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Comparisons of LASE, aircraft, and satellite measurements of aerosol optical properties and water vapor during TARFOX

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Abstract. We examine aerosol extinction and optical thickness from the Lidar Atmospheric Sensing Experiment (LASE), the in situ nephelometer and absorption photometer on the University of Washington C-131A aircraft, and the NASA Ames Airborne Tracking Sun Photometer (AATS-6) on the C-131A measured during the Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX) over the east coast of the United States in July 1996. On July 17 and 24 the LASE profiles of aerosol extinction and aerosol optical thickness (AOT) had a bias difference of 0.0055 km^{-1} (10%) and a root-mean-square difference of 0.026 km^{-1} (42%) when compared to corresponding profiles derived from the airborne in situ data when the nephelometer measurements are adjusted to ambient relative humidities. Larger differences for two other days were associated with much smaller aerosol optical thicknesses (July 20) and differences in the locations sampled by the two aircraft (July 26). LASE profiles of AOT are about 10% higher than those derived from the airborne Sun photometer, which in turn are about 10-15% higher than those derived from the airborne in situ measurements. These differences are generally within the error estimates of the various measurements. The LASE measurements of AOT generally agree with AOT derived from both the Along-Track and Scanning Radiometer 2 (ATSR 2) sensor flown on the European Remote Sensing Satellite 2 (ERS-2) and from the Moderate-Resolution Imaging Spectroradiometer (MODIS) airborne simulator (MAS) which flew with LASE on the NASA ER-2 aircraft. Effective particle sizes derived from the MAS data indicate that the LASE retrievals of AOT are valid for effective particle radii less than 0.4 μm. Variations in the relative humidity derived from the LASE water vapor measurements on July 26 are found to be highly correlated with variations in the effective particle size derived from the MAS.

1. Introduction

During the TARFOX (Tropospheric Aerosol Radiative Forcing Observational Experiment) intensive field campaign, which was conducted off the east coast of the United States between July 10 and 31, 1996, various ground, aircraft, and satellite-based sensors measured the sensitivity of radiative fields to aerosol optical properties (i.e., optical thickness, phase function, single-scattering albedo) and to the vertical profile of aerosols [*Russell et al.*, 1999]. Included in these objectives were "external closure" studies designed to compare aerosol optical properties, namely aerosol extinction and optical depth, which were derived from various methods, including surface and aircraft-based transmission measurements, in situ measurements on aircraft, satellite measurements of scattered solar radiation, and ground- and aircraft-based lidars. Such closure studies are important for determining the uncertainties associated with measurements of atmospheric properties and aerosol radiative forcing.

In a separate paper, *Ferrare et al.* [this issue] discuss the aerosol optical properties derived from two lidars (the ground-based Goddard Space Flight Center (GSFC) Raman lidar and the airborne Lidar Atmospheric Sensing Experiment (LASE) system) and the aerosol optical thickness (AOT) measurements derived from transmission measurements made by ground- and aircraft-based Sun photometers. Using an estimate of the aerosol extinction/backscattering ratio (S_a) derived from the GSFC Raman lidar, profiles of aerosol extinction and estimates of AOT were derived using data from both lidar systems. The lidar measurements of AOT are found to be generally within 25% of the AOT measured by the NASA Ames Airborne Tracking Sun Photometer (AATS-6). However, during certain periods the lidar and Sun photometer measurements of AOT differed significantly, possibly because of variations in the aerosol physical characteristics (e.g., size, composition) which affect S_a and, consequently, the lidar retrievals of aerosol optical properties [*Quinn et al.*, 1996].

In the present paper we use additional airborne and satellite data to further investigate the lidar retrievals of aerosol extinction and AOT. The LASE measurements of aerosol extinction profiles are compared with those derived from airborne in situ measurements of aerosol scattering and absorption obtained aboard the University of Washington (UW) C-131A research aircraft [*Hobbs*, 1999]. The lidar and in situ aerosol extinction profiles are then used to derive profiles of AOT which are compared to those measured by an airborne Sun photometer aboard the UW

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aircraft. We also compare the lidar measurements of AOT with those derived remotely from two additional systems. The first is the Moderate Resolution Imaging Spectroradiometer (MODIS) airborne simulator (MAS), which flew along with LASE on the NASA ER-2. In addition, visible and near-IR radiances measured by MAS were used to estimate effective particle size. These measurements are used to show the range of particle sizes for which the LASE aerosol extinction and AOT measurements are valid. Profiles of relative humidity (RH) derived from the LASE water vapor measurements are used to investigate changes with RH of the effective particle size measured by MAS during one of the TARFOX flights. The second system with which the LASE AOT are compared is the Along-Track and Scanning Radiometer 2 (ATSR-2) sensor flown on the European Remote Sensing Satellite 2 (ERS-2).

In the first part of this paper we discuss briefly LASE measurements of aerosol and water vapor profiles. The water vapor profiles measured by LASE are compared with those measured by radiosondes and by the aircraft in situ measurements. We then discuss the airborne aerosol scattering and extinction measurements and compare these with the lidar and airborne Sun photometer measurements. The MAS measurements of AOT and particle size obtained simultaneously with LASE are discussed next. Finally, the ATSR-2 measurements of AOT are discussed and compared with the LASE measurements.

2. LASE System and Measurements

Detailed descriptions of the LASE system and measurements are given *by Ismail et al.* [this issue] and by *Ferrare et al.* [this issue], so we shall only briefly describe LASE here. LASE provides simultaneous measurements of water vapor and aerosol profiles in the troposphere and lower stratosphere during both daytime and nighttime operations. LASE uses a frequency-doubled flashlamp-pumped Nd:YAG laser to pump a double-pulsed Ti:sapphire laser that operates in the 815-nm absorption band of water vapor. LASE can be operated by alternating between strong (line center) and weak (side of strong line) water vapor cross sections for the on-line DIAL wavelength in order to measure water vapor mixing ratio throughout the troposphere.

In addition to measuring water vapor mixing ratio, LASE also simultaneously measures aerosol backscattering at the off-line wavelength near 815 nm. Profiles of the total scattering ratio, defined as the ratio of total (aerosol plus molecular) scattering to molecular scattering, are determined by normalizing the scattering in the region containing enhanced aerosol scattering to the expected scattering by the "clean" atmosphere at an altitude where the aerosol scattering is assumed to be negligible. The aerosol backscatter coefficient is then computed from the total scattering ratio and the molecular backscattering cross section derived from radiosonde pressure and temperature profiles. Since both aerosol backscattering and extinction are unknown, an iterative technique is used to determine the aerosol-scattering ratio profile as well as an estimate of the aerosol extinction profile. This technique, described by *Ismail et al.* [this issue], produces results equivalent to those derived using Bernoulli inversion method [*Klett*, 1981; *Fernald*, 1984; *Ismail et al.*, this issue]. These techniques require an estimate of the aerosol extinction/backscatter ratio (S_a). Since this parameter depends on the physical characteristics of the aerosol (i.e., size and composition) which vary, it is difficult to know the appropriate value of S_a to use. The ground-based NASA GSFC scanning Raman lidar system [*Ferrare et al.*, 1998a, b], which measures both aerosol backscattering and extinction directly, also operated during TARFOX [*Ferrare et al.*, this issue]. Using measurements from this system, an estimate of S_a = 60 sr was derived, which was used for the LASE retrievals of total scattering ratio and aerosol extinction profiles. This value of S_a was derived from the SRL measurements (355 nm) acquired on July 27. The LASE measurements of aerosol extinction coefficient profiles were integrated with altitude to derive AOT. Profiles of AOT were computed as a function of altitude for the LASE data by integrating the aerosol extinction profiles between the top of the profile (about 16 km) and each altitude. When compared to AOT measured by an airborne Sun photometer, AOT derived from the LASE extinction profiles were found to have a bias difference of 0.002 (5%) and a root-mean-square (rms) difference of 0.01 (24%) [*Ferrare et al.*, this issue].

For operations in TARFOX, LASE was mounted in the Q-bay of the NASA ER-2 aircraft, which normally flew at an altitude of about 19 km at a speed of about 200 m s^{-1}. The nominal averaging interval for the water vapor data was 3 min, corresponding to a horizontal distance of about 36 km. The vertical resolution for the water vapor data varied with altitude, from 150 m for 0-1 km to 330 m for 1-10 km, and 510 m for 10-15 km. The aerosol profiles, which span the altitude range between 0.03 and 18 km, typically have horizontal and vertical resolutions of 600 and 60 m, respectively.

During TARFOX, LASE collected a total of 24 flight hours of data over nine flights between July 14 and July 26, 1996. These flights were coordinated with overflights of the NOAA-14, ERS-2, and Landsat satellites and with flights by the other TARFOX aircraft including the UW C-131A, the United Kingdom (UK) Meteorological Research Flight C-130, and the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) Pelican. These flights occurred predominantly over the Atlantic Ocean 100-300 km east of Wallops Island, Virginia, although several flight legs were flown over surface sites at Wallops Island and other east coast sites. A complete description of TARFOX operations is given by *Whiting et al.* [1996], of the UW C-131A operations by *Hobbs* [1999], and of the LASE measurements by *Ismail et al.* [this issue].

3. LASE Water Vapor Measurements

LASE profiles of water vapor mixing ratio were compared with those measured by other sensors. Figure 1 (left) shows a comparison of the water vapor profiles measured by LASE and a Vaisala radiosonde launched on Bermuda. The LASE profile represents a 3-min average profile acquired about 45 min after the radiosonde launch. These two measurements agree well below about 10 km, with the radiosonde reporting increasingly drier values above 10 km. Other LASE comparisons [*Browell et al.*, 1997], and additional lidar comparisons [*Ansmann et al.*, 1992; *Ferrare et al.*, 1995], have shown similar differences. Although radiosondes were launched from Wallops Island normally twice a day during TARFOX, there were few opportunities to compare coincident and colocated LASE and radiosonde water vapor measurements since the ER-2 flew over the ocean some distance away from Wallops, during most of TARFOX.

LASE water vapor measurements were also compared with those measurements acquired by dew point hygrometers flown on the UK C-130 and the UW C-131. Figure 1 (right) shows an example of the water vapor mixing ratio profiles measured by

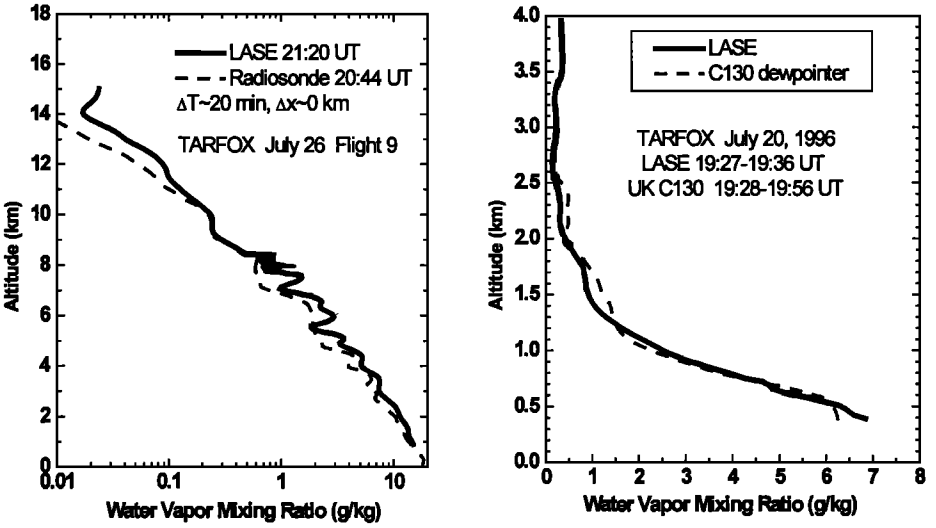

Figure 1. (left) Water vapor mixing ratio profiles measured by Lidar Atmospheric Sensing Experiment (LASE) and a Vaisala radiosonde launched from Bermuda on July 26, 1996. (right) Water vapor mixing ratio profiles measured by LASE and the dew point hygrometer on the U.K. Meteorological Office C-130 on July 20, 1996.

LASE and the C-130 dew point hygrometer on July 20 [*Hignett et al.*, 1999]; these profiles, which were acquired within 30 min and 30 km of each other, show excellent agreement. On several occasions the LASE water vapor measurements were acquired within close proximity to water vapor profiles acquired by the dewpoint hygrometer on the UW C-131A. Figure 2 shows a comparison of the water vapor measurements acquired by LASE and this dew point hygrometer during 12 periods when the LASE measurements were within about 30 km and 30 min of the C-131A. The C-131A and LASE water vapor measurements shown in Figure 2 are for altitudes between 0.9 and 4.0 km. These measurements show that the water vapor measurements acquired by the dew point hygrometer on the C-131A were about 13% drier than those acquired by LASE. However, this difference may be explained by an intermittent problem in the C-131A dew point hygrometer that caused the dew point temperatures oc-

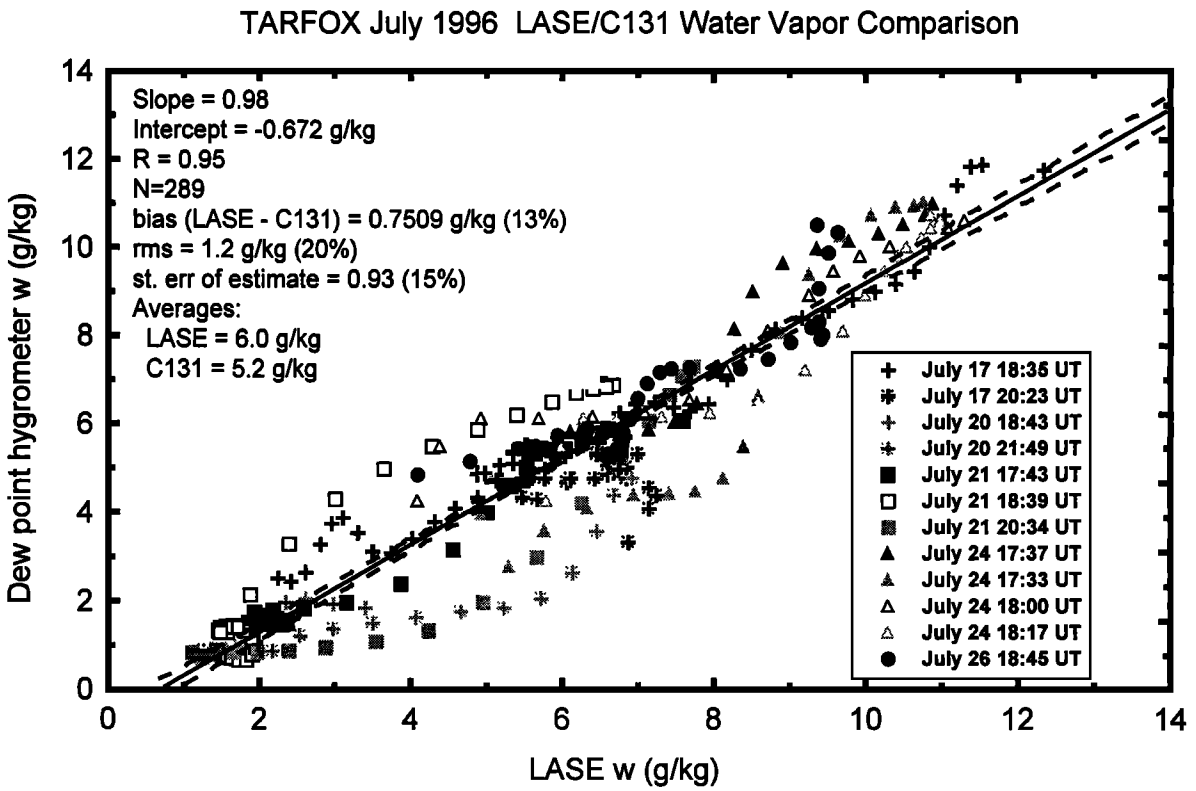

Figure 2. Comparison of water vapor mixing ratio values measured by LASE and the dew point hygrometer flown on the UW C-131A aircraft.

casionally being shifted by about 1.5°C toward lower temperatures. This periodic shift produced a periodic dry bias of 10-12% in the C-131A dew point hygrometer water vapor mixing ratios. Examination of the individual LASE/C-131A dew point hygrometer comparisons showed a periodic offset between the two measurements that could be explained by this behavior. Note that during the LASE Validation Experiment, LASE water vapor measurements were found to be in good agreement with those measured by a General Eastern model 1011B dew point hygrometer flown on the NASA Lear jet [*Browell et al.*, 1997]. Additional comparisons involving precipitable water vapor derived from the LASE measurements and from coincident ground and airborne Sun photometer measurements are described by *Ferrare et al.* [this issue].

4. LASE and Airborne In situ Aerosol Extinction Comparison

Aerosol extinction and AOT profiles derived from the LASE measurements were compared with corresponding profiles derived from simultaneous in situ measurements onboard the UW C-131A aircraft. *Hobbs* [1999] has described in detail the instrumentation on this aircraft, so we shall describe only briefly the instrumentation here. Retrievals of aerosol scattering and absorption from the C-131A aircraft data involve three different aerosol measurements. An ME Electron nephelometer measured the light scattering coefficient at 450, 550, and 700 nm for aerosol particles dried to a relative humidity of about 30%. The hygroscopic scattering growth factor was derived by measuring the change in the aerosol scattering coefficient as the relative humidity of an air sample was ramped from about 30 to 85%. Details of these humidification procedures and results are given by *Kotchenruther et al.* [1999]. The aerosol hygroscopic scattering growth factor was then used to derive aerosol scattering at ambient relative humidities. Aerosol absorption was measured at 535 nm and at 40% relative humidity [*Kotchenruther et al.*, 1999] using a Radiance Research aerosol absorption photometer. The hygroscopic growth factor for absorption, which was used to determine aerosol absorption at ambient relative humidities, was estimated to be between unity and the hygroscopic growth factor for scattering [*Hartley et al.*, this issue]. The uncertainty in the aerosol extinction associated with these methods of estimating the hygroscopic growth factor for aerosol absorption is small.

Figure 3 (left) shows a comparison of the aerosol extinction profiles derived from LASE and the corresponding profiles derived from the measurements on board the C-131A on July 17. These profiles were acquired while the C-131A performed a spiral ascent between 1830 and 1900 UTC. The LASE profile corresponds to a 1-min average at approximately 1831 UTC. The wavelength dependence of aerosol extinction (e.g., Ångstrom exponent α) between 450 and 700 nm was computed as a function of altitude from the airborne in situ data. This wavelength de-

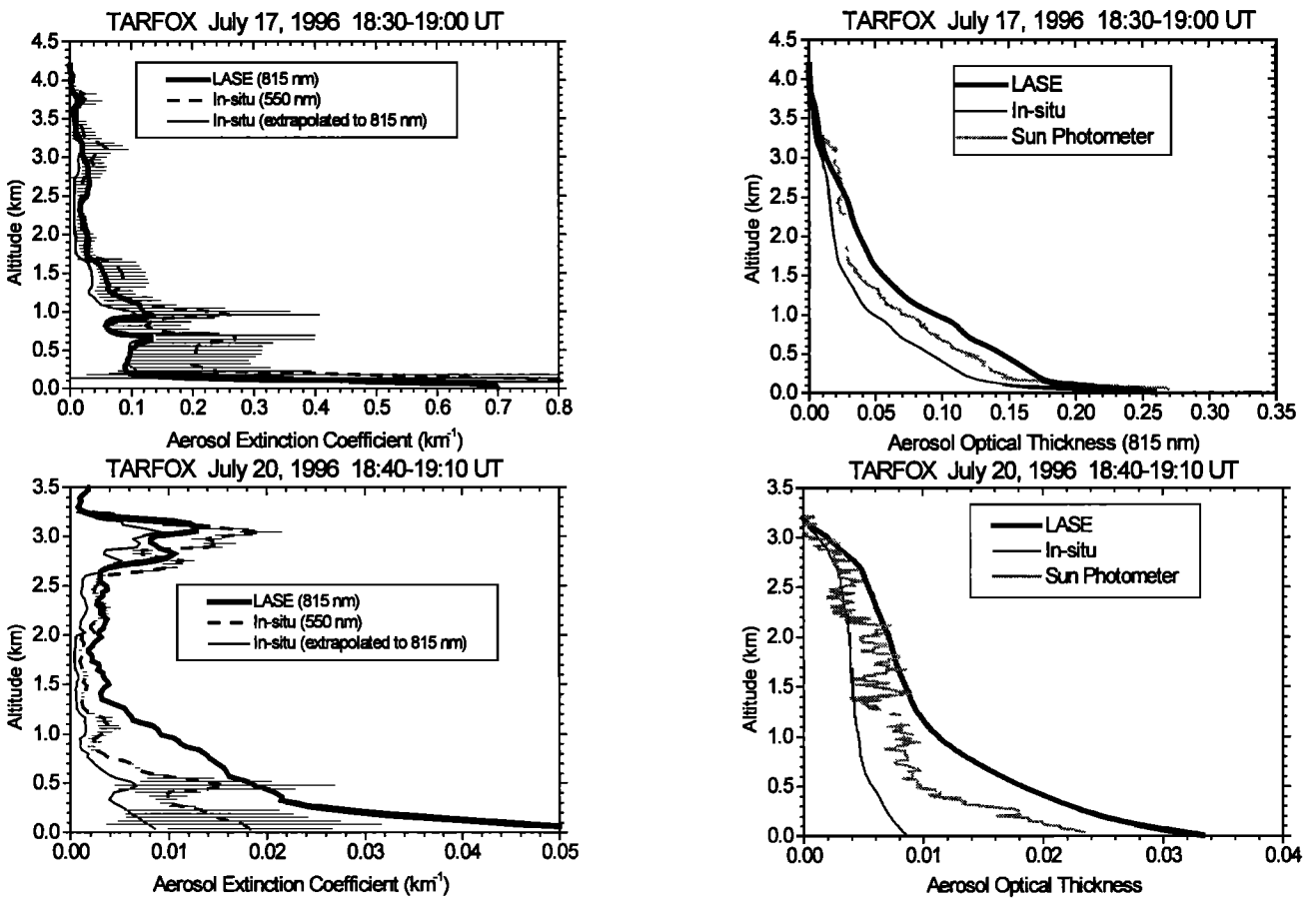

Figure 3. (top left) Comparison of aerosol extinction profiles derived from LASE aboard the NASA ER-2 and airborne in situ measurements obtained aboard the UW C-131A on July 17, 1996. (top right) Comparison of AOT profiles derived from LASE aboard the NASA ER-2, airborne in situ, and Sun photometer measurements made aboard the UW C-131A on July 17, 1996. (bottom left) Same as top left except for July 20. (bottom right) Sme as top right except for July 20.

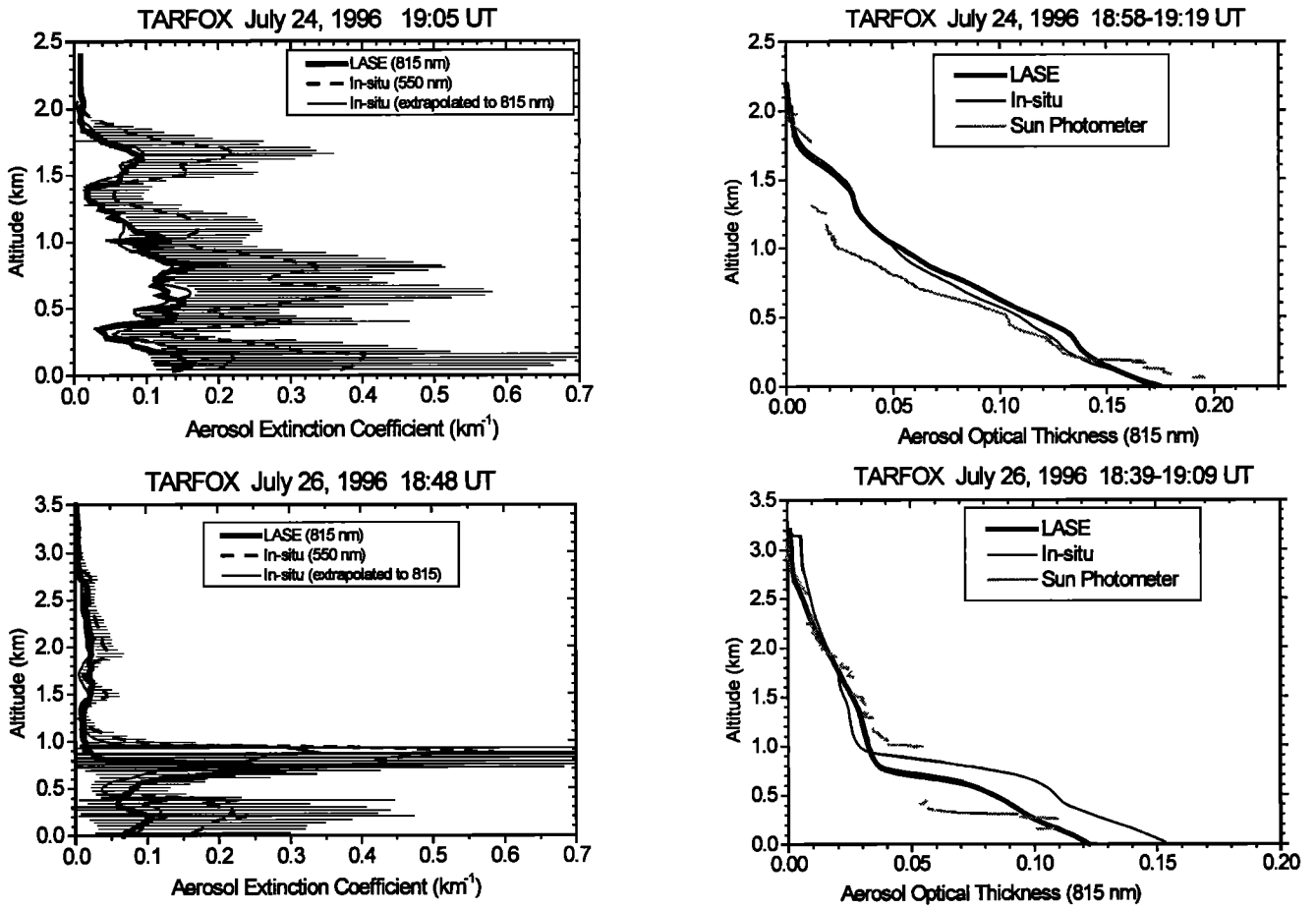

Figure 4. (top left) Comparison of aerosol extinction profiles derived from LASE aboard the NASA ER-2 and airborne in situ measurements obtained aboard the UW C-131A on July 24, 1996. (top right) Comparison of AOT profiles derived from LASE aboard the NASA ER-2, airborne in situ, and Sun photometer measurements made aboard the UW C-131A on July 24, 1996. (bottom left) Same as Figure 3 (top left) except for July 26. (bottom right) Same as Figure 3 (top right) except for July 26.

pendence was then used together with the aerosol extinction profile at 700 nm to estimate the aerosol extinction profile at the LASE 815 nm wavelength. The Ångstrom exponent derived from the airborne in situ data generally varied between 1.8 and 2.2 for this profile. Ångstrom exponents derived from the MAS AOT retrievals at 655 and 867 nm also varied between 1.8 and 2.2, while Ångstrom exponents derived from the airborne AATS-6 AOT measurements at 525 and 1021 nm varied between 1.2 to 2.4. Therefore the wavelength variation of aerosol extinction derived from the airborne in situ data is within the range observed by the airborne remote sensing instruments.

The LASE and airborne in situ aerosol extinction profiles were integrated with altitude to derive profiles of AOT. Figure 3 (top right) shows these profiles for data acquired on July 17 along with the measurements of AOT measured as a function of altitude by the AATS-6 airborne Sun photometer. The airborne Sun photometer data were logarithmically interpolated between 525 and 1021 nm to the LASE wavelength of 815 nm. These profiles represent the AOT above each altitude. Since the maximum altitude of the airborne in situ profiles was 4.2 km, the LASE and AATS-6 AOT profiles were also normalized to zero at this altitude. The small gaps in the Sun photometer profiles represent the removal of cloud contamination effects.

Additional comparisons between the LASE and in situ aerosol extinction profiles for July 20, 24, and 26 are shown in Figures 3 (bottom left) and 4 (top left, bottom left), respectively, while the corresponding AOT comparisons are shown in Figures 3 (bottom right) and 4 (top right, bottom right). With the exception of July 26, both the LASE and the C-131A measurements were within 5 km of each other and were coincident in time. On July 20 the in situ profile was acquired when the C-131A flew a spiral ascent between 1840 and 1910 UTC; the LASE profile represents a 1-min profile acquired at 1840 UTC. On July 24 the in situ profile was acquired when the C-131A flew a spiral ascent between 1858 and 1919 UTC; the LASE profile represents a 1-min profile acquired at 1905 UTC. On July 26 the in situ profile was acquired between 1839 and 1909 UTC, while the LASE profile was acquired at 1848 UTC. The ER-2 and C-131A flights were about 15-20 km apart at their closest approach on this day. However, it is clear that except for the altitude shift below 1 km, all sensors observed similar aerosol extinction profiles.

The LASE and in situ aerosol extinction profiles acquired on July 17 and 24 generally show good agreement. Bias differences (LASE-in situ) for these two days are 0.0055 km^{-1} (10%), and rms differences are 0.026 km^{-1} (42%). Comparisons between AOT derived from the in situ measurements at 450 nm and from

the simultaneous AATS-6 Sun photometer measurements at 451 nm found the AOT from the in situ data to be about 12-15% lower than the Sun photometer values [*Hegg et al.*, 1997; *Hartley et al.*, 1999]. When the AATS-6 measurements were interpolated to match the in situ measurements at 700 nm, the in situ and AATS-6 AOT values agreed within their uncertainties, provided that the uncertainty in the wavelength extrapolation was accounted for [*Hartley et al.*, 1999]. Thus the LASE and in situ profiles of aerosol extinction and optical thickness generally show good agreement considering the uncertainty associated with the measurements and the in situ extrapolation to 815 nm. The reason for the larger difference between the LASE and in situ measurements on July 20 is not clear. While the aerosol extinction and AOT values on this day were very low compared to the other cases, these low values were not anticipated to significantly affect either the in situ or LASE measurements. Recall that the lidar ratio was determined from the GSFC Raman lidar measurements acquired on July 27 when the aerosol extinction and AOT values were much higher. It is possible that when conditions were much cleaner and drier on July 20, the lidar ratio was smaller than the value of S_a = 60 sr observed on July 27. The larger difference between the LASE and the in situ measurements on July 26 was because the two measurements were not colocated; the ER-2 and C-131A flights were 15-20 km apart at their closest approach.

5. LASE and MAS Aerosol Optical Thickness Comparison

The LASE retrievals of AOT were compared with those derived from radiances measured by the MODIS (Moderate-Resolution Imaging Spectroradiometer) airborne simulator (MAS). This instrument, which was aboard the NASA ER-2 during TARFOX, scans in the across-track direction. It has a half scan angle of 42.96° corresponding to a swath width of 36 km at the nominal flight altitude of 20 km. Data acquired within a cone of 30° half angle were rejected to avoid specular reflection. The spatial resolution is 50 m at nadir and pixels are averaged into 40 × 40 boxes in order to derive aerosol parameters on a 2 × 2 km^2 scale. Complete details are given by *King et al.* [1996]. Five channels (centered at 549, 655, 867, 1643, and 2105 nm) corresponding to the MODIS/EOS channels are used to derive aerosol parameters that include AOT, effective particle radius, and the ratio of AOT of the small (accumulation) to large (coarse) modes.

The aerosol retrieval algorithm used for TARFOX is given by *Tanré et al.* [1999], while a more complete description is given by *Tanré et al.* [1997]. Basically, the algorithm uses the solar reflected spectral radiances to derive the aerosol size distribution, which is then used along with the corresponding aerosol phase function to derive the AOT. The algorithm derives aerosol pa-

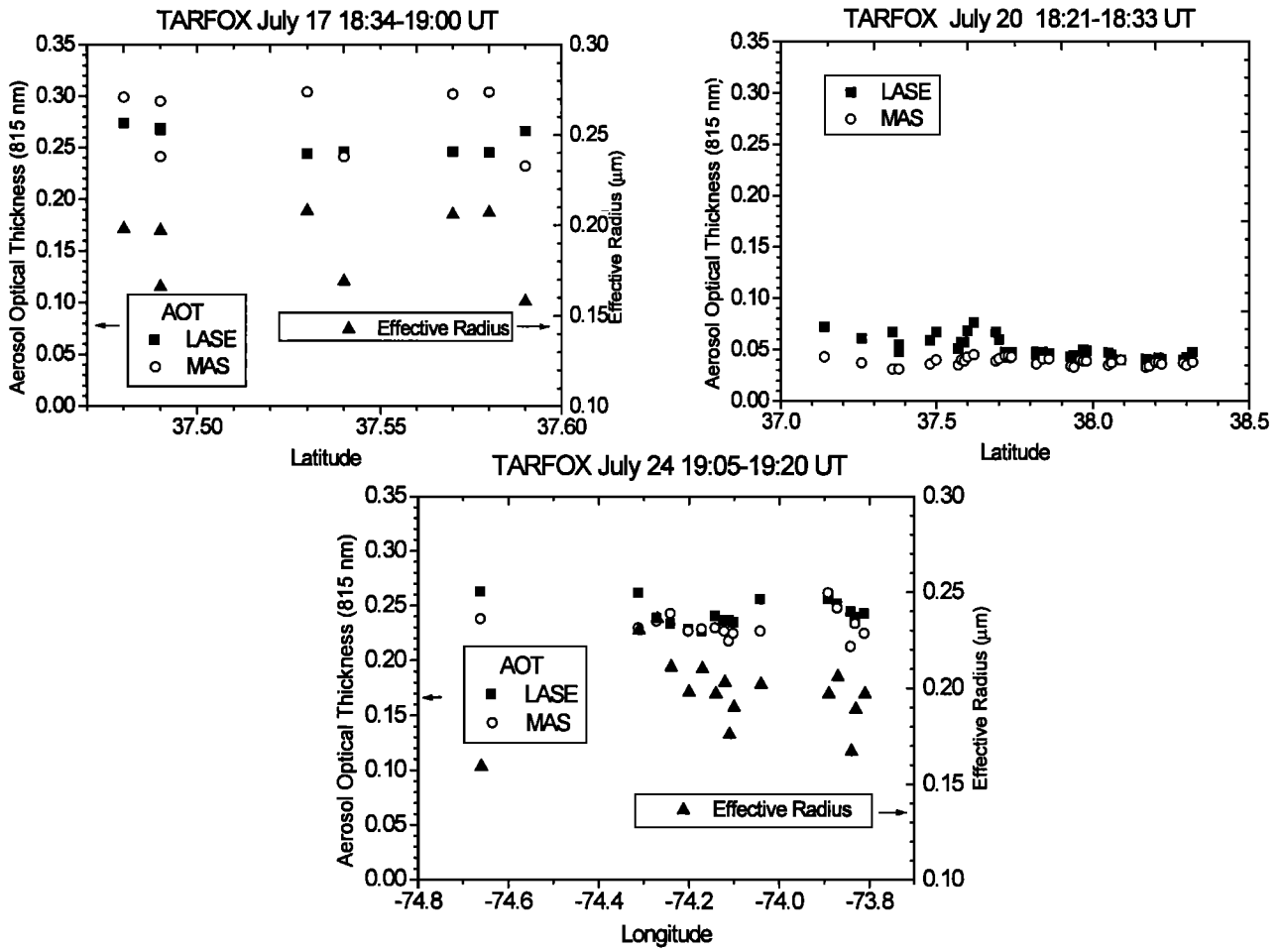

Figure 5. (top left) Comparison of the aerosol extinction and aerosol optical thickness (AOT) measured by LASE and Moderate Resolution Imaging Spectroradiometer (MODIS) airborne simulator (MAS) (left axis) and effective particle radius derived from MAS (right axis) on July 17, 1996. (top right) Same except for July 20. (bottom) Same except for July 24.

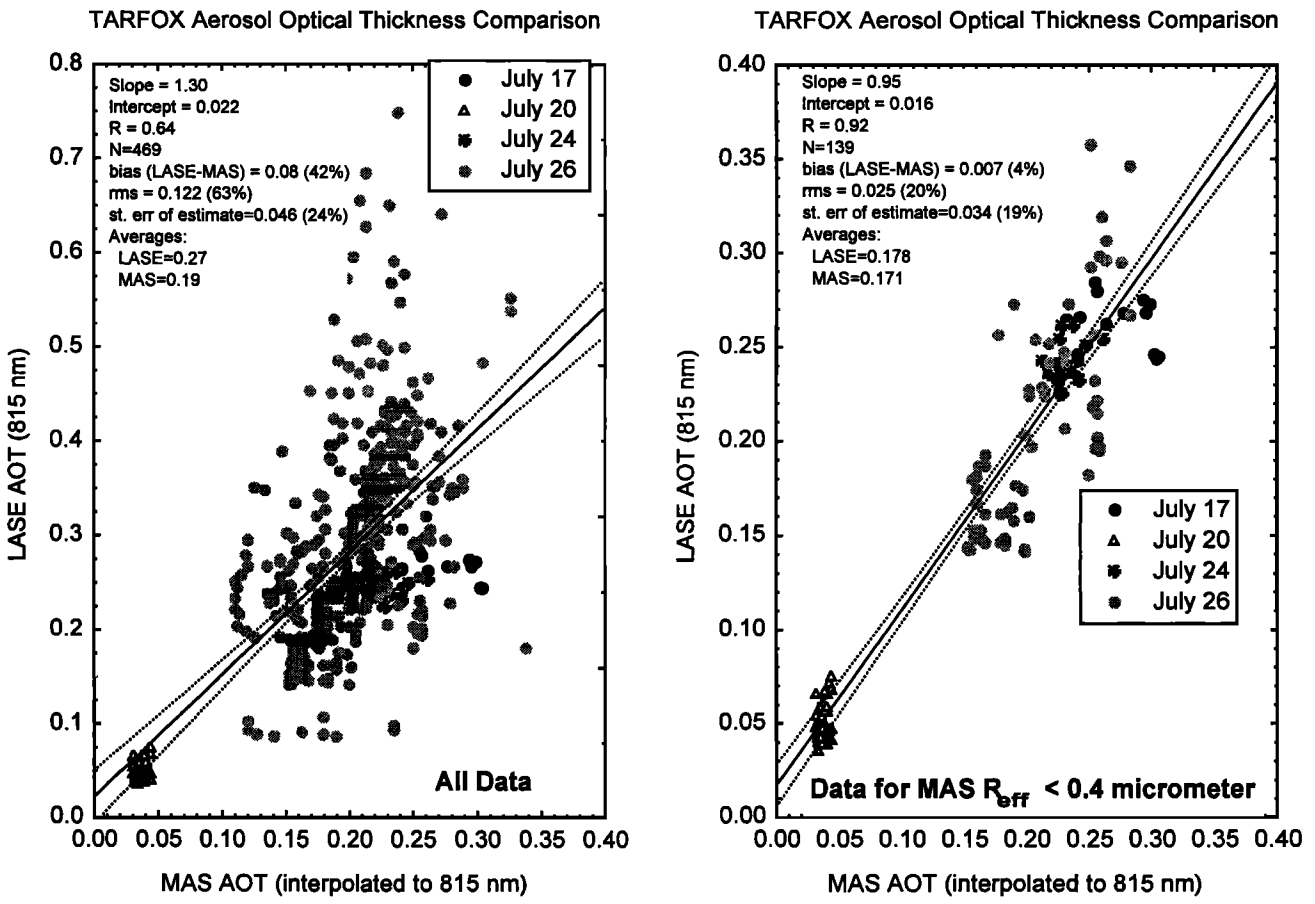

Figure 6. (left) Comparison of AOT measured by MAS and LASE during TARFOX. (right) Same except limited to effective particle radii <0.4 μm as derived from MAS.

rameters by comparing measured and modeled radiances; the aerosol parameters corresponding to the best match between measured and modeled radiances represent the best solution. The algorithm assumes that the aerosol size distribution can be represented by two lognormal distributions, which correspond to the accumulation and coarse particle modes. The small mode represents gas and cloud phase processes, while the large mode represents maritime particles and dust. These aerosol models are derived primarily from ground-based observations and so may not fully represent the optical properties of the integrated vertical column [*Tanré et al.*, 1997]. The theoretical accuracy for AOT at 550 nm derived from the MAS is $\Delta\tau_a = \pm 0.05 \pm 0.05\tau_a$ [*Tanré et al.*, 1997], although comparisons with AOT measured by the AATS-6 Sun photometer on the C-131A aircraft during TARFOX showed an even better accuracy of $\Delta\tau_a = \pm 0.01 \pm 0.05\tau_a$ [*Tanré et al.*, 1999]. Comparisons of effective particle radius derived from MAS with those computed from the PCASP (Passive Cavity Aerosol Spectrometer Probe) in situ aerosol size distribution measurements on the C-131A during TARFOX confirmed previous accuracy estimates of $\Delta r_{eff} = 0.3 r_{eff}$ [*Tanré et al.*, 1999].

On four of the TARFOX flights, AOT and particle effective radius were derived from the MAS measurements near nadir away from Sun glint and therefore could be compared with the measurements derived from LASE. Figure 5 shows a comparison of the AOT measured by LASE and MAS on portions of flight tracks from July 17, 20, and 24. Results are shown for cases where the distances between the MAS and the LASE measurements were less than about 10 km. The MAS AOT at 655 and 867 nm were logarithmically interpolated to the LASE wavelength at 815 nm. LASE data were used to identify cloud-free profiles. With the exception of July 20 the particle effective radii derived from the MAS measurements are also shown in Figure 5. On July 20 the very low AOT prevented accurate retrieval of r_{eff} from the MAS measurements. PCASP measurements on this day indicated that r_{eff} was around 0.3 μm [*Tanré et al.*, 1999]. Therefore for these three days, r_{eff} was generally between 0.15 and 0.30 μm.

On July 26, MAS and LASE acquired a series of coincident measurements on the long flight legs to and from the Wallops area to Bermuda. Plate 1 shows the comparison of AOT derived from LASE and MAS on the trip from Wallops to Bermuda. Plate 1 shows the vertical structure of the aerosol extinction coefficient derived from the LASE measurements on this same flight leg. At the beginning of this leg the LASE estimates of AOT were significantly larger than those derived from MAS; nearer to Bermuda the measurements showed better agreement. A somewhat similar trend can be seen for the comparison between the two measurements on the return leg from Bermuda to Wallops shown in Plate 2. A possible explanation of the apparent overestimate of aerosol extinction and AOT by LASE during parts of these flights can be seen in Plates 1 and 2. On the first flight leg, r_{eff} derived from the MAS data decreased significantly, from about 1 μm in the Wallops region to about 0.3 μm in the area

around Bermuda. The return flight leg did not show the same consistent behavior although r_{eff} did vary between about 0.3 μm to 0.7 μm. Plates 1 and 2 show that the LASE AOT measurements showed much better agreement with the MAS measurements when r_{eff} was below about 0.4 μm. This can also be seen more clearly in Figure 6, which shows the correlation between LASE and MAS AOT for all data acquired on these four days. This shows that LASE measurements of AOT were generally higher than the AOT measured by MAS on July 26. However, when the effective particle size was restricted to be below 0.4 μm, the correlation between the LASE and the MAS AOT increased dramatically, with agreement between the two sensors generally within about 20%. *Gassó and Hegg* [1998] also found good agreement between the AOT derived from airborne lidar measurements and the AOT derived from MAS for a biomass burning plume over the ocean. The lidar retrieval of AOT in their study used the lidar ground return method discussed by *Ross et al.* [1996]. The AOT measurements in these lidar/MAS comparisons ranged from 0.4 to 1.5, compared to the range of 0.0 to 0.4 in the current study.

The variation in r_{eff} observed by MAS on July 26, as well as the differences between the LASE and the MAS AOT measurements, shown in Plates 1 and 2, may be explained by variations in the size and resulting scattering properties of the aerosols caused by hygroscopic growth of the particles. As the relative humidity increases, hygroscopic aerosol particles acquire water and grow, and the particle composition also changes, causing the scattering, extinction, and optical thickness to increase [*Kotchenruther et al.*, 1999]. This hygroscopic growth can also cause the S_a value to be significantly different from the S_a = 60 sr value assumed in the LASE retrievals and would lead to erroneous LASE AOT retrievals. Temperature profiles from radiosondes launched at Wallops Flight Facility at 1830 UTC and at Bermuda at 2006 UTC were used, along with the LASE water vapor mixing ratio profiles, to estimate relative humidity profiles along these flight tracks. Temperature profiles to match the ER-2 location were computed by interpolating between the Wallops and the Bermuda radiosondes. The resulting relative humidity profiles for these flight tracks are shown in Plates 1 and 2. The white regions around 2053, 2202, and 2215 UTC were caused by cloud attenuation interfering with the LASE water vapor retrievals. The relative humidity near the surface was generally above 90% for much of these legs. The average relative humidity was computed between 200 and 500 m where the LASE aerosol extinction profiles showed the greatest values as shown in Plates 1 and 2. The LASE aerosol extinction images also show frequent occurrences of low-level clouds during these legs. These average relative humidity values are plotted along with r_{eff} for these flight legs in Plates 1 and 2. The correlation between r_{eff} and average relative humidity is especially pronounced for the first flight leg from Wallops to Bermuda. These images indicate the utility in having coincident measurements of water vapor and temperature to better understand the behavior of AOT and r_{eff} derived from the MAS.

6. LASE and ATSR-2 Aerosol Optical Thickness Comparison

The LASE measurements of AOT were compared with those measured by the Along-Track Scanning Radiometer 2 (ATSR-2) onboard the European ERS-2 satellite launched in 1995. This sensor has seven spectral bands, of which four (0.555, 0.659, 0.865, and 1.6 μm) are used for aerosol retrieval. A detailed description of the aerosol retrieval algorithm is given by *Veefkind and de Leeuw* [1998]. *Veefkind et al.* [1999] compared the AOT derived from the radiances measured by the ATSR-2 with those measured by the AATS-6 Sun photometer flown during TARFOX; differences were less than 0.03 in the midvisible. Plate 3 [*Veefkind et al.*, 1999] shows the ATSR-2 retrieved AOT at 0.659 μm at 1552 UTC on July 25. Those regions over the ocean, where no AOT are displayed, were caused by the presence of clouds, which preclude ATSR-2 retrieval of AOT. The black line in the image represents a coincident flight track of the ER-2, which flew from northeast to southwest over this region between 1543 and 1556 UTC. Note that the ATSR-2 image shows a gradient in the AOT under the ER-2 flight track. Plate 3 shows the vertical cross section of aerosol extinction coefficient (815 nm) derived from the LASE measurements during this period and shows that this aerosol gradient was also observed by LASE. The LASE measurements show two separate aerosol layers in the region of higher AOT observed between 1548 and 1556 UTC. The first region, associated with the marine boundary layer below about 600 m, shows high aerosol extinction near the top of this layer, which is most likely caused by high relative humidity. A vertical profile of relative humidity measured on the C-131A at this same time (but in region approximately 40 km southwest of the ER-2 flight track) showed that the relative humidity exceeded 80% near the top of this layer [*Veefkind et al.*, 1999]. The second aerosol layer, which had considerably lower aerosol extinction values, extended from about 700 to 2300 m. A comparison of the AOT measured by LASE (815 nm) and the ATSR 2 (865 nm) is shown in Plate 3. In the region of lower AOT measured by LASE between 1543 and 1549 UTC, the AOT measured by both sensors generally agreed to within about 0.02. However, in the region of high AOT between 1549 and 1556 UTC, the LASE estimates of AOT are greater than the values from the ATSR 2 by 25-45%. The reasons for this difference are not clear. The enhanced aerosol extinction near the top of the marine boundary layer associated with the increase in relative humidity implies that the particle size increases in this region. This would imply that the constant S_a = 60 sr value used would be inappropriate in this region, where aerosol particle characteristics are variable.

As an additional comparison, the AOT derived from the MAS on this day is also shown in Plate 3. The MAS retrievals could not be performed during this 1543-1556 UTC period because of Sun glint. (Sun glint did not interfere with the ATSR-2 retrievals because this sensor looks at 55° along the scan path as well as at nadir.) However, during the period 1807-1815 UTC the MAS was able to derive AOT. The MAS measurements were not directly below the ER-2 at this time, so no direct comparison with the LASE measurements was possible. These AOT values, which are shown in Plate 3, show a slight gradient in AOT similar to that derived from the LASE measurements. The values of r_{eff} derived from the MAS measurements at this same time were less than 0.3 μm. On the basis of comparisons presented in section 5 for cases when r_{eff} derived from the MAS measurements were less than 0.3 μm, AOT derived from LASE and MAS compared well. The difference between the LASE and the ATSR-2 AOT measurements is not clear. Note that ATSR-2 measurements of AOT on July 25 in another region of the TARFOX area 50-100 km away from the ER-2 flight track agreed well with those measured by the AATS-6 airborne Sun photometer [*Veefkind et al.*, 1999].

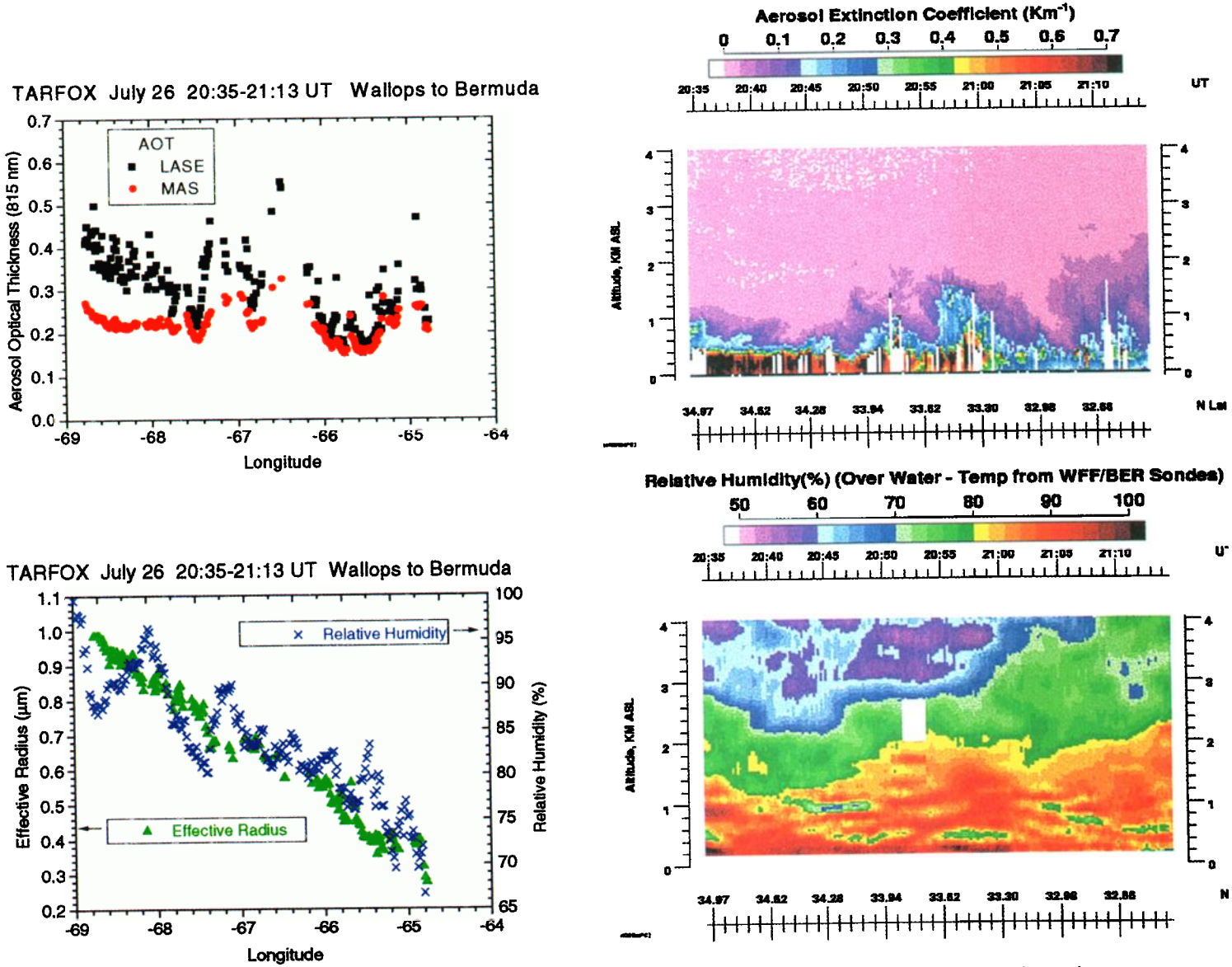

Plate 1. (top left) Comparison of AOT measured by LASE and MAS during flight from Wallops to Bermuda on July 26, 1996. (top right) Aerosol extinction profiles measured by LASE during this flight leg. (bottom left) Particle effective radius measured by MAS (left axis) and relative humidity in lowest 500 m derived from LASE measurements (right axis) during this flight leg. (bottom right) Relative humidity profiles measured by LASE during this flight leg.

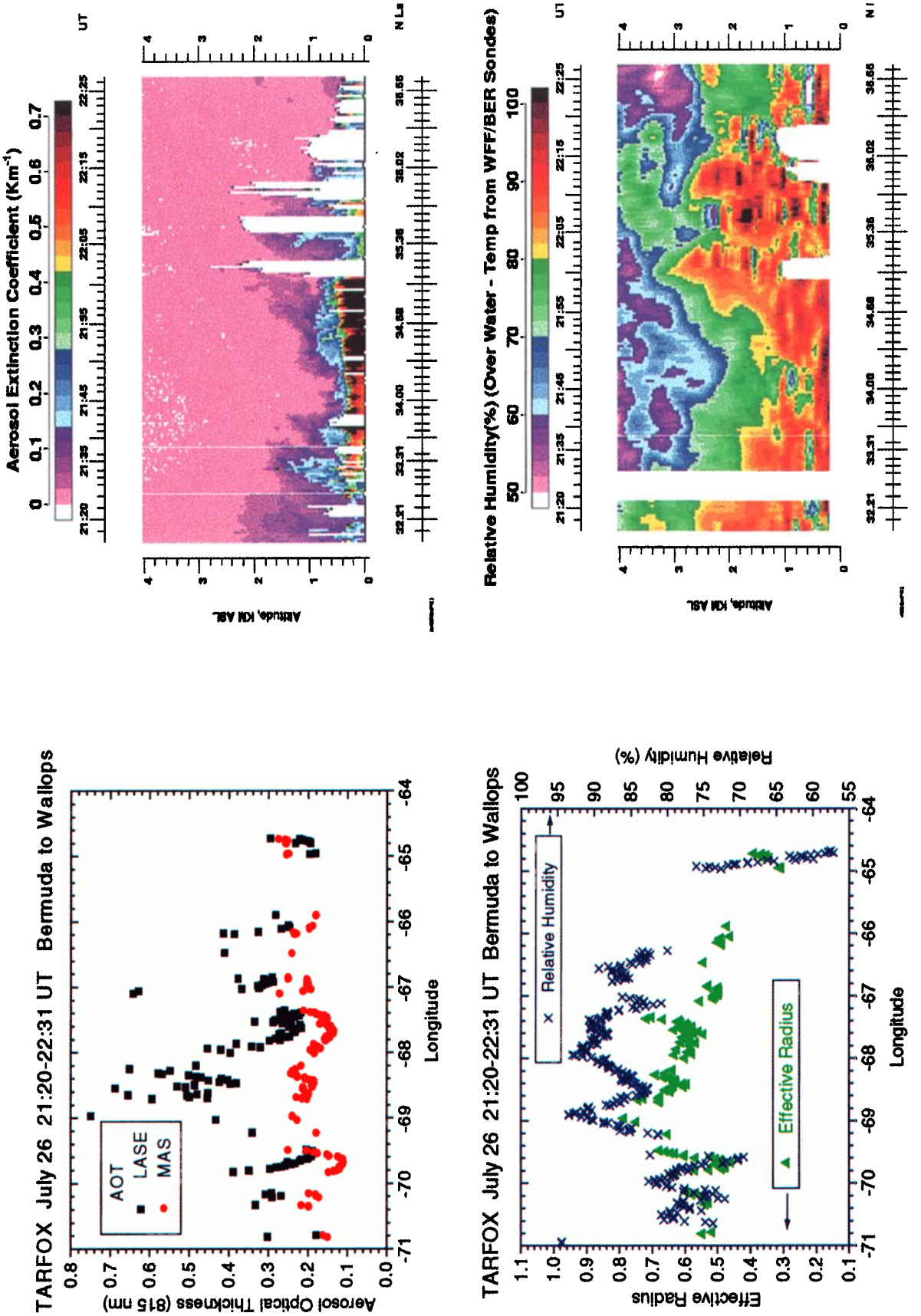

Plate 2. Same as Plate 1 except for the return flight leg from Bermuda to Wallops Island on July 26.

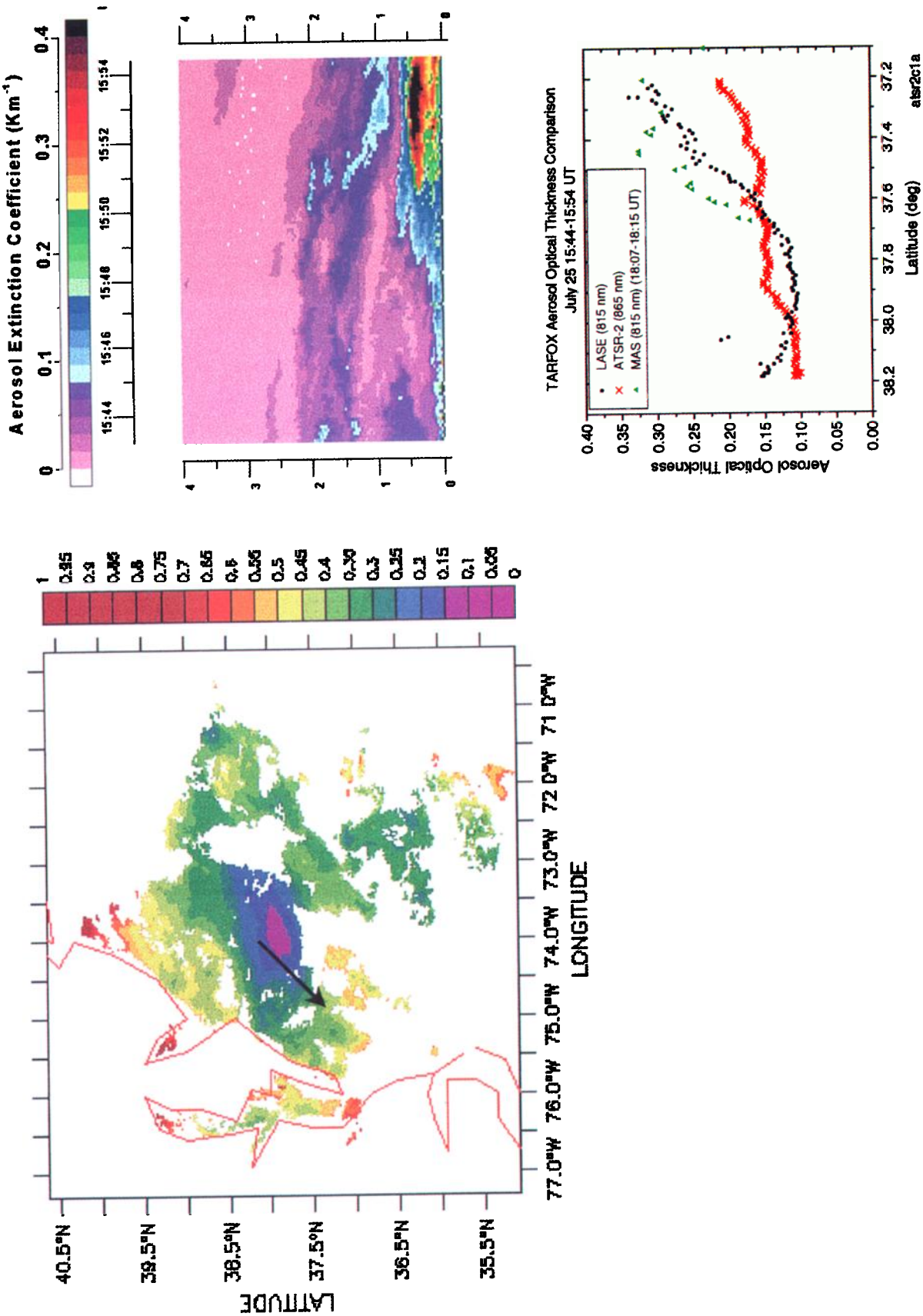

Plate 3. (top left) ATSR-2 retrieved AOT at 659 nm at 1552 UT on July 25, 1996 [from *Veefkind et al.*, 1999]. The simultaneous ER-2 flight track is also indicated. (top right) Aerosol extinction profiles derived from LASE during this ER-2 flight leg. (bottom right) Comparison of AOT measured by LASE and ATSR-2 during the ER-2 flight leg. The AOT measured by MAS over this same region about 2-2.5 hours later is also shown.

7. Conclusions

Aerosol extinction profiles derived from LASE aerosol backscattering measurements have been compared with those derived from airborne in situ and Sun photometer measurements. Although the LASE aerosol extinction profiles were derived using a single value of S_a = 60 sr for the aerosol extinction/backscattering ratio, the lidar profiles acquired on July 17 and 24 were generally in good agreement with the other measurements. Bias differences (LASE in situ) for these two days are 0.0055 km^{-1} (10%) and root-mean-square (rms) differences are 0.026 km^{-1} (42%). Larger (>50%) differences found for two other days were associated with much smaller aerosol optical thicknesses (July 20) and differences in the locations sampled by the two aircraft (July 26). Profiles of AOT derived from the LASE aerosol extinction profiles were generally higher than AOT profiles derived from an airborne Sun photometer and from in situ aerosol measurements. The results were consistent with previous comparisons that showed the LASE AOT had a small (5-10%) bias and were generally within 25% of airborne Sun photometer measurements [*Ferrare et al.*, this issue]. Similar comparisons between the AOT derived from in situ measurements and measured by the airborne Sun photometer indicated that the AOT from the in situ data were about 10-15% lower than the Sun photometer values [*Hegg et al.*, 1997; *Hartley et al.*, 1999]. Considering the uncertainty associated with these measurements, these comparisons represent good agreement among the various independent techniques.

The LASE measurements of AOT were compared with AOT derived from the MAS instrument that flew with LASE on the NASA ER-2. Using data from three of the four days (July 17, 20, and 24), the AOT derived from the LASE measurements had a bias difference (LASE-MAS) of 0.008 (6%) and a rms difference of 0.02 (16%) when compared to the AOT derived from MAS data. On the fourth day (July 26), during flights from Wallops Island to Bermuda and back, the LASE measurements of AOT were generally higher than the MAS AOT measurements. This difference is most likely due to the changes in the aerosol extinction/backscatter ratio due to the increase in particle size on this day as indicated from the MAS measurements of effective particle radius. These comparisons highlight the importance of having additional information regarding the relationship between aerosol extinction and backscattering. Such information can be provided using Raman-scattering channels or by constraining the lidar retrievals using AOT measured by another sensor, such as ground or airborne Sun photometers [*Ferrare et al.*, this issue]. The aerosol effective radius varied between 0.4 and 1.0 μm on July 26, in contrast to values between 0.15 and 0.30 μm observed on the other three days. Water vapor mixing ratio profiles measured by LASE on July 26 were used to derive high temporal resolution profiles of relative humidity in order to investigate the variations in particle size. The effective particle sizes were highly correlated to variations in the relative humidity in the lowest 500 m.

The comparisons of AOT measured by LASE and the ATSR-2 instrument on the ERS-2 satellite on July 25 show mixed results. The AOT measurements agreed well over about half of the 100-km-wide measurement path, while over the other half, the LASE measurements of AOT were up to 50% higher. This difference may be due to variations in the aerosol particle size, and consequently S_a, due to relative humidity variations. These comparisons also show how simultaneous water vapor measurements add important information for understanding the remote measurements of aerosol optical properties. In those cases of where hygroscopic aerosols are observed in high relative humidity conditions, simultaneous measurements of relative humidity profiles provide valuable information for assessing aerosol optical and physical characteristics.

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