, 2002: Clear-column radiative closure during ACE-Asia: Comparison of multiwavelength extinction derived from particle size and composition with results from sunphotometry. *J. Geophys. Res*., **107**(D23), 4688, doi:10.1029/2002JD002465.