The Vertical Distribution of Aerosols: Lidar Measurements vs. Model Simulations

R. A. Ferrare[1], E.V. Browell[1], J.W. Hair[1], S. Ismail[1], D. D. Turner[2], M. Clayton[3], C.F. Butler[3], V.G. Brackett[3], M.A. Fenn[3], A. Notari[3], S.A. Kooi[3], M. Chin[4], S. Guibert[5], M. Schulz[5], C. Chuang[6], M. Krol[7], S. E. Bauer[8], X. Liu[9], G. Myhre[10], Ø. Seland[10], D. Fillmore[11], S. Ghan[12], S. Gong[13], P. Ginoux[14], T. Takemura[15]

[1]NASA Langley Research Center, MS 401A, Hampton, VA, 23681, USA, r.ferrare@larc.nasa.gov, e.v.browell@larc.nasa.gov, j.w.hair@larc.nasa.gov, s.ismail@larc.nasa.gov
[2]University of Wisconsin-Madison, Madison, WI, 53706, USA, dturner@ssec.wisc.edu
[3]SAIC/NASA Langley Research Center, MS 929, Hampton, VA 23681, USA, m.b.clayton@larc.nasa.gov, c.f.butler@larc.nasa.gov, vgb829@earthlink.net, m.a.fenn@larc.nasa.gov, a.notari@larc.nasa.gov, s.a.kooi@larc.nasa.gov
[4]NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA, mian.chin@nasa.gov
[5] Laboratoire des Sciences du Climat et de l'environnement, Gif-sur-Yvette, France, Sarah.Guibert@cea.fr, michael.schulz@cea.fr
[6]Lawrence Livermore National Lab, Livermore, CA, 94550, USA, chuang1@llnl.gov
[7]Institute for Marine and Atmospheric Research Utrecht (IMAU) Utrecht, The Netherlands, maarten.krol@jrc.it
[8]The Earth Institute at Columbia University, New York, NY, USA, sbauer@giss.nasa.gov
[9]University of Michigan, Ann Arbor, MI, USA, xiaohong.liu@pnl.gov
[10]University of Oslo, Department of Geosciences, Oslo, Norway, gunnar.myhre@geo.uio.no, oyvind.seland@geofysikk.uio.no
[11]NCAR, Boulder, Colorado, USA, fillmore@cgd.ucar.edu
[12]Battelle, Pacific Northwest National Laboratory, Richland, USA, Steve.Ghan@pnl.gov
[13]ARQM Meteorological Service Canada, Toronto, Canada, Sunling.Gong@ec.gc.ca
[14]NOAA, Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA, pag@gfdl.noaa.gov
[15]Kyushu University, Fukuoka, Japan, toshi@riam.kyushu-u.ac.jp

ABSTRACT

The vertical distributions of aerosols simulated by global aerosol models are evaluated using aerosol profiles measured by two lidars. Aerosol extinction profiles and aerosol optical thickness (AOT) simulated by aerosol models participating in the Aerosol module inter-Comparison in global models (AEROCOM) project are compared with Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility (CRF) Raman lidar (CARL) measurements acquired during 2000 and 2001. Average aerosol extinction profiles from the AEROCOM models typically show good agreement with the Raman lidar profiles above about 2 km; below 2 km the average model profiles are significantly (30-50%) lower than the Raman lidar profiles. The vertical variability in the average model aerosol extinction profiles is less than the variability in the corresponding Raman lidar profiles. Aerosol profiles simulated by the Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model during the Transport and Chemical Evolution over the Pacific (TRACE-P) and Intercontinental Chemical Transport Experiment – North America (INTEX-NA, Phase-A) missions are evaluated using measurements from the NASA Langley Research Center airborne Differential Absorption Lidar (DIAL) that was deployed on the NASA DC-8 aircraft. During TRACE-P, which occurred over the western Pacific Ocean during March-April 2001, the GOCART aerosol extinction profiles were generally 10-40% lower than profiles derived from the airborne DIAL system; greatest relative differences were near the top of the boundary layer (~1 km). During INTEX-NA, which occurred over the northeastern U.S. and western Atlantic Ocean during July-August 2004, the GOCART aerosol extinction profiles showed better agreement, with differences generally largest in the lowest 1 km.

1. INTRODUCTION

Global models have been increasingly used to assess climate change scenarios. Since some of the largest uncertainties in model simulations of climate change are associated with aerosols, evaluating how these models portray aerosol characteristics is vital for determining uncertainties in climate change simulations. Such evaluations are being conducted as part of the Aerosol module inter-Comparison in global models (AEROCOM) project [1], which seeks to diagnose aerosol modules of global models and subsequently identify and eliminate weak components in aerosol modules used for global modeling. (A list of the AEROCOM models is provided at http://nansen.ipsl.jussieu.fr/AEROCOM/data.html.) AEROCOM intercomparisons have shown large differences in how models represent the vertical distribution of aerosols [2]. Consequently, lidar profiles

of aerosol extinction provide an important means of evaluating and hopefully improving aerosol models.

2. RAMAN LIDAR

Through its design as a turnkey, automated system for unattended, around-the-clock profiling of water vapor and aerosols, the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Climate Research Facility Raman lidar (CARL) has provided a climatological database of aerosol and water vapor profiles [3]. CARL autonomously measures profiles of aerosols, clouds and water vapor in the low to mid troposphere throughout the diurnal cycle over the ARM Southern Great Plains (SGP) CRF (36.62 N, 97.5 W, 317 m) [4]. Profiles of water vapor mixing ratio, relative humidity, aerosol backscattering, and aerosol extinction (355 nm) are derived using a set of automated algorithms [5]. Water vapor mixing ratio profiles are computed using the ratio of the Raman water vapor signal to the Raman nitrogen signal. Relative humidity profiles are computed using these profiles and the temperature profiles from a collocated Atmospheric Emitted Radiance Interferometer (AERI). Profiles of aerosol scattering ratio are derived using the Raman nitrogen signal and the signal detected at the laser wavelength. Aerosol volume backscattering cross section profiles are then computed using the aerosol scattering ratio and molecular scattering cross section profiles derived from atmospheric density data. Aerosol extinction profiles are computed from the derivative of the logarithm of the Raman nitrogen signal with respect to range. AOT is derived by integration of the aerosol extinction profile with altitude.

3. RAMAN LIDAR/AEROCOM COMPARISONS

Figure 1 shows the average annual aerosol optical thickness (AOT) (355 nm) over the ARM SGP CRF from the various AEROCOM models, as well as annual averages derived from CARL and the AERONET Cimel Sun photometer located at the SGP site. Averages were computed from the monthly averages and error bars represent standard deviations. Note how the average annual AOT from the various models and the CARL and Sun photometer measurements agree within the standard deviations of the averages. Figure 2 shows the average vertical distribution of aerosol extinction (355 nm) for 2000 simulated by several AEROCOM models and measured by CARL. These distributions were comprised of monthly averages. Note the wide range in how the models represent the aerosol extinction profiles over the ARM SGP site. Deviations between mean aerosol extinction profiles are generally small (~20-30%) for altitudes above 2 km, and grow considerably larger below 2 km. The generally low bias of the model aerosol extinction profiles with respect to the lidar measurements within the lowest 2 km is similar to an earlier study that

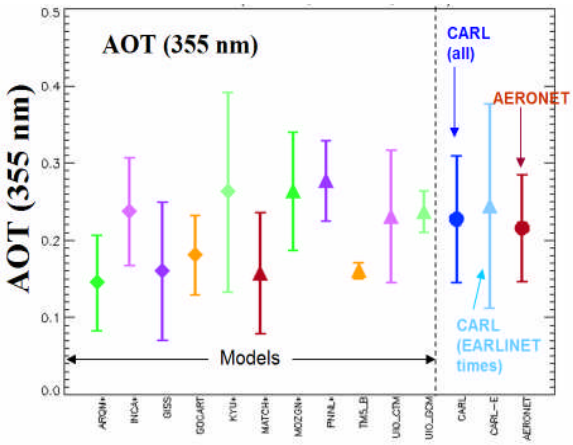

Figure 1. Average annual AOT over the ARM SGP CRF site during 2000.

compared Raman lidar measurements from European Lidar Network (EARLINET) Raman lidar measurements [6] and simulations from the Interaction with Chemistry and Aerosols (INCA) model [7]. The larger differences near the surface may be due to too little vertical mixing or not enough humidification of the aerosol simulated by the models. CARL measurements often show high aerosol extinction and relative humidity values located within thin layers near the surface. Average annual relative humidity (RH) profiles were also examined. RH Differences between the CARL measurements and model simulations were generally small (<10%) except near the surface, where the CARL profiles, especially at night, show significantly higher amounts than the models.

Comparisons for 2001 are very similar to those shown in Figures 1 and 2 for 2000. A subset of models also participated in comparison experiment that used identical prescribed emissions and meteorological fields. The model annual average profiles from this experiment also exhibited large model-to-model differences and were also systematically lower than the average CARL profile within the lowest 2 km.

In contrast to the periodic EARLINET Raman lidar measurements, which were derived from lidar data

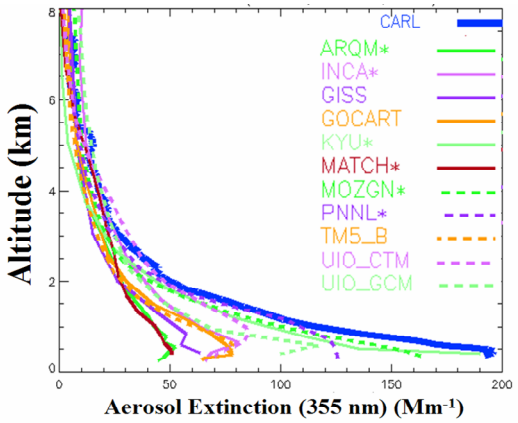

Figure 2. Average aerosol extinction profiles over the ARM SGP CRF site during 2000.

collected only near sunset on two days per week, the results presented here use CARL profiles collected essentially continuously, 24 hours per day and 7 days per week. The impact of periodic (i.e. EARLINET) vs. continuous (i.e. ARM) sampling on the lidar/model comparisons was also examined using a subset of CARL data collected during the EARLINET sampling times. As an example, Figure 1 shows two average AOT values for CARL; the first corresponds to all CARL data and the second corresponds to the subset of data acquired only during the EARLINET sampling times. The difference between these two AOT average values is small. In contrast, bias and rms differences between the model and CARL aerosol extinction profiles were significantly larger, and correlations were smaller, when using the periodic sampling times than when using the continuous sampling times. Additional studies using CARL data also showed significant diurnal variations in the vertical distributions of aerosols and water vapor.

4. AIRBORNE DIAL

The NASA Langley airborne DIAL has been deployed extensively on the NASA DC-8 to measure ozone and aerosol distributions [8, 9]. Four laser beams are transmitted simultaneously into the atmosphere below (288.2, 299.6, 576.4, and 1064 nm) and above (288.2, 299.6, 599.2, and 1064 nm) the aircraft for lidar measurements of ozone, aerosols, and clouds from near the surface to about 3 km above the tropopause. AOT values from the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) measurements and model simulations were used to constrain the total transmission through the atmosphere and derive a column mean value of the aerosol extinction/backscattering ratio (S_a). These S_a values were then used to derive the aerosol extinction profiles. Because MODIS AOT measurements often did not coincide with the flight tracks of the DC-8 during these missions, AOT from the GOCART model was used to provide complete spatial and temporal coverage for these flights. The GOCART simulations of AOT have been extensively evaluated using both satellite (e.g. MODIS) and AERONET measurements [10]. For TRACE-P, the GOCART AOT values (550 nm) were biased slightly lower (~0.05 or 12%) than the MODIS AOT measurements over water. Consequently, prior to use in the lidar retrievals, the GOCART AOT values were increased by this amount to remove this bias. Profiles of aerosol extinction, optical thickness, and backscatter (576 and 1064 nm) were computed for the 17 TRACE-P DC-8 flights. For INTEX-NA, a similar procedure was used, except that AOT values from the NCAR Model for Atmospheric Transport and Chemistry (MATCH) were used to constrain the lidar retrievals. MATCH is an assimilation model that employs MODIS AOT measurements [11]. Profiles of aerosol extinction, optical thickness, and backscatter were then computed for 17 INTEX-NA DC-8 flights.

5. DIAL/GOCART COMPARISONS

Figure 3 shows an example of aerosol extinction profiles measured by DIAL (576 nm) and simulated by GOCART (550 nm) for TRACE-P DC-8 flight 14 (March 24, 2001). This flight occurred over the Pacific Ocean southeast of Japan. GOCART profiles generally agree with the lidar retrievals and show good correspondence with the height of the boundary layer. Differences are larger in those cases of elevated, thin aerosol layers where the coarse resolution of the GOCART model can not resolve these elements. Figures 4a and 4b show comparisons of DIAL and GOCART extinction profiles averaged over all the TRACE-P and INTEX-NA flights. During TRACE-P, the GOCART aerosol extinction profiles tended to be lower than the DIAL profiles throughout the troposphere; smaller relative differences were found within 1 km of the surface. In contrast, during INTEX-NA, the average GOCART and DIAL profiles were in excellent agreement above 1-2 km with differences increasing close to the surface. The reasons for this behavior are not clear, but may be related to the more frequent occurrence during TRACE-P of elevated layers associated with the long range transport of aerosols. Figures 4c and 4d show profiles of the aerosol extinction wavelength dependence (α) (i.e. Ångström exponent for aerosol extinction) from DIAL and

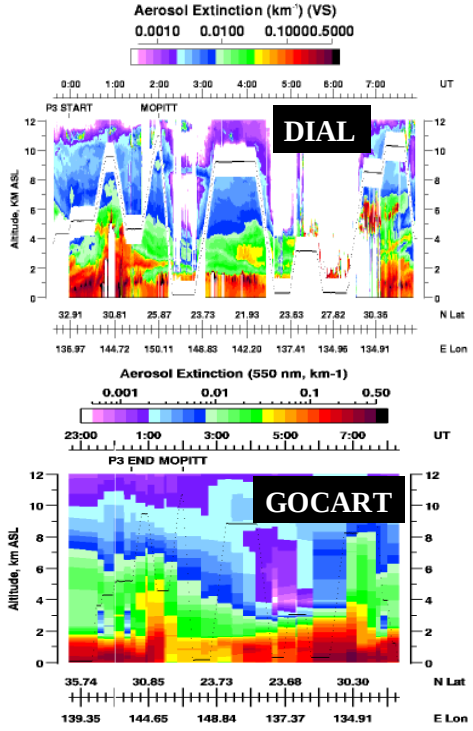

Figure 3. DIAL (576 nm) and GOCART (550 nm) aerosol extinction profiles on March 24, 2001.

GOCART for TRACE-P and INTEX-NA. Larger α values correspond to smaller particles. GOCART simulations show less vertical variability in α (and consequently particle size) than the DIAL profiles. The DIAL profiles also suggest aerosol particle sizes decreased with altitude in contrast to the GOCART profiles. Additional studies are underway to investigate the differences between the DIAL and GOCART profiles; these studies will use airborne in situ aerosol measurements that were acquired during these missions.

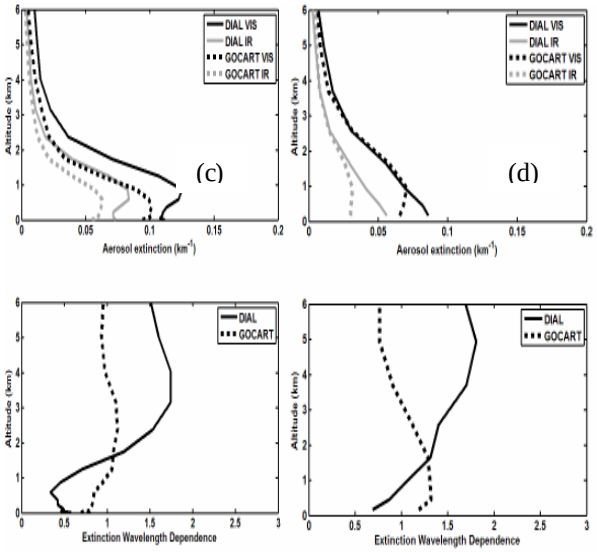

Figure 4. (a) Average DIAL (VIS=576 nm, IR=1064 nm) and GOCART (VIS=550 nm, IR=1000 nm) extinction profiles during TRACE-P, (b) same except for INTEX-NA, (c) average DIAL and GOCART aerosol extinction wavelength dependence for TRACE-P, (d) same except for INTEX-NA.

6. SUMMARY

On average, aerosol extinction profiles simulated by global aerosol models generally agree with corresponding profiles measured by the ground-based DOE ARM Raman lidar and the NASA Langley airborne DIAL for altitudes above 2 km. Below 2 km, the model profiles are systematically lower than the lidar profiles. Comparisons of AOT over the ARM SGP site show good agreement among the AEROCOM models and between the models and measurements; in contrast, there are large differences in the vertical profiles of aerosol extinction among the models and between the models and lidar measurements. The large variability among the AEROCOM profiles remained even when the models used similar input emissions and meteorological fields. Airborne DIAL and GOCART aerosol extinction profiles derived during the INTEX-NA campaign showed excellent agreement except within the lowest 1km. During TRACE-P, GOCART extinction profiles tended to be lower than the DIAL profiles throughout the troposphere.

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8. REFERENCES

1. Kinne, S., et al., An AeroCom initial assessment – optical properties in aerosol component modules of global models, Atmos. Chem. Phys. Discuss., 5, 8285–8330, 2005, SRef-ID: 1680-775/acpd/2005-5-8285.

2. Textor, C., et al., 25, Analysis and quantification of the diversities of aerosol life cycles within AeroCom, Atmos. Chem. Phys. Discuss., 5, 8331–8420, 2005, SRef-ID: 1680-7375/acpd/2005-5-8331.

3. Turner, D.D., R.A. Ferrare, L.H. Brasseur, "Average Aerosol Extinction and Water Vapor Profiles Over the Southern Great Plains", *Geophys. Res. Letters,* Vol. 28, No. 23, 4441-4444, 2001.

4. Goldsmith J. E. M., F.H. Blair, S.E. Bisson, and D.D. Turner, Turn-Key Raman lidar for profiling atmospheric water vapor, clouds, and aerosols. *Appl. Opt*., 37, 4979–4990, 1998.

5. Turner D.D., R.A. Ferrare, L.A. Heilman, W.F. Feltz, and T. Tooman, Automated Retrievals of Water Vapor and Aerosol Profiles over Oklahoma from an Operational Raman Lidar, *J. Atmos. Oceanic Tech.,* 19, 37-50, 2002.

6. Bösenberg, J., et al., "EARLINET: a European aerosol research lidar network" in Laser Remote Sensing of the Atmosphere (Edition Ecole Polytechnique, Palaiseau, France. 2001), pp. 961-976, 2002.

7. Guibert, S., et al., The vertical distribution of aerosol over Europe - Synthesis of one year of EARLINET aerosol lidar measurements and aerosol transport modeling with LMDzT-INCA, Atmos. Environ., 39 (16), 2933-2943, 2005.

8. Browell E. V., Ismail S., and Grant W. B., Differential Absorption Lidar (DIAL) Measurements from Air and Space, *Appl. Phys. B, 67,* 399-410, 1998

9. Butler, C.F., et al., Aerosol types and characteristics measured with airborne lidar during INTEX-NA, 23rd ILRC (this issue).

10. Chin, M., et al., Tropospheric aerosol optical thickness from the GOCART model and comparisons with satellite and sunphotometer measurements, J. Atmos. Sci., 59, 461–483, 2002.

11. Collins, W. D., P. J. Rasch, B. E. Eaton, B. V. Khattatov, J.-F. Lamarque, and C. S. Zender, 2001: Simulating aerosols using a chemical transport model with assilimiation of satellite aerosol retrievals: Methodology for INDOEX. J. Geophys. Res., 106, 7313-7336.