6.13 AEROSOL RETRIEVALS USING AIRBORNE LIDAR AND MODIS MEASUREMENTS

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1. INTRODUCTION

Knowledge of the vertical distribution of aerosol optical properties is important for determining the direct radiative forcing of absorbing aerosols, assessing aerosol/cloud indirect radiative forcing, and for evaluating and subsequently improving global aerosol model parameterizations of aerosol transport and removal processes. Combining remote sensing data from both active and passive sensors provides a method to retrieve ambient aerosol properties for these atmospheric studies. This presentation will describe how Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) measurements of spectral radiance and retrievals of aerosol optical properties are combined with multiwavelength lidar profiles of aerosol backscattering acquired by the NASA Langley airborne Differential Absorption Lidar (DIAL) during recent field experiments to retrieve profiles of aerosol optical properties. The evaluation of these retrievals using airborne in situ and remote sensing data and the use of these retrievals to evaluate the vertical distribution of aerosol optical properties simulated by the Goddard Chemistry Aerosol Radiation and Transport (GOCART) global aerosol model are also discussed.

2. AIRBORNE DIAL

The NASA Langley airborne DIAL has been deployed extensively on the NASA DC-8 to measure ozone and aerosol distributions (Browell et al., 1998). 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. Aerosol Optical Depth (AOD) values from the 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 AOD measurements often did not coincide with the flight tracks of the DC-8 during these missions, we also used AOD from the GOCART and/or NCAR Model for Atmospheric Transport and Chemistry (MATCH) models to provide complete spatial and temporal AOD coverage for these flights. MATCH is an assimilation model that directly employs MODIS AOD measurements (Collins et al., 2001). Profiles of aerosol extinction, optical thickness, and backscatter were then computed for measurements acquired during the TRAnsport and Chemical Evolution over the Pacific (TRACE-P, 2001) campaign and the Intercontinental Chemical Transport Experiment-North America (INTEX-NA, 2004) campaign.

3. RETRIEVAL EVALUATIONS

Figure 1 shows a comparison of the aerosol extinction profiles derived from the lidar measurements on July 22, 2004 during the INTEX-NA mission with corresponding profiles derived from the 14 channel NASA Ames Airborne Tracking Sunphotometer (AATS-14) (604 nm), and from in situ aerosol scattering (550 nm) (nephelometer) and absorption (530 nm) (Particle Soot Absorption Photometer-PSAP) measurements. AATS14 was deployed on the J-31 aircraft and the in situ instruments were deployed on the DC-8. For the period shown in Figure 1, the J-31 aircraft spiraled up while the NASA DC-8 flew overhead within about 30-50 km and 30 minutes of the J-31 measurements. Figure 2 shows a regression comparison of the aerosol extinction values derived from the lidar profiles (588 nm) during INTEX-NA using method described above with the corresponding values derived from the in situ data (550 nm) on the NASA DC-8. Although bias differences were

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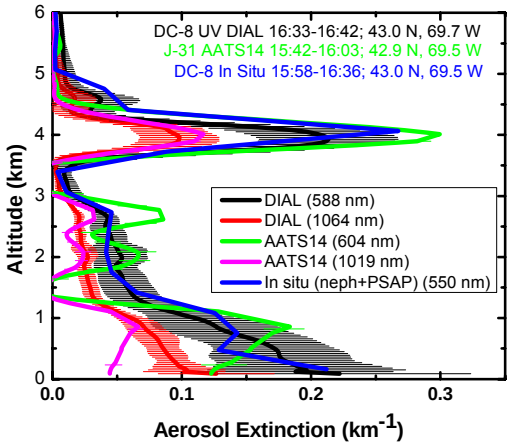

Figure 1. Aerosol extinction profiles derived from airborne DIAL, airborne Sun photometer, and DC-8 in situ measurements on July 22, 2004.

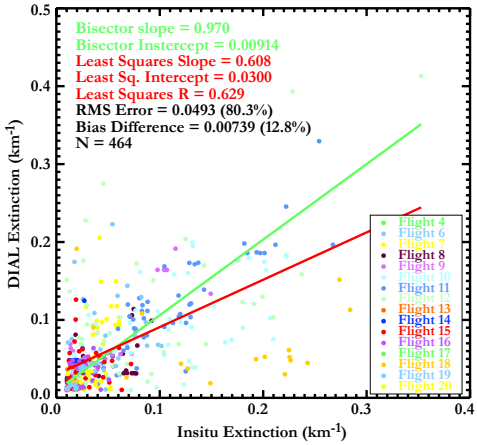

Figure 2. Comparison of aerosol extinction derived from DC-8 in situ scattering and absorption (550 nm) and DIAL (576 nm) backscattering measurements during INTEX NA.

relatively small (0.007 km^{-1} or about 13%, DIAL larger), rms differences were considerably larger (0.05 km^{-1}, 80%). Since the lidar and in situ measurements were acquired on the same aircraft, they could not simultaneously sample the same location. The lidar profiles were acquired just before or after spiral and/or ramp aircraft ascents and/or descents; the in situ profiles were measured during ascents and descents. This produced relatively large temporal (10-20 minutes) and spatial (30-200 km) differences between the lidar and in situ profiles; these differences contributed significantly to the large rms differences between these measurements.

4. COMPARISONS WITH GOCART MODEL

The extinction profiles derived from the lidar measurements were used to evaluate GOCART simulations of aerosol extinction profiles. Figure 3 shows an example of aerosol extinction profiles measured by DIAL (588 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

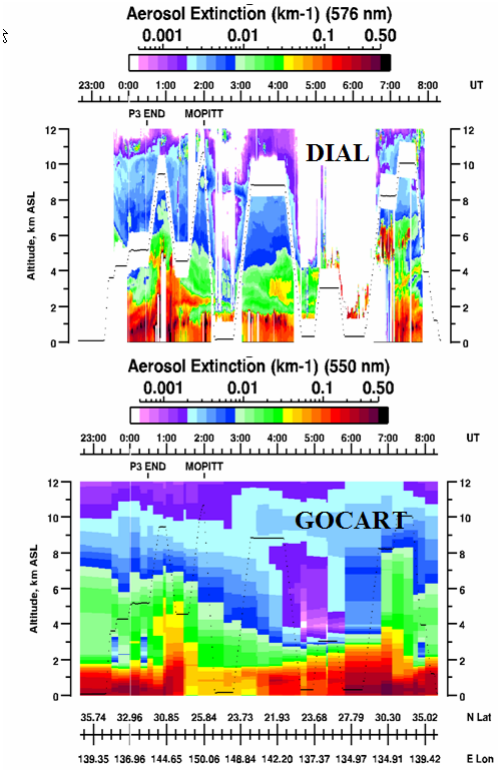

Figure 3. DIAL (588 nm) (top) and GOCART (550 nm) (bottom) aerosol extinction profiles on March 24, 2001.

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 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.

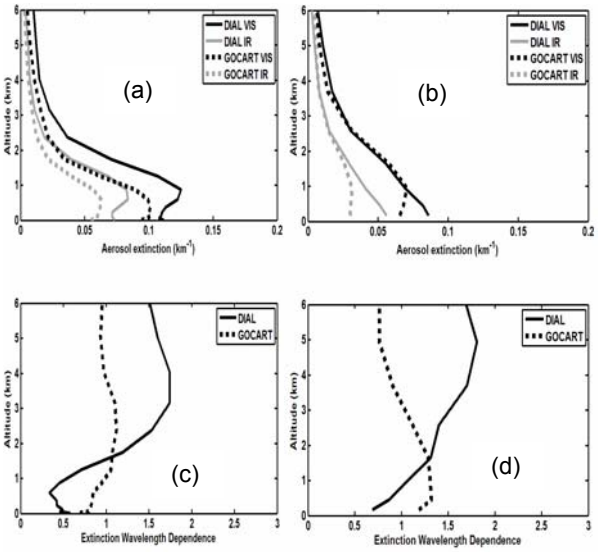

Figure 4. (a) Average DIAL (VIS=576 nm, IR=1064 nm) and GOCART (VIS=550 nm, IR=1000 nm) extinction profiles during TRACE-P, (b) same except for INTEX-NA, (c) average DIAL and GOCART aerosol extinction wavelength dependence for TRACE-P, (d) same except for INTEX-NA.

5. ADVANCED LIDAR+MODIS RETRIEVALS

We have also examined two additional methods of combining the lidar and MODIS measurements (over water) to retrieve aerosol profiles. In the first method, which is based on the algorithm described by Kaufman et al. (2003), the atmospheric column is assumed to be composed of only one fine aerosol mode and one coarse mode; each mode has a fixed particle size but varying concentrations as a function of height. In cases where the size of the fine or coarse mode varies with altitude, the inversion chooses the average size. The inversion result is a combination of 4 possible fine modes and 5 possible coarse modes that were selected to be used in the inversion of the MODIS data (Remer et al., 2005). For each of the 20 combinations the properties of the fine and coarse modes are predetermined, and are assumed not to vary with altitude (Kaufman et al., 2003). The value of the fine mode aerosol fraction is derived from the spectral ratio of the measured backscattering coefficients at 532 nm and 1064 nm corrected for attenuation. The algorithm finds the extinction coefficient of the fine and coarse modes so that they fit the two lidar measured backscatter coefficients. After this is completed, the resulting retrieved aerosol profiles for each of the 20 combinations are used to calculate 20 sets of MODIS spectral reflectances. The set that most closely matches the MODIS measurements of spectral reflectances is the chosen solution.

We implemented a revised version of this algorithm (hereafter referred to as 3-wavelength) that includes significant enhancements over the algorithm described above. First, the new algorithm uses the third aerosol backscatter wavelength (300 nm) from the UV DIAL in addition to the visible (588 nm) and infrared (1064 nm) wavelengths. The addition of this third backscatter wavelength in the UV provides important information for specifying the fine mode fraction. Second, the algorithm uses the lidar depolarization profile measurements at 588 nm to help specify the aerosol coarse particle mode. Third, the algorithm uses the MODIS measurements of aerosol optical thickness to help adjust for calibration uncertainties in the lidar data. This third feature is an important addition; the DIAL backscatter profiles have larger uncertainties associated with combining both nadir and zenith returns into a single profile as well as with calibration uncertainties caused by frequent changes in the DC-8 aircraft altitude.

We have also used an alternative method (hereafter referred to as 2-wavelength) of retrieving profiles of aerosol extinction and effective radius using MODIS and lidar data (*Léon et al.,* 2003). In this case, the spectral optical thickness derived by MODIS is used to constrain the aerosol extinction/backscatter ratio and aerosol attenuation correction at two lidar wavelengths (588 and 1064 nm). The effective radius derived from the MODIS data is also used to constrain the lidar solutions. This algorithm is being designed for operational use with Aqua MODIS and CALIPSO lidar measurements.

Figures 5a-d show examples of the results using these airborne lidar+MODIS algorithms as well as additional airborne lidar measurements for the July 22 case shown earlier in Figure 1. Figure 5a shows the aerosol extinction profiles derived from these two techniques. Those profiles labeled as UV DIAL are those constrained using the MATCH AOD and discussed in section 3; the profiles labeled lidar (3-wavelength) and lidar (2-wavelength) are those derived using the methods discussed above. These latter profiles were processed at a much coarser altitude resolution than profiles that were shown in Figure 1 (~0.5-2 km vs. 0.060 km); hence they do not capture the fine detail such as the peak near 4 km. With the exception of the lowest altitude, the profiles show very good agreement with the extinction profiles derived from airborne Sun photometer (J-31 aircraft) and airborne in situ (DC-8) measurements. Figure 5b shows the fine mode effective radius derived from the lidar+MODIS algorithms as well as from the in situ Optical Particle Counter (OPC) on the DC-8. An estimate of the effective radius at ambient relative humidity was derived from the OPC measurements of dry effective radius and coincident measurements of the aerosol humidification factor (f(RH)) and relationships between the humidification factor and hygroscopic growth factor (g(RH)) discussed by Howell et al. (2006). In this case, again with the exception of the lowest altitude, both methods show reasonably good agreement with the in situ measurements. The 2-wavelength method also shows slight variations near 4 km. In situ chemical measurements and trajectory analyses indicate that the aerosols located near 4 km were smoke from forest fires located in northwest Canada and Alaska. The particle depolarization profile shown in Figure 7c shows higher particle depolarization associated with these aerosols.

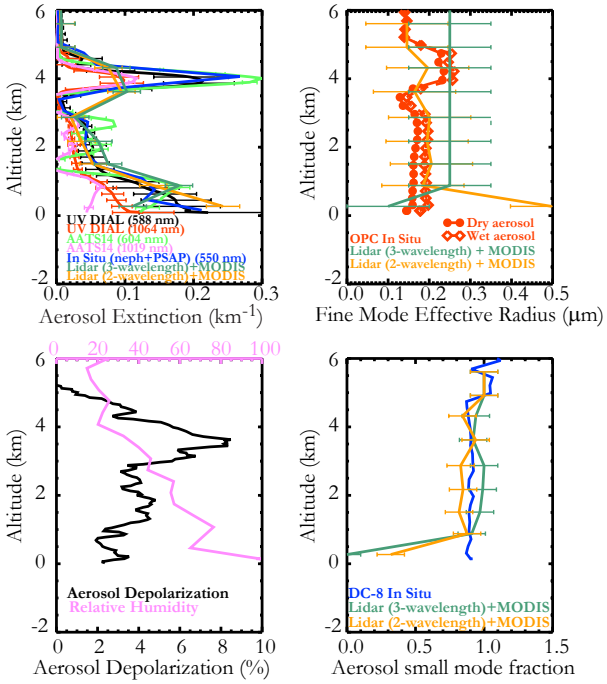

Figure 5. a) aerosol extinction profiles derived from airborne DIAL, AATS14 Sun photometer, in situ, and lidar+MODIS retrieval algorithms on July 22, 2004. b) particle effective radius derived from in situ OPC measurements and lidar+MODIS retrievals, c) aerosol depolarization measured by DIAL and relative humidity measured by DC-8 in situ instruments, d) aerosol small (fine) mode fraction derived from airborne in situ scattering and absorption measurements and derived from lidar+MODIS retrievals.

Figure 5d shows a comparison of aerosol fine mode fraction (FMF) derived from the lidar+MODIS measurements and the small mode fraction (SMF) estimated from coincident in situ measurements of submicron and total scattering and absorption (550 nm); the scattering measurements have been adjusted to ambient RH using the in situ measurements of f(RH). There is excellent agreement between the methods with the exception of the lowest altitude. The disagreement at this lowest altitude may be due to cloud contamination in the lidar coarse resolution profiles used for the retrievals. Other cases examined showed generally good agreement between the retrievals and in situ measurements when AOT was greater than about 0.15.

6. SUMMARY

Profiles of aerosol optical properties derived from retrieval algorithms that combine airborne lidar multiwavelength backscatter and MODIS measurements are presented. These retrievals include techniques that employ a combination of measured radiances and aerosol optical thickness and particle size measurements from MODIS along with multiwavelength lidar backscatter measurements to derive profiles of aerosol fine mode fraction and effective radius. Profiles of aerosol effective radius and fine mode fraction derived from the combined lidar+MODIS retrievals are also examined using airborne in situ measurements. Results from these retrievals are evaluated using airborne in situ and remote sensing measurements. Aerosol extinction profiles simulated by the GOCART global aerosol transport model are evaluated using the lidar retrieval results. 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.

7. ACKNOWLEDGEMENTS

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