

## Coordinated airborne, spaceborne, and ground-based measurements of massive thick aerosol layers during the dry season in southern Africa

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[1] During the dry season airborne campaign of the Southern African Regional Science Initiative (SAFARI 2000), coordinated observations were made of massive thick aerosol layers. These layers were often dominated by aerosols from biomass burning. We report on airborne Sun photometer measurements of aerosol optical depth ( $\lambda = 0.354\text{--}1.557\ \mu\text{m}$ ), columnar water vapor, and vertical profiles of aerosol extinction and water vapor density that were obtained aboard the University of Washington's Convair-580 research aircraft. We compare these with ground-based AERONET Sun/sky radiometer results, with ground based lidar data (MPL-Net), and with measurements from a downward pointing lidar aboard the high-flying NASA ER-2 aircraft. Finally, we show comparisons between aerosol optical depths from the Sun photometer and those retrieved over land and over water using four spaceborne sensors (TOMS, MODIS, MISR, and ATSR-2). *INDEX TERMS:* 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0345 Atmospheric Composition and Structure: Pollution—urban and regional (0305); 0394 Atmospheric Composition and Structure: Instruments and techniques; *KEYWORDS:* aerosol, Sun photometer, biomass burning, optical depth, satellite

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### 1. Introduction

[2] From 13 August to 25 September 2000, the Southern African Regional Science Initiative's (SAFARI 2000) dry season airborne campaign coordinated ground-based measurement teams, multiple research aircraft, and satellite overpasses across nine African nations [Swap *et al.*, 2002]. Among many other accomplishments, coordinated observations were made of the evolution of massive, thick haze layers produced by biomass burning, industrial emissions, and biogenic and marine sources.

[3] During SAFARI 2000, the NASA Ames Airborne Tracking 14-channel Sun photometer (AATS-14) was oper-

ated aboard the University of Washington's (UW) Convair-580 research aircraft (Appendix A by P. V. Hobbs in the work of Sinha *et al.* [2003]). The AATS-14 measures the transmission of the direct solar beam at 14 discrete wavelengths from 0.354 to 1.557  $\mu\text{m}$  from which spectral aerosol optical depths  $\tau_a(\lambda)$ , columnar water vapor (CWV) and columnar ozone can be derived. Flying at different altitudes over a fixed location allows derivation of layer  $\tau_a(\lambda)$  or CWV. Data obtained in vertical profiles allows derivation of spectral aerosol extinction  $E_a(\lambda)$  and water vapor density  $\rho_w$ .

[4] Here we discuss a subset of AATS-14 results from 24 data flights. We also show data from ground-based Sun/sky radiometers, from a ground-based lidar, and from a downward pointing lidar aboard the high-flying NASA ER-2 aircraft for all cases where a comparison between one of these instruments and AATS-14 is possible. Finally, we show all comparisons of  $\tau_a(\lambda)$  as measured by AATS-14 and retrieved over water and over land by four different spaceborne instruments (TOMS, MODIS, MISR and ATSR-2).

### 2. Measurements

#### 2.1. Airborne Measurements

##### 2.1.1. NASA Ames Airborne Tracking 14-Channel Sun Photometer (AATS-14)

[5] The AATS-14 measures the transmission of the direct solar beam in 14 spectral channels (0.354 to 1.557  $\mu\text{m}$ ). Azimuth and elevation motors controlled by tracking-error signals derived from a quad-cell photodiode rotate a track-

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ing head to lock on to the solar beam and keep detectors normal to it. The tracking head is mounted outside the aircraft skin to minimize blockage by aircraft structures and to avoid data contamination by aircraft-window effects. Window defogging is achieved by a foil heater. Each channel consists of a baffled entrance path, interference filter, photodiode detector, and integral preamplifier. The filter/detector/preamp sets are temperature controlled to avoid thermally induced calibration changes.

[6] The AATS-14 is designed to operate on a variety of aircraft, some of which may be remotely piloted. It can locate and track the Sun without input from an operator and record data in a self-contained data system. In addition, it must interface to an aircraft-provided data system, and receive and execute commands from a remote operator station (laptop), and transmit science and instrument-status data to that station. Using aircraft-provided data on latitude, longitude and ambient static pressure,  $\tau_a(\lambda)$  and CWV are computed in real time and displayed at the operator station (along with raw data, instrument status, and aircraft-provided data). Radiometric calibration is determined via Langley plots [Schmid and Wehrli, 1995], either at high-mountain observatories or during specially designed flights [Schmid et al., 2000].

[7] The AATS-14 made its first science flights on the Pelican (modified Cessna) aircraft of the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) during the Tropospheric Aerosol Radiative Forcing Observational Experiment (TARFOX) in July 1996 [Russell et al., 1999a, 1999b]. More extensive flights on the Pelican were made in the second Aerosol Characterization Experiment (ACE 2), which provided many measurements of marine, European, and African aerosol optical depth spectra, as well as water vapor columns [Schmid et al., 2000].

[8] Our methods for data reduction, calibration, and error analysis have been described previously [Russell et al., 1993; Schmid and Wehrli, 1995; Schmid et al., 1998, 2001]. A brief summary is given here. The AATS-14 channels are chosen to allow separation of aerosol, water vapor, and ozone transmission. From these slant-path transmissions we retrieve  $\tau_a(\lambda)$  in 13 narrow wavelength bands and the columnar amounts of water vapor (CWV) and ozone. Due to large transmission loss of the 0.606- $\mu\text{m}$  bandpass filter (the AATS-14 channel most sensitive to ozone) and hence large calibration uncertainty, the ozone retrieval was turned off for the results shown here and the total column ozone values were taken from the Total Ozone Mapping Spectrometer (TOMS) on the Earth Probe satellite. In addition to the corrections for Rayleigh scattering and  $\text{O}_3$  absorption, some channels require corrections for  $\text{NO}_2$ ,  $\text{H}_2\text{O}$  and  $\text{O}_2\text{-O}_2$  absorption. Most cross sections were computed using LBLRTM 5.21 [Clough and Iacono, 1995] using the ESA-WV  $\text{H}_2\text{O}$  line list of Schermaul et al. [2001].  $\text{NO}_2$  and  $\text{O}_2\text{-O}_2$  cross sections not included in LBLRTM 5.21 were taken from Harder et al. [1997], Schneider et al. [1987], Greenblatt et al. [1990] and Michalsky et al. [1999].  $\text{NO}_2$  was assumed constant at  $2 \times 10^{-15}$  molecules  $\text{cm}^{-2}$ .

[9] During SAFARI 2000, AATS-14 acquired data of good quality during 24 data flights. Unlike in ACE 2 [Schmid et al., 2000] we did not perform in-flight Langley plots during SAFARI 2000. Instead, AATS-14 was cali-

brated at the Mauna Loa Observatory, Hawaii, three months before and one month after the SAFARI 2000 campaign using the Langley plot technique [Schmid and Wehrli, 1995]. As a result of band-pass filter degradation, the calibration constants obtained from the postmission calibration were lower than those obtained from the premission calibration. However, for seven of the 14 wavelengths the change was only 0.5% or less. Six of the other seven channels had degraded by 1 to 6% and one filter lost 11% of its transmission. We decided to discard the results from the last mentioned filter. Thus, the SAFARI 2000 data set consists of 12 wavelengths (0.354, 0.380, 0.449, 0.499, 0.525, 0.606, 0.675, 0.778, 0.864, 1.019, 1.241, and 1.557  $\mu\text{m}$ ) at which we retrieve  $\tau_a$  and the 0.940- $\mu\text{m}$  wavelength, which we use to determine CWV. Note that

$$\Delta\tau_a(\lambda) = \frac{1}{m} \frac{\Delta V_0(\lambda)}{V_0(\lambda)} \quad (1)$$

with

$$m \approx \frac{1}{\cos\theta}. \quad (2)$$

[10] Hence a relative uncertainty of 1% in the calibration constant  $V_0$  will lead to an absolute uncertainty in the aerosol optical depth  $\Delta\tau_a(\lambda)$  of 0.01 for a solar zenith angle  $\theta = 0^\circ$ . To determine the most plausible set of calibration constants applicable to the SAFARI 2000 data set we inspected  $\tau_a(\lambda)$  spectra measured during higher altitude legs (typically around 4 km). We focused on days with low  $\tau_a$  (0.007 to 0.04 at 0.499  $\mu\text{m}$ , at around 4 km). This resulted in 13 spectra taken during 11 flights between 14 and 31 August 2000. The cleanest conditions were observed early in the campaign before the onset of intense biomass burning. Leaving the calibration constants of the seven stable channels unchanged we then adjusted the calibration constants of the other five aerosol wavelengths in such a fashion that the retrieved  $\tau_a(\lambda)$  yielded “smooth”  $\tau_a(\lambda)$  spectra for all 13 high-altitude cases. In all but one channel the adjusted calibration constants were within the bounds of premission and postmission calibration.

[11] The total uncertainty of the retrieved  $\tau_a(\lambda)$ , due to uncertainties in calibration, Sun tracking, signal measurement, airmass computation, and corrections of molecular scattering and absorption, was computed following the procedures given by Russell et al. [1993]. The uncertainty in CWV was computed following Schmid et al. [1996]. During SAFARI 2000, AATS-14 data were recorded every 4 s consisting of an average of 9 samples taken in the first 3 of the 4 s. The sample standard deviation of all science detector outputs is also stored in the data files. These standard deviations were used in our cloud-screening algorithm that is based on clouds exhibiting higher standard deviations than clear sky.

### 2.1.2. Cloud Physics Lidar (CPL)

[12] The Cloud Physics Lidar (CPL) was built for use on the NASA ER-2 high-altitude aircraft. Its purpose is to provide multiwavelength (0.355  $\mu\text{m}$ , 0.532  $\mu\text{m}$ , and 1.064  $\mu\text{m}$ ) measurements of cirrus, subvisual cirrus, and aerosols with high

**Table 1.** University of Washington's Convair-580 Low-Altitude Flybys at AERONET Sites in SAFARI 2000

Site	Country	Latitude, S	Longitude, E	Altitude, m	Aircraft Altitude, m	Separation, km	Date, Time	Subplot
Skukuza	South Africa	24°59'	31°35'	150	384	31	17 Aug., 08:06	Figure 3a
					429	45	17 Aug., 09:37	Figure 3b
					324	3	22 Aug., 10:07	Figure 3c
Inhaca Island	Mozambique	26°02'	32°54'	73	61	4	24 Aug., 08:37	Figure 3d
Kaoma	Zambia	14°47'	24°47'	1179	1261	34	1 Sep., 09:09	Figure 3e
Sua Pan	Botswana	20°31'	26°04'	900	947	12	3 Sep., 08:50	Figure 3f
Senanga	Zambia	16°06'	23°17'	1025	1172	9	6 Sep., 07:56	Figure 3g
Mongu	Zambia	15°15'	23°09'	1107	1041	11	6 Sep., 08:15	Figure 3h
					1228	2	6 Sep., 09:14	Figure 3i
					1142	20	16 Sep., 09:24	Figure 3k
Etosha Pan	Namibia	19°10'	15°54'	1131	1195	7	16 Sep., 10:53	Figure 3l

temporal and spatial resolution. This instrument together with initial SAFARI 2000 measurement results has been described by McGill *et al.* [2002].

[13] The CPL is the successor of the Cloud Lidar System (CLS), which was the first high-altitude lidar system designed specifically for studying clouds and aerosols and was first flown on the ER-2 aircraft in 1983. The first deployment of the CPL was the SAFARI 2000 field campaign. Pointing downward from the ER-2 operational altitude of  $\sim 20$  km, CPL obtained 120 flight hours of data with no problems or failures. The results are discussed by McGill *et al.* [2003].

[14] In this paper we use aerosol extinction  $E_a(\lambda)$  and  $\tau_a(\lambda)$  profiles at 0.532 and 1.064  $\mu\text{m}$  obtained from CPL in five ER-2 flights (the 0.355- $\mu\text{m}$  channel was not yet operational during SAFARI 2000). The CPL data segments were chosen to coincide temporally and spatially with Convair-580 vertical profiles to allow comparisons with AATS-14 measurements.

## 2.2. Ground-Based Measurements

### 2.2.1. Aerosol Robotic Network (AERONET)

[15] AERONET is a globally dispersed network of automatic ground-based Sun/sky scanning radiometers from which  $\tau_a(\lambda)$ , CWV, aerosol size distribution and aerosol single-scattering albedo,  $\omega_0$ , are retrieved [Holben *et al.*, 1998, 2001; Eck *et al.*, 2001; Dubovik *et al.*, 2002]. Seventeen southern African AERONET sites were operational during SAFARI 2000. Detailed results are presented by Eck *et al.* [2003]. Here we present data from seven AERONET sites (Table 1) coincident with Convair-580 low-altitude flybys, thereby allowing comparisons with AATS-14 airborne measurements and satellite sensors.

### 2.2.2. Micropulse Lidar Network (MPL-Net)

[16] The Micro-Pulse Lidar (MPL) [Spinhirne *et al.*, 1995] is a single channel (0.523  $\mu\text{m}$ ), autonomous, eye-safe lidar system originally developed at the NASA Goddard Space Flight Center and is now commercially available. MPL-Net [Welton *et al.*, 2001] is a worldwide network of ground-based MPL systems, colocated with AERONET Sun/sky radiometers. The MPL is used to determine the vertical structure of clouds and aerosols. The MPL data is analyzed to produce optical properties, such as extinction and optical depth profiles of clouds and aerosols.

[17] During SAFARI 2000, MPL systems were deployed at Skukuza in the Kruger National Park, South Africa, and in Mongu, Zambia (Figure 1; Table 1). Detailed results are presented by Campbell *et al.* [2003]. Several times during the campaign the ER-2 flew over the MPL sites to allow

comparison with the airborne CPL. The Convair-580 flew one vertical profile over each MPL site to permit comparison with airborne AATS-14 measurements.

## 2.3. Spaceborne Measurements

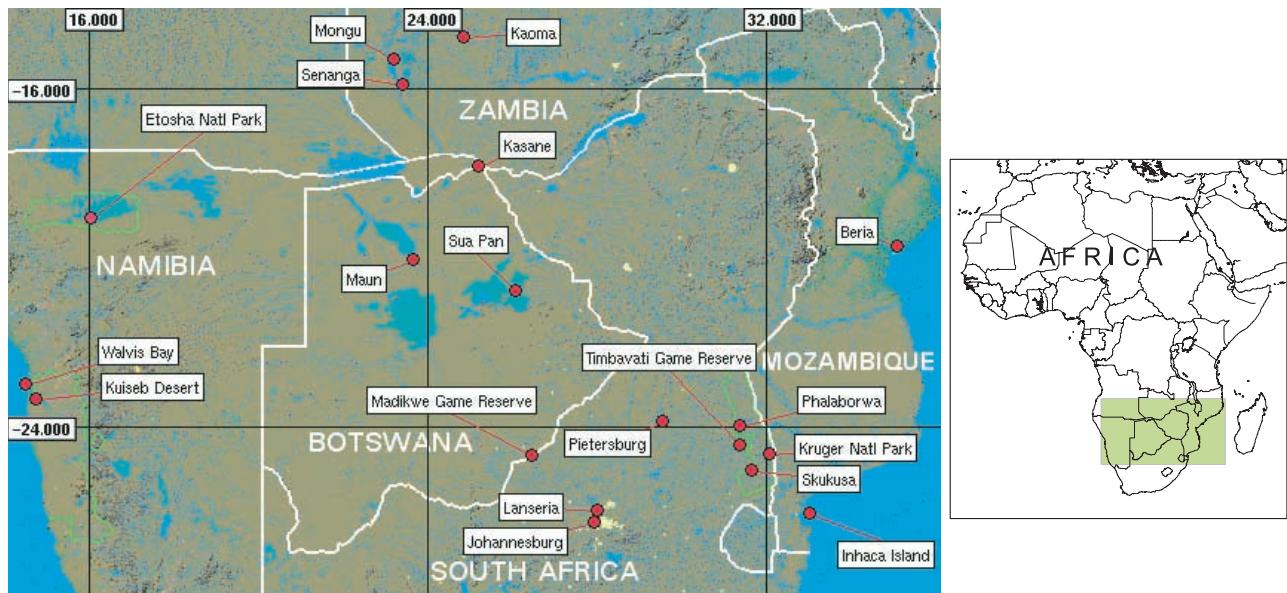
[18] A major focus of the SAFARI 2000 dry season campaign was validation of satellite retrieved aerosol properties. Mostly, these validations are accomplished using ground-based AERONET data [e.g., Diner *et al.*, 2001; Chu *et al.*, 2002; Remer *et al.*, 2002; Torres *et al.*, 2002; Zhao *et al.*, 2002]. Airborne sensors (such as AATS-14 and CPL) have less temporal coverage but they can provide aerosol optical properties over water, in vertical profiles, and along aerosol gradients. They can also help address the problem of small-scale, subpixel variability. During SAFARI 2000, ER-2 and Convair-580 flights were coordinated with overpasses of the Terra and, to a lesser extent, with the Earth Probe satellite.

### 2.3.1. Total Ozone Mapping Spectrometer (TOMS)

[19] TOMS radiation measurements at two near-UV channels are used to retrieve aerosol optical depth and single scattering albedo [Torres *et al.*, 1998]. The retrieval technique applied to the TOMS data makes use of two advantages of near-UV remote sensing not available in the visible or near IR: (1) low reflectivity of all land surface types (including deserts, which are normally bright in the visible), enabling aerosol retrieval over the continents and (2) high sensitivity to aerosol types that absorb in the UV, allowing clear separation between carbonaceous and mineral aerosols from purely scattering particles such as sulfate and sea salt aerosols.

[20] The near-UV method of aerosol characterization has been validated by comparison with AERONET ground based observations [Torres *et al.*, 2002]. The predicted uncertainty of TOMS retrieved  $\tau_a$  at 0.38  $\mu\text{m}$  is the larger of 0.1 and 20% of  $\tau_a$  for nonabsorbing aerosols and the larger of 0.1 and 30% of  $\tau_a$  for absorbing aerosols. Torres *et al.* [2002] performed 496 individual comparisons with six AERONET sites and found 74% of all  $\tau_a$  to agree within the predicted uncertainties. A long-term record of  $\tau_a$  over oceans and continents has been derived using observations of backscattered near ultraviolet radiation from the TOMS sensors on board the Nimbus-7 (1979–1992) and the Earth Probe (mid-1996 to present) satellites [Torres *et al.*, 2002].

[21] During SAFARI 2000, several Convair-580 flights were coordinated with overpasses of the Earth Probe satellite allowing comparisons of TOMS aerosol retrievals with AATS-14 column and profile measurements.



**Figure 1.** Map of study area, showing many of the locations over which measurements were obtained from the University of Washington's Convair-580 research aircraft in SAFARI 2000 [from Hobbs, 2001].

### 2.3.2. Moderate Resolution Imaging Spectroradiometer (MODIS)

Aerosol physical parameters are among the numerous products operationally retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Earth Observing System's (EOS) Terra satellite launched on 18 December 1999. The MODIS aerosol algorithm routinely retrieves  $\tau_a(\lambda)$  at 0.47 and 0.66  $\mu\text{m}$  wavelengths (and interpolates to 0.55  $\mu\text{m}$ ) over vegetated land surfaces, and at seven spectral bands (0.47, 0.55, 0.66, 0.87, 1.24, 1.64 and 2.13  $\mu\text{m}$ ) over oceans [Kaufman *et al.*, 1997; Tanré *et al.*, 1997]. Other aerosol parameters retrieved include the Angstrom exponent over land and ocean, and effective radius and ratio of small to large particle size modes over ocean [from Ichoku *et al.*, 2002].

[22] The MODIS aerosol retrievals over ocean and land have been validated by comparison with AERONET ground based observations. For the over-ocean retrievals, Remer *et al.* [2002] performed 64 individual comparisons with data from 11 coastal and island AERONET stations covering a time span of 2 months starting 21 August 2000. They found MODIS retrieved  $\tau_a$  at 0.66  $\mu\text{m}$  and 0.87  $\mu\text{m}$  to agree within the expected uncertainty  $\Delta\tau_a = \pm 0.03 \pm 0.05 \tau_a$ .

[23] To validate the over-land  $\tau_a(\lambda)$  retrieval, Chu *et al.* [2002] performed 315 individual comparisons with 32 AERONET land sites covering the period from July to September 2000. They found that nearly all points (at 0.47  $\mu\text{m}$  and 0.66  $\mu\text{m}$ ) fell within the retrieval errors of  $\Delta\tau_a = \pm 0.05 \pm 0.2 \tau_a$ .

[24] During SAFARI 2000, numerous Convair-580 flights were coordinated with overpasses of the Terra satellite allowing comparisons of MODIS aerosol retrievals with AATS-14 column and profile measurements.

### 2.3.3. Multiangle Imaging Spectroradiometer (MISR)

[25] The MISR, also onboard the Terra satellite, images the Earth at nine discrete view angles from nadir up to 70.5° fore and aft of the local vertical. Multispectral (0.446, 0.558, 0.672 and 0.866  $\mu\text{m}$ ) imagery is obtained at each angle. MISR

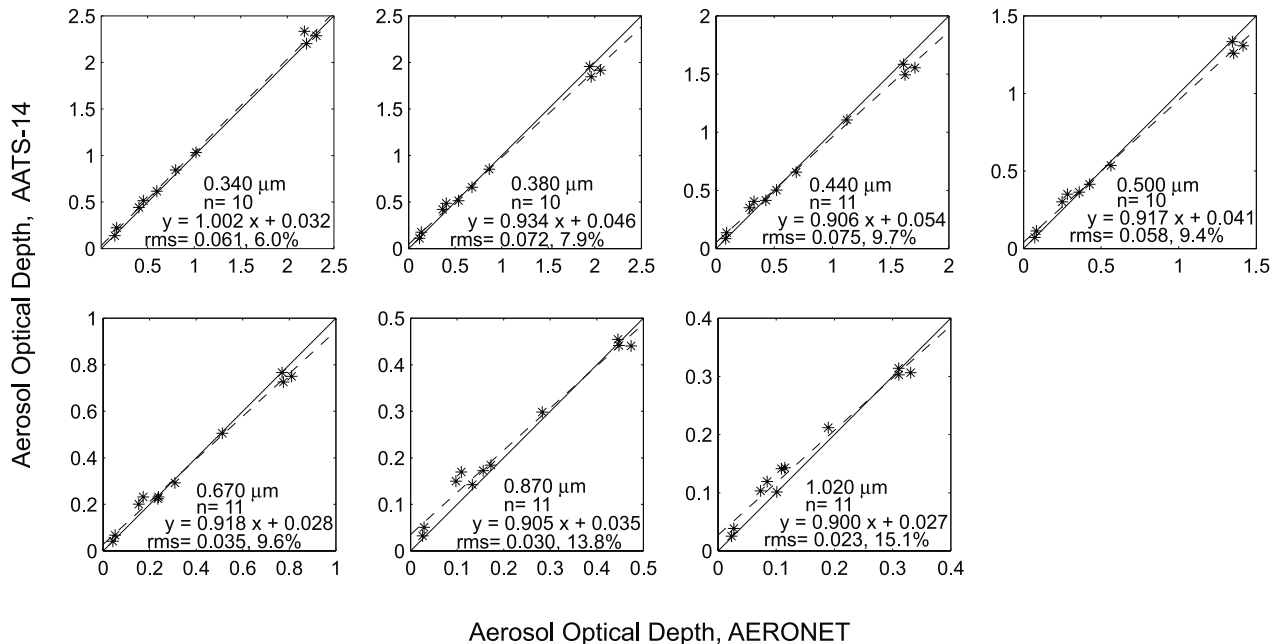
globally provides 275-m sampling in all bands of the nadir camera and the red band of each of the off-nadir cameras and 1.1 km for the remaining cameras. It takes 7 min for all nine cameras to image a given location. Aerosol optical properties over land and water are retrieved over  $17.6 \times 17.6 \text{ km}^2$  regions. The aerosol retrieval algorithm has been described by Martonchik *et al.* [1998] and Kahn *et al.* [2001]. A first validation of the over-land retrieval using SAFARI 2000 AERONET data has been discussed by Diner *et al.* [2001].

### 2.3.4. Along-Track Scanning Radiometer 2 (ATSR-2)

[26] The ATSR-2 is a radiometer aboard the European ERS-2 satellite, which was launched in April 1995. ATSR-2 has seven spectral bands; four of these are potentially useful for aerosol retrieval. The effective wavelengths of these four channels are 0.555, 0.659, 0.865 and 1.6  $\mu\text{m}$ . The spatial resolution is approximately  $1 \times 1 \text{ km}^2$  at nadir. The swath width is 500 km. The ATSR-2 has a conical scanning mechanism, thus producing two views of each region: first a forward view (zenith angle approximately 55°) and about two minutes later a nadir view. Validations of the over-water and the over-land  $\tau_a$  retrievals using AERONET and also airborne Sun photometer data have been presented by Veeffkind *et al.* [1998, 1999] and Robles-Gonzalez *et al.* [2000]. No flight coordination with ATSR-2 overpasses was made during SAFARI 2000, but we present one comparison of opportunity below.

## 3. Results

[27] All locations for which we discuss results are shown in the map in Figure 1. From 10 August to 9 September the Convair-580 was based in Pietersburg, South Africa for the purpose of carrying out flights over South Africa, Botswana, Zambia and Mozambique. From 10 to 18 September, the Convair-580 was based in Walvis Bay, Namibia to carry out flights over Namibia and off the Namibian coast (Appendix A by P. V. Hobbs in the work of Sinha *et al.* [2003]).



**Figure 2.** Scatterplot comparison of  $\tau_a(\lambda)$  from AERONET and AATS-14 during low-altitude flybys at each of the seven AERONET wavelengths. The identity line is indicated by the full line, the broken line is the least squares fit to the data.

### 3.1. Comparing $\tau_a(\lambda)$ Obtained From AATS-14 and AERONET

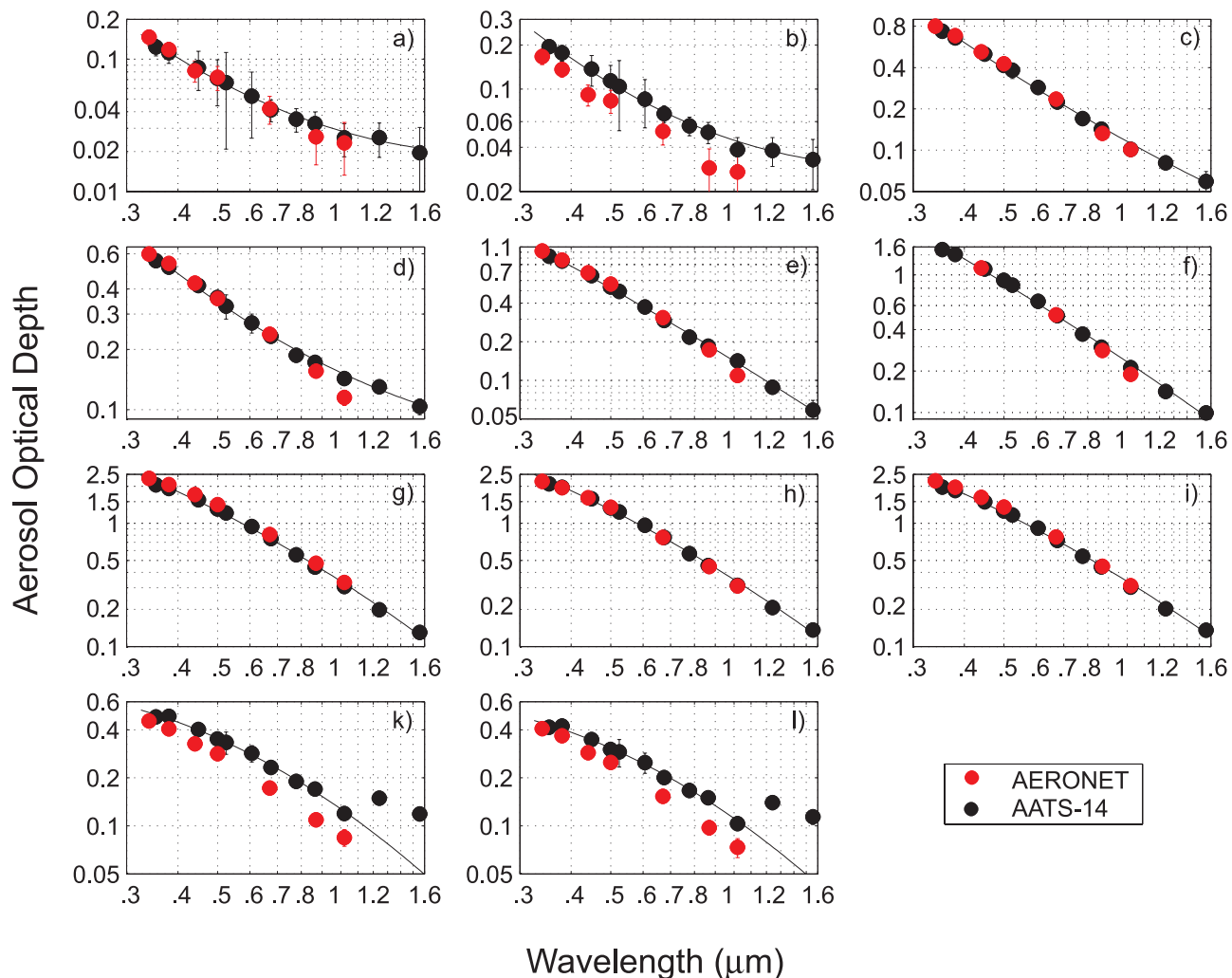
[28] As shown in Table 1, the Convair-580 made eleven low-altitude flybys of seven AERONET sites, allowing comparison of  $\tau_a(\lambda)$  derived from the airborne AATS-14 and the ground-based Sun/sky radiometers measurements. The low-altitude AATS-14  $\tau_a(\lambda)$ , consisting of 4 to 54 s averages, were usually compared to the AERONET  $\tau_a(\lambda)$  closest to the overflight time. In one case we linearly interpolated the AERONET  $\tau_a(\lambda)$  to the exact AATS-14 time, because there was a considerable change in the AERONET observed  $\tau_a(\lambda)$ . Note that except at low Sun angles AERONET measures  $\tau_a(\lambda)$  every 15 min. Due to safety considerations and competing mission objectives, the vertical (−66 to 279 m) and/or horizontal separation (2 to 45 km) between the airplane and AERONET sites was not always optimal. Note that in cases where there is a horizontal separation it is possible for the Convair-580 to fly below the AERONET site altitude. For this and also for the subsequent comparisons with satellite results we have made no correction for aerosol extinction below the lowest altitude of the airplane.

[29] The results of the intercomparison are shown in Figures 2 and 3. With the exception of the Sua Pan location, all AERONET Sun/sky radiometers operated at 0.34, 0.38, 0.44, 0.5, 0.67, 0.87, and 1.02  $\mu\text{m}$  wavelengths. In the scatterplots in Figure 2 we directly compared the AERONET and AATS-14  $\tau_a$  at 0.38/0.38, 0.5/0.499, 0.67/0.675, 0.87/0.864, and 1.02/1.019  $\mu\text{m}$  without any adjustments for the slight differences in wavelength. However, we inter/extrapolated the AATS-14  $\tau_a(\lambda)$  to the 0.34 and 0.44  $\mu\text{m}$  AERONET wavelengths using the equation

$$\ln \tau_a(\lambda) = a_0 + a_1 \ln \lambda + a_2 (\ln \lambda)^2, \quad (3)$$

where the constants  $a_0$ ,  $a_1$ , and  $a_2$  are determined by a second order polynomial fit to each individual AATS-14  $\tau_a(\lambda)$  spectrum. An excellent discussion of (3), applied to a variety of aerosol types is given by *Eck et al.* [1999]. As can be seen in Figure 3, equation (3) provides a good representation of the measured  $\tau_a(\lambda)$ . Figures 3k and 3l show the effect of dirt on the AATS-14 optical window affecting the longest two wavelengths. It is typical for AATS-14 that if the optical window picks up dirt after flying through a cloud or through sea spray, then this tends to happen first in the two longest wavelengths channels since their position is behind the uppermost section of the window which protrudes most above the aircraft skin. The statistical comparison shown in Figure 2 results in RMS differences ranging from 0.023 to 0.075 (6 to 15%) and regression line slopes between 0.9 and 1.

[30] *Schmid et al.* [1999] compared  $\tau_a$  derived from four ground-based solar radiometers (one was an AERONET Sun/sky radiometer and one was AATS-6, an abbreviated version of AATS-14) operated at the same site during a 3-week field campaign in Oklahoma. They found that the  $\tau_a$  values from 0.38 to 1.02  $\mu\text{m}$  agreed to within 0.015 (rms). The somewhat larger absolute RMS differences (0.023 to 0.075) found in the flyby comparisons shown here are a result of spatial (vertical and horizontal) and temporal separations, the effects of dirt on the AATS-14 optical window, tracking imperfections of AATS-14, the larger number of individual instruments involved, and most importantly, larger  $\tau_a$  in SAFARI 2000 than found by *Schmid et al.* [1999]. In fact the relative differences (rms/ $\tau_a(\lambda)$ ) for the comparison between the AERONET Cimel and AATS-6 found by *Schmid et al.* [1999], were 7%, 6%, 12%, 18% and 12% at 0.380, 0.450, 0.525, 0.864, and 1.021  $\mu\text{m}$ , respectively, and thus comparable to the relative differ-



**Figure 3.** Comparison of  $\tau_a(\lambda)$  spectra from AERONET and AATS-14 during low-altitude flybys. Information pertaining to each of the subplots (a) through (l) is given in Table 1. The lines are fits of equation (3) to the AATS-14 data.

ences found in SAFARI 2000 (Figure 2) with the flyby comparisons.

### 3.2. AATS-14 Measurements of a Biomass Burning Smoke Plume: A Case Study

[31] Smoke from biomass burning was a major component of the Southern African aerosol during SAFARI 2000. Thus, significant portions of the Convair-580 flight hours were devoted to studying smoke from prescribed fires and fires of opportunity (see Appendix A by P. V. Hobbs in the work of *Sinha et al.* [2003], and references therein).

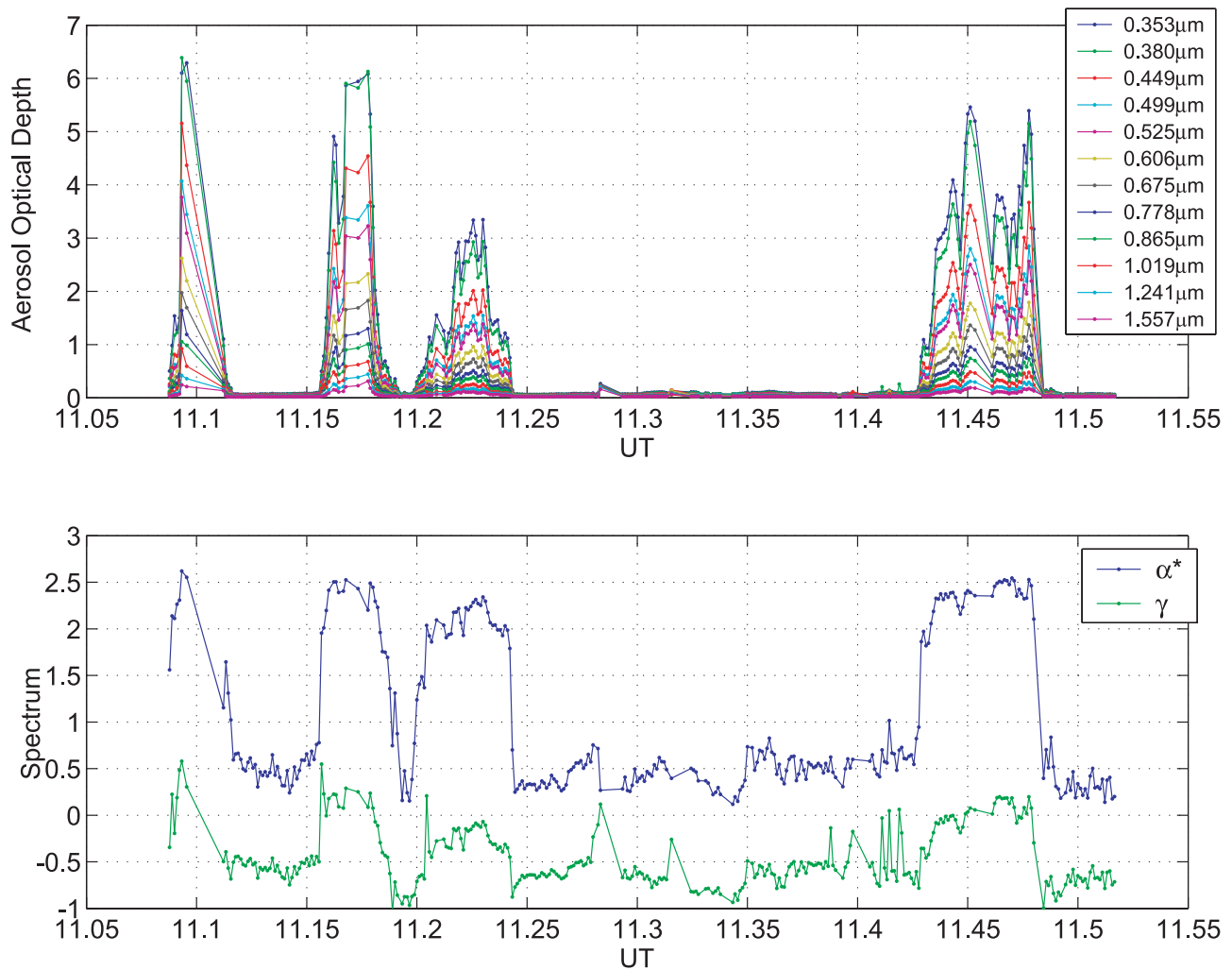
[32] Here we discuss airborne  $\tau_a(\lambda)$  measurements of smoke originating from a flaming-hot grass fire on 17 August 2000 in the Kruger National Park north of Skukuza ( $24^{\circ}28'S/31^{\circ}50'E$ ). Between 11:05 and 11:31 UT the Convair-580 penetrated the smoke plume four times at a near constant flight altitude of 1100 m (113 m a.g.l.). Figure 4 shows the time traces of  $\tau_a(\lambda)$  obtained from the four consecutive penetrations. Measurement gaps in time traces are caused by temporary loss of Sun tracking after blockage of the Sun by aircraft structures. Due to an AATS-14 tracking-software glitch (discovered and fixed

after SAFARI 2000), any temporary obstruction of the solar beam hitting the Sun sensor caused the instrument to lock at its current position for 10 s before re-acquiring the Sun.

[33] The atmosphere outside the plume was exceptionally clear with  $\tau_a(\lambda) < 0.1$  at all wavelengths, whereas inside the plume  $\tau_a(\lambda)$  occasionally exceeds 6 in the ultraviolet. The flight pattern flown in and outside the plume allowed derivation of the  $\tau_a$  map shown in Figure 5. The  $\tau_a$  measurements were taken at each individual white dot along the white Convair-580 flight track shown in Figure 5. A triangle-based linear interpolation was used to fill in  $\tau_a$  values between the flight tracks. The map clearly reveals the position and the spatial extent ( $9 \times 13$  km with  $\tau_a(0.5 \mu\text{m}) > 0.5$ ) of the plume.

[34] The spectral parameters  $\alpha^*$  and  $\gamma$  shown in Figure 4 are obtained by applying (3) to each  $\tau_a(\lambda)$  spectrum, where  $\alpha^* = -a_1$  and  $\gamma = -a_2$ . In fact, (3) is an extension of the traditional Ångström law

$$\tau_a(\lambda) = \beta\lambda^{-\alpha}, \quad (4)$$

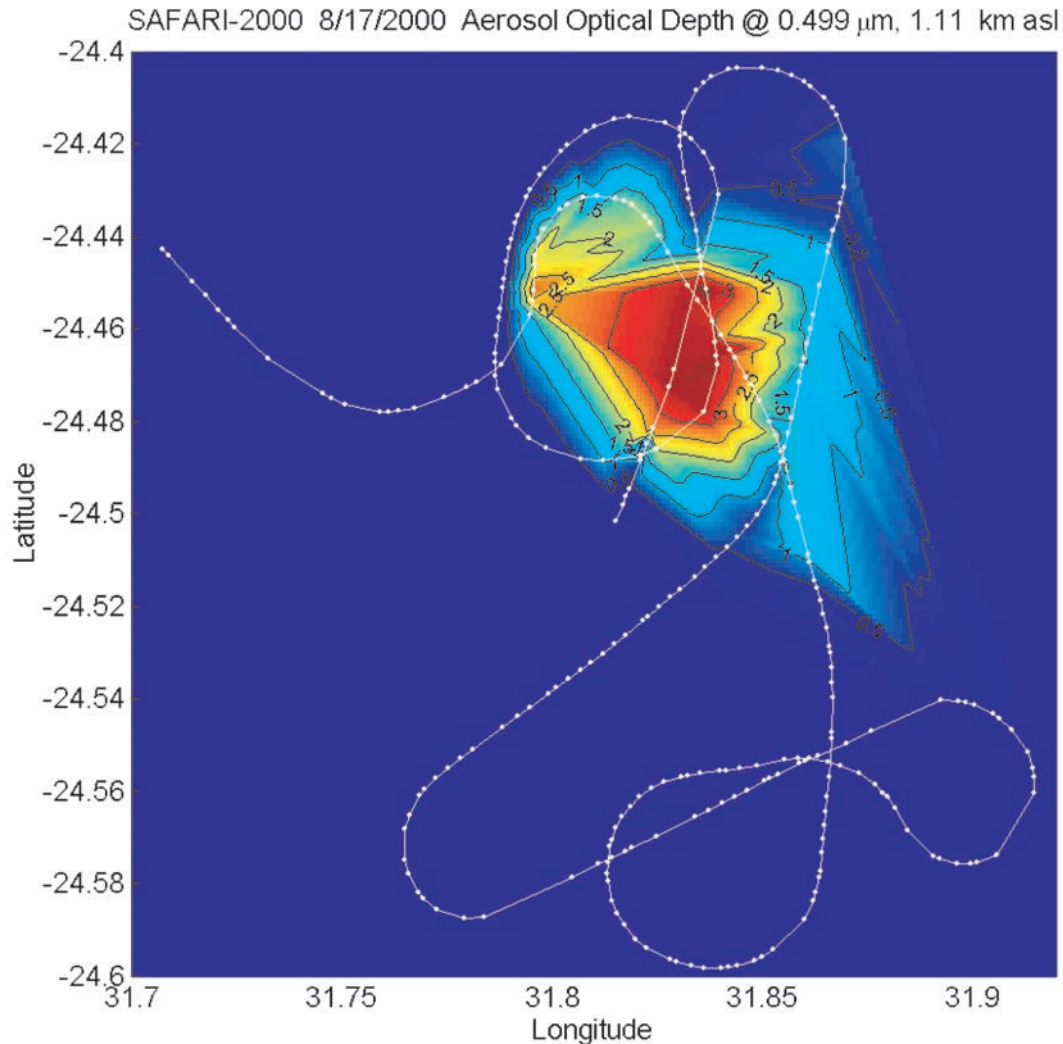


**Figure 4.** Time traces of  $\tau_a(\lambda)$  and spectral parameters obtained from four consecutive penetrations by the Convair-580 of a smoke plume originating from a flaming-hot grass fire on 17 August 2000 in the Kruger National Park North of Skukuza ( $24^{\circ}28'S/31^{\circ}50'E$ ). Data gaps are explained in the text. Time axis is UTC in decimal hours.

where the wavelength exponent  $\alpha$  is related to the aerosol size distribution see, e.g., Schmid *et al.* [1997]. Typically  $\sim 0 < \alpha < 1$  is found for larger particles and  $1 < \alpha \leq \sim 2$  for smaller particles. However, we often find (4) to be a poor representation of  $\tau_a(\lambda)$ , as did Eck *et al.* [1999]. Hence we prefer to use (3), which was also used by Eck *et al.* [1999], where  $\alpha^*$  is still related to aerosol size and  $\gamma$  describes the curvature of the spectrum (in log-log space) or deviations from (4). Of course, if  $\gamma = 0$  then (3) reduces to (4) and  $\alpha^* = \alpha$ . The time traces of the spectral parameters in Figure 4 indicate rather flat slightly curved spectra ( $\alpha^* \cong 0.5$ ,  $\gamma \cong -0.75$ ) outside the plume, suggesting the presence of larger particles there, whereas, inside the plume the spectra are very steep with almost no curvature ( $\alpha^* \cong 2$  to 2.5,  $\gamma \cong 0$ ) indicating the dominance of small particles.

[35] Figure 6a shows  $\tau_a(\lambda)$  measured inside the smoke plume (average of fourth penetration) and outside the smoke plume (from 11:21 to 11:24 UT, south of the plume). Also shown in Figure 6a is the difference between the two  $\tau_a(\lambda)$  spectra. The difference spectrum can be interpreted as the  $\tau_a(\lambda)$  spectrum of the smoke alone. The aerosol size

distributions can be estimated by inverting the  $\tau_a(\lambda)$  spectra using the constrained linear inversion method of King *et al.* [1978] [see also King, 1982; González Jorge and Ogren, 1996]. In its present formulation, the inversion assumes an aerosol consisting of homogeneous spherical particles that are nondispersive (i.e., refractive index  $m$  independent of wavelength or size) over the wavelength range of the observations. For the inversion, we used  $m = 1.51 - 0.021i$  determined from AERONET Sun/sky radiometers for African Savanna biomass burning aerosol [Dubovik *et al.*, 2002]. Figure 6b shows the area size distributions inverted from the  $\tau_a(\lambda)$  spectra in Figure 6a. Three inversion results are shown per case obtained by using three different initial estimates of the size distribution [King *et al.*, 1978; Schmid *et al.*, 1997]. The solid lines in Figure 6a are  $\tau_a(\lambda)$  spectra computed from the size distributions in Figure 6b. All size distributions exhibit a fine particle mode, but the fine mode is drastically enhanced in the in-plume and plume-only surface area distributions. The size distribution outside the plume appears bi-modal revealing also a coarse mode possibly caused by soil dust. This coarse mode may also



**Figure 5.** Map of  $\tau_a(0.499 \mu\text{m})$  of a smoke plume originating from a flaming-hot grass fire on 17 August 2000, in the Kruger National Park North of Skukuza ( $24^\circ 28' \text{S} / 31^\circ 50' \text{E}$ ). The  $\tau_a(\lambda)$  measurements are taken at each individual white dot along the white Convair-580 flight track. A triangle-based linear interpolation is used to fill in  $\tau_a$  values between the flight tracks. Size of the map is  $22.25 \times 22.25 \text{ km}^2$ .

be present in the smoke size distributions, but the inversion cannot retrieve it because its contribution to  $\tau_a(\lambda)$  is negligible.

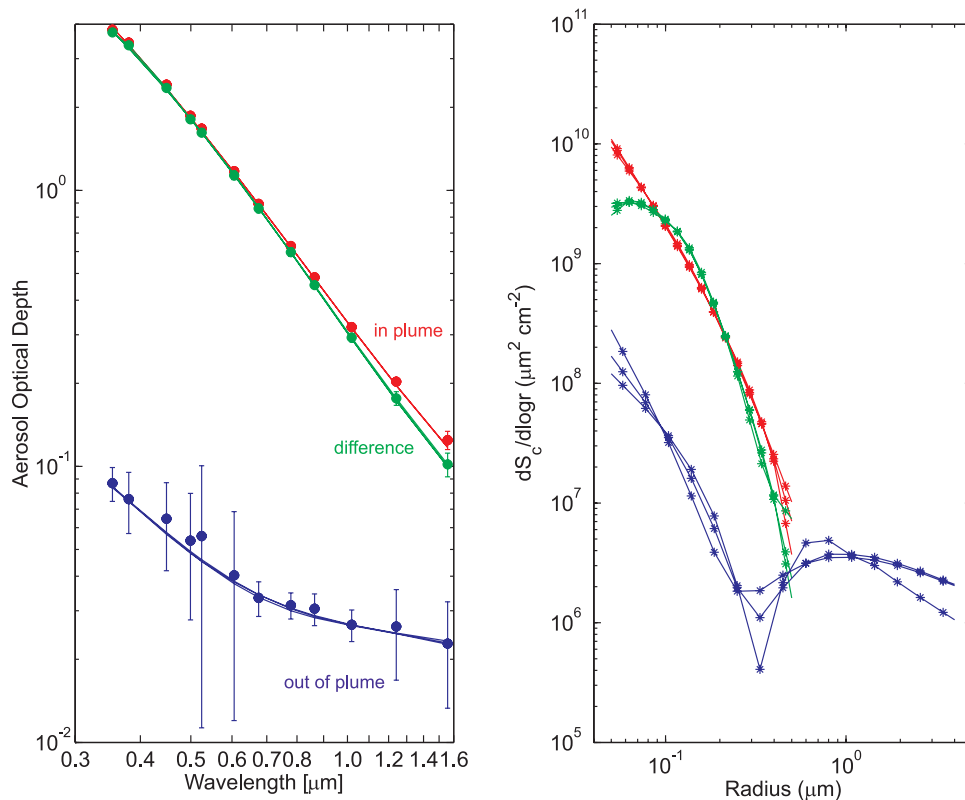
### 3.3. AATS-14 Vertical Profiles

[36] When the Convair-580 flew vertical profiles, AATS-14 could be used to measure vertical profiles of  $\tau_a(\lambda)$  and CWV. Differentiation of these profiles leads to spectral aerosol extinction  $E_a(\lambda)$  and water vapor density ( $\rho_w$ ) profiles [Schmid *et al.*, 2000]. In Figure 7, we show nine examples of AATS-14 vertical profiles obtained during SAFARI 2000. To facilitate comparisons we plotted all profiles on the same scale. Occasionally  $\tau_a(\lambda)$  or CWV decreased (increased) when the plane descended (ascended). In a horizontally homogeneous, time-invariant atmosphere, this would be impossible. However, in the real atmosphere it can occur because (1) the Sun photometer can only measure the transmittance of the Sun photometer-to-Sun

path, (2) that path in general passes through a horizontally inhomogeneous, time-varying atmosphere, and (3) the path and the atmosphere move with respect to each other as the aircraft moves and the wind blows. Before the Sun photometer  $\tau_a(\lambda)$  or the CWV profile is vertically differentiated to obtain  $E_a(\lambda)$  or  $\rho_w$ , it has to be smoothed (in a nonbiased manner) to eliminate increases in  $\tau_a(\lambda)$  or CWV with height. In this study, smoothed spline fits (dashed lines in Figure 7) were used for this purpose. However, to avoid over-smoothing at altitudes that exhibit actual variations of  $\tau_a(\lambda)$  we occasionally allow  $E_a(\lambda)$  or  $\rho_w$  to become slightly negative.

[37] The profiles for Skukuza (22 August), Inhaca Island (24 August), Beria (31 August) and Maun (2 September) show aerosol layers with  $E_a(0.5 \mu\text{m})$  around  $0.15 \text{ km}^{-1}$ , with most or all of the aerosol below the highest flight altitude. The profiles for Sua Pan (Sep 3) and Mongu (Sep 6) show massive thick aerosol layers extending above the





**Figure 6.** (a)  $\tau_a(\lambda)$  spectra measured in and outside of a smoke plume originating from a flaming-hot grass fire on 17 August 2000, in the Kruger National Park North of Skukuza ( $24^{\circ}28'S/31^{\circ}50'E$ ). Also shown is the  $\tau_a(\lambda)$  difference spectrum. b) Area size distributions inverted from the  $\tau_a(\lambda)$  spectra in a). Three inversion results are shown per case obtained by using three different initial estimates of the size distribution. Solid lines in a) are  $\tau_a(\lambda)$  spectra computed from the size distributions in b).

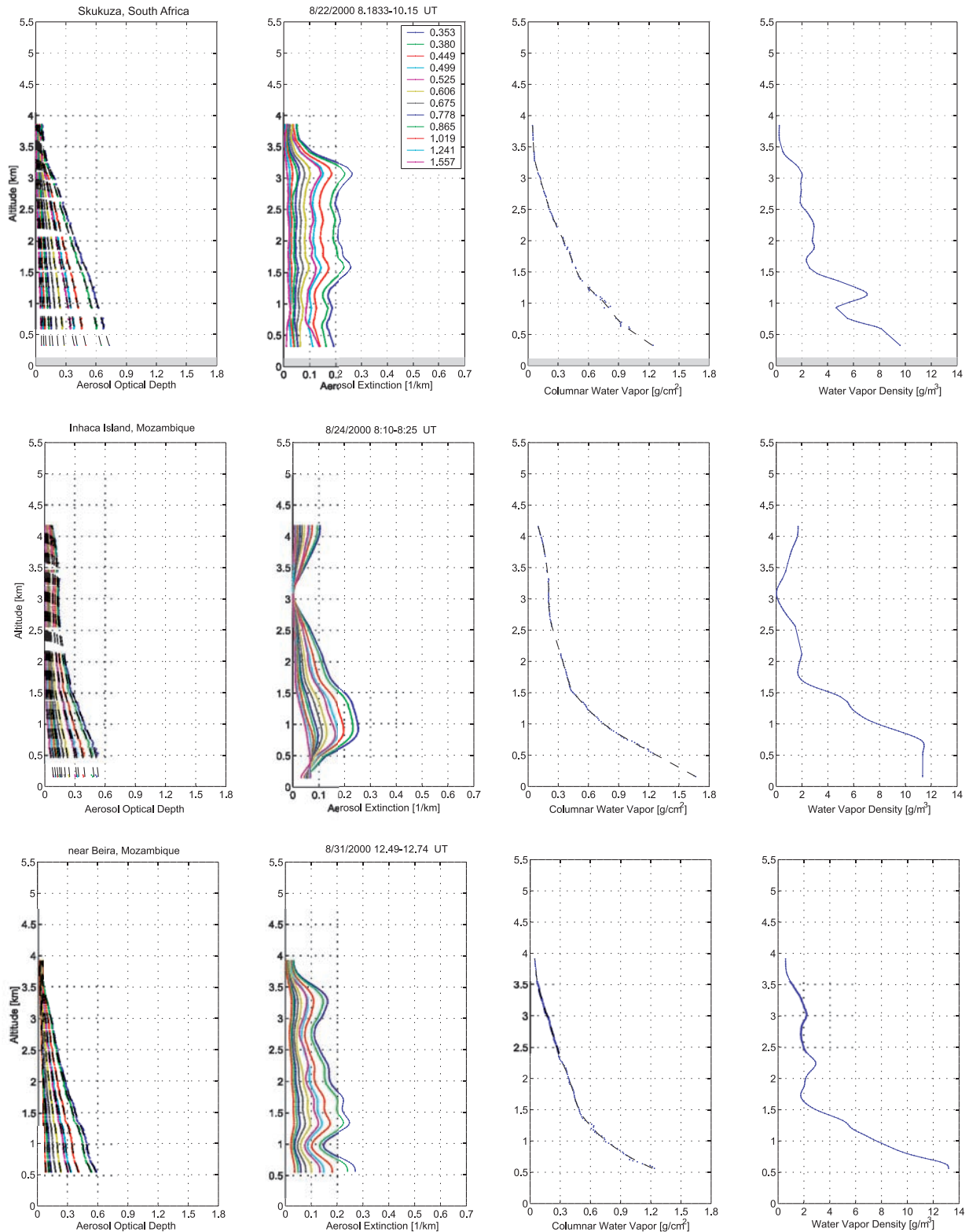
maximum flight altitude, with  $E_a$  ( $0.5 \mu\text{m}$ ) as large as  $0.35 \text{ km}^{-1}$ . In contrast, the profile over Phalaborwa (Sep 7) shows a very clean situation with virtually the entire aerosol confined to altitudes below 3.5 km. The profiles off the Namibian Coast (Sep 13) and over Etosha National Park (Sep 16) show elevated aerosol layers extending above the maximum flight altitude. Layers of remarkably low extinction between heavily polluted air were a common feature during SAFARI 2000. Examples can be seen on 24 August and on 7 and 13 September. *Hobbs* [2002, 2003] studies these layers, which he refers to as “clean air slots,” using Convair-580 in situ aerosol measurements. Figure 7 shows that the clean air slots coincide with local minima of  $\rho_w$ . The CWV and  $\rho_w$  profiles reach high values only if the profiles extend to low altitudes above sea level. In the cases where the aerosol extends above the maximum flight altitude the same behavior is observed for the water vapor. We also applied (3) to each of the  $\tau_a(\lambda)$  and  $E_a(\lambda)$  spectra shown in Figure 7. The spectral parameters  $\alpha^*$  and  $\gamma$  obtained from  $\tau_a(\lambda)$  are indicative of the particle size distribution of the atmospheric column above the aircraft, whereas,  $\alpha^*$  and  $\gamma$  obtained from  $E_a(\lambda)$  describe the local size distribution. For virtually all of the profiles we found  $\alpha^* \cong 2$  and  $\gamma \cong 0$  (obtained from  $E_a(\lambda)$ ) indicative of small biomass burning aerosol. Exceptions are Skukuza (22 August) with  $\alpha^* \cong 1.5$  (larger particles mixed in), Phalaborwa with  $\alpha^* \cong 1$  (clean, no biomass burning aerosols) and Inhaca Island where  $\alpha^*$

decreased toward 0 at lower altitudes (effect of larger sea salt particles).

### 3.4. AATS-14 Aerosol Vertical Profiles Compared With Lidar Measurements (MPL and CPL)

[38] The accuracies of the vertical profiles of  $\tau_a(\lambda)$  and CWV measured with AATS-14 depend on the measurement errors discussed earlier, but the accuracies are also limited by the horizontal inhomogeneity and time variance of the atmosphere. While all time-independent measurement errors in  $\tau_a(\lambda)$  or CWV cancel out when the profiles are differentiated, horizontal inhomogeneity and time variance of the atmosphere have significant impact on the  $E_a(\lambda)$  and  $\rho_w$  profiles. The advantage of an airborne Sun photometer is that the measured  $\tau_a(\lambda)$  and  $E_a(\lambda)$  represent the ambient aerosol unperturbed by sampling effects, yet they can be matched in space and time to in situ measurements made on the same aircraft. In a companion paper, *Magi et al.* [2003] compare AATS-14 layer  $\tau_a(\lambda)$  and  $\tau_a(\lambda)$  profiles with Convair-580 in situ aerosol measurements. Here we compare the  $\tau_a(\lambda)$  and  $E_a(\lambda)$  profiles obtained from AATS-14 with the ground based MPL at Skukuza and with the CPL instrument aboard the ER-2.

[39] Good flight plan coordination between the ER-2 and Convair-580 (i.e., the Convair-580 flying a vertical profile with the ER-2 passing over the same area) led to five aerosol vertical profile comparisons between CPL on the



**Figure 7.** Vertical profiles of  $\tau_a(\lambda)$ , aerosol extinction, columnar water vapor, and water vapor density, for nine different locations and dates. All locations can be found on the map in Figure 1. The shaded areas depict the altitude above sea level of the underlying terrain. The wavelengths are indicated in units of  $\mu\text{m}$ .

ER-2 and AATS-14. One of the comparisons was carried out over the Skukuza MPL site and another one over the Mongu MPL site. Due to an operator error, the Mongu MPL data was not stored on the day of the comparison.

[40] Figure 8 shows the comparison over Skukuza on 22 August. The AATS-14  $\tau_a(\lambda)$  are identical to those shown in Figure 7, but only the wavelengths most closely matching the lidar wavelengths are shown. The CPL and MPL inversions

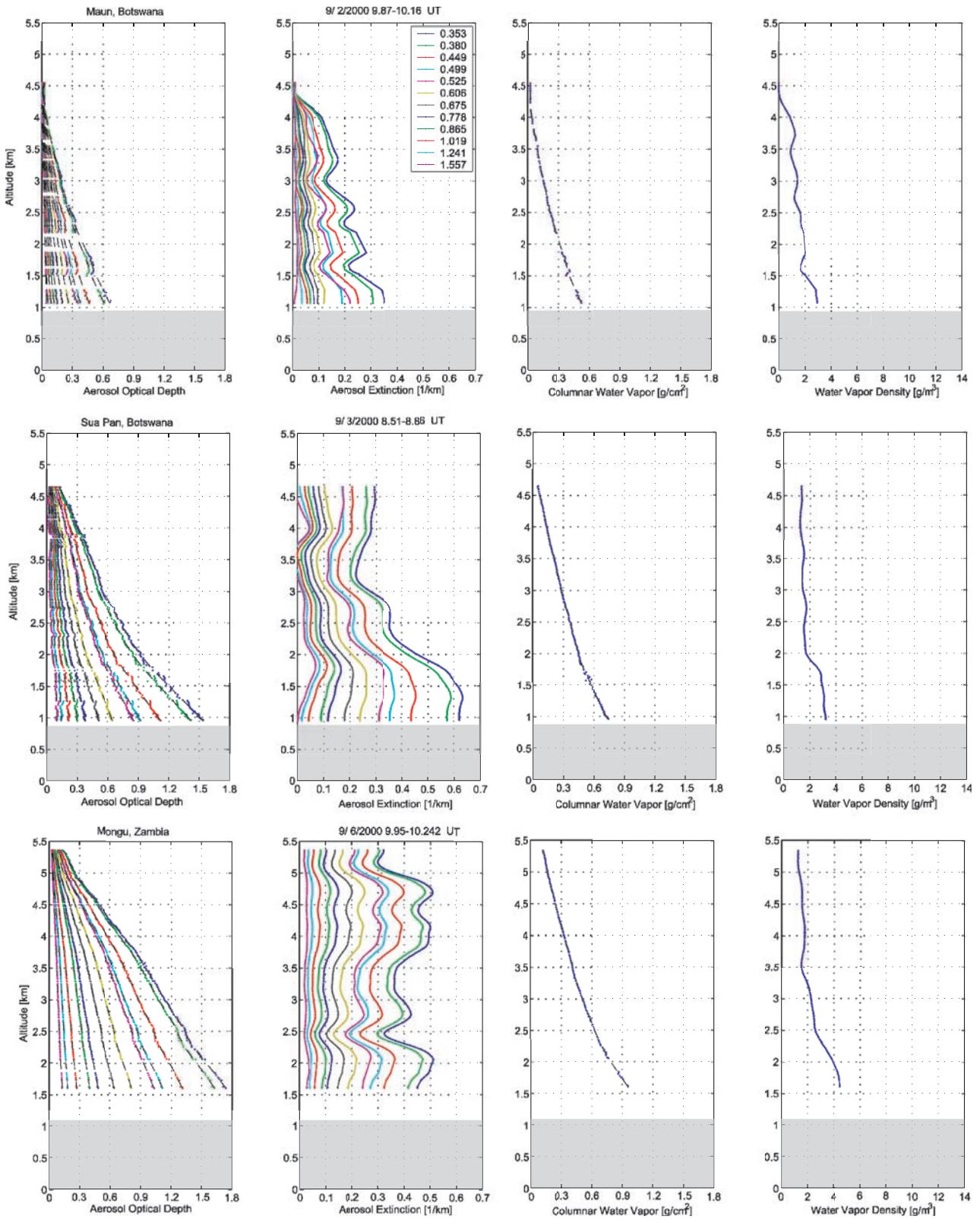


Figure 7. (continued)

used an altitude-independent extinction-to-backscatter ratio,  $S_a$ , constrained so that the height integral of each lidar extinction profile matches the corresponding  $\tau_a(\lambda)$  observed simultaneously by the Skukuza AERONET Sun/sky radio-

meter. As shown in Figure 3c, the  $\tau_a(\lambda)$  spectrum measured by AATS-14 at the lowest Convair-580 flight altitude agrees well with AERONET. Therefore, as expected the  $\tau_a(\lambda)$  profiles agrees well near the ground. However, the agree-

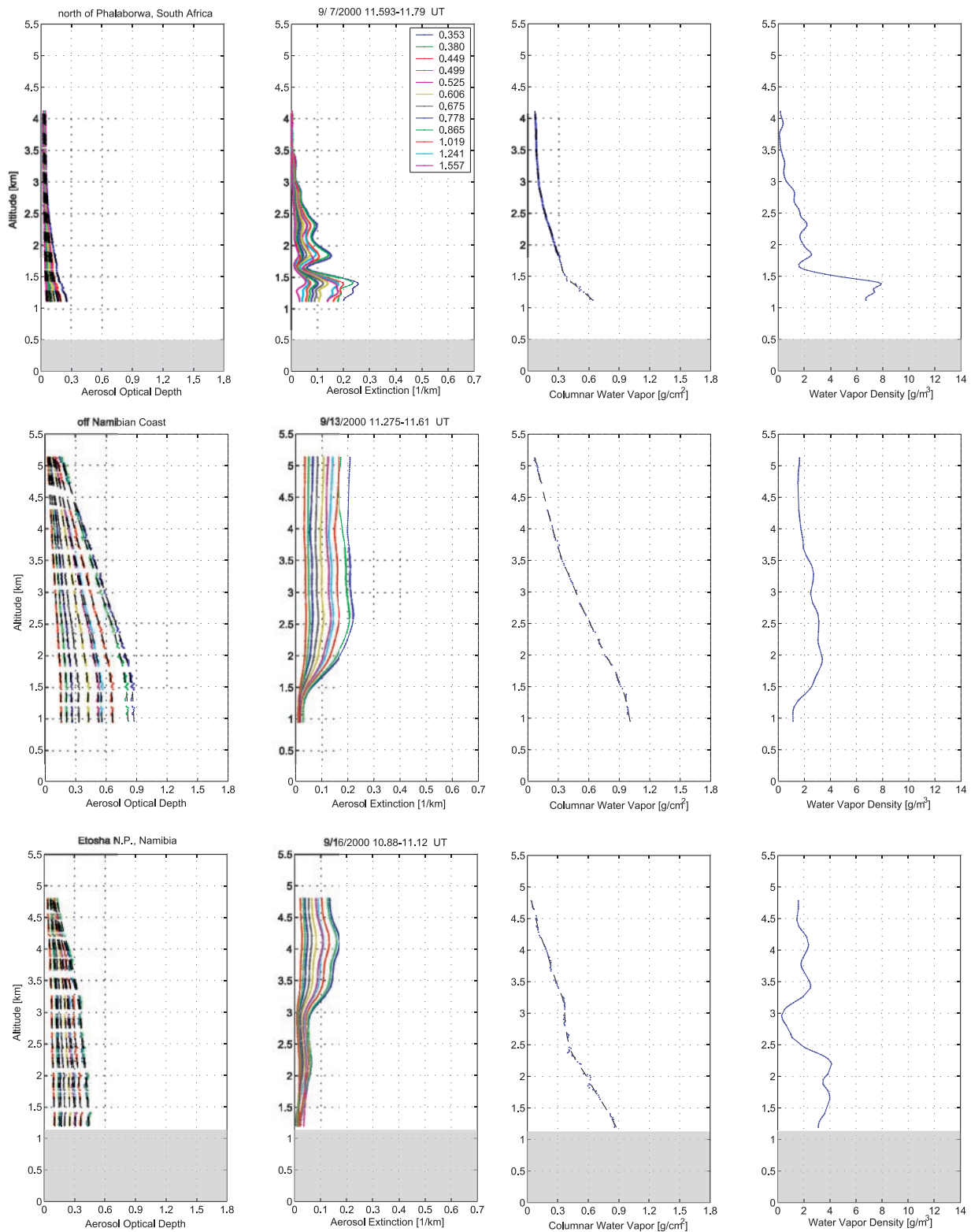
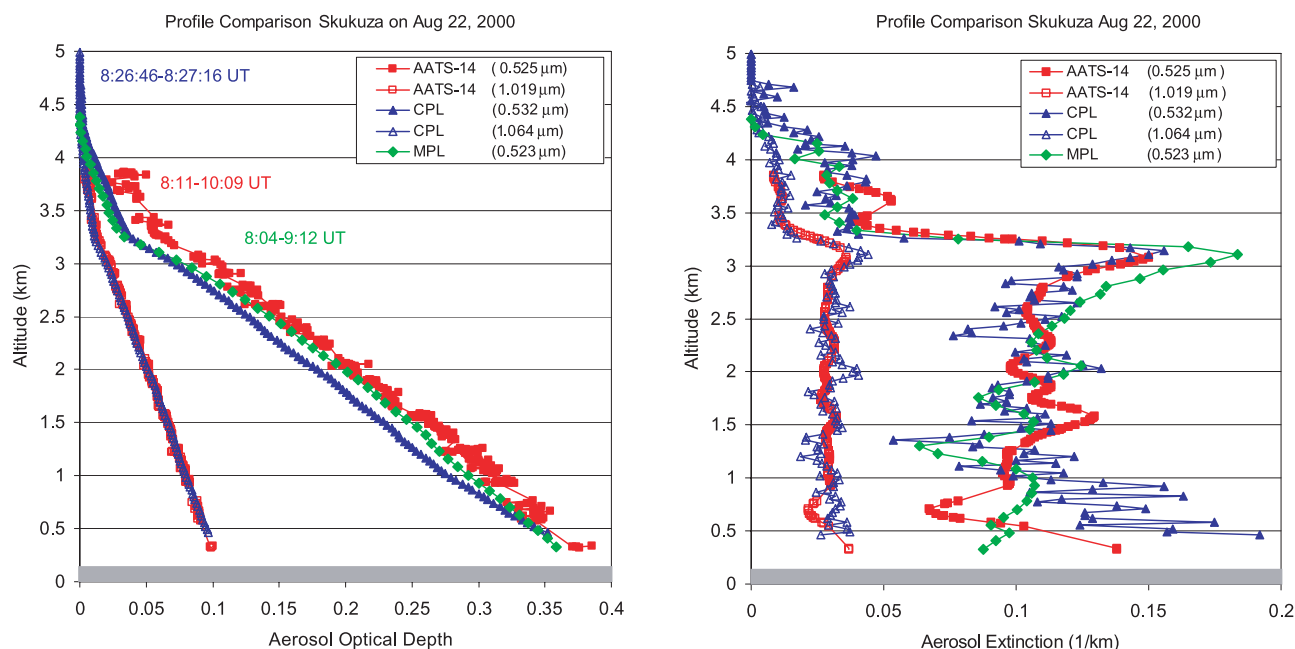


Figure 7. (continued)

ment among all three instruments is remarkable throughout the entire profile ( $\tau_a(\lambda)$  and  $E_a(\lambda)$ ). Adjusting the CPL results from 0.532  $\mu\text{m}$  to 0.525  $\mu\text{m}$  would further increase the agreement. All instruments show strong capping near 3.2 km, and the lidars indicate a second aerosol layer topping out at 4.5 km (above the Convair-580 profile top).

The resulting  $S_a$  values are 66 sr for the MPL (0.523  $\mu\text{m}$ ) and 60.5 sr and 36 sr for the CPL at 0.532  $\mu\text{m}$  and 1.064  $\mu\text{m}$ , respectively.

[41] Figure 9 shows the comparison over Inhaca Island on 24 August. The AATS-14  $\tau_a(\lambda)$  profile at all wavelengths is shown in Figure 7, but for the comparison in Figure 9 we



**Figure 8.** Comparison of aerosol vertical profiles from AATS-14 on the Convair-580 aircraft, CPL on the ER-2 aircraft, and ground-based MPL over Skukuza, South Africa, 22 August 2000. The shaded area depicts the altitude above sea level of the underlying terrain.

interpolated the AATS-14  $\tau_a(\lambda)$  and  $E_a(\lambda)$  to the CPL wavelengths using equation (3). The inversion of the CPL data was constrained so that the integrated extinction profiles return the  $\tau_a(\lambda)$  observed simultaneously by the Inhaca AERONET Sun/sky radiometer. This resulted in  $S_a$  values of 46.7 sr and 27.9 sr at 0.532  $\mu\text{m}$  and 1.064  $\mu\text{m}$ , respectively. As shown in Figure 3d, the  $\tau_a(\lambda)$  measured by AATS-14 at the lowest Convair-580 flight altitude agree well with AERONET in the UV and visible but not in the near-IR. Consequently, the CPL and AATS-14  $\tau_a(\lambda)$  profiles near the ground agree well at 0.532  $\mu\text{m}$  but not at 1.064  $\mu\text{m}$ . However, the 0.532  $\mu\text{m}$  AATS-14  $\tau_a$  is offset from the CPL  $\tau_a$  for most of the profile. The  $E_a(\lambda)$  profiles match closely above 1 km, but below that altitude, the AATS-14  $E_a(\lambda)$  profile exhibits an unrealistic behavior. Both instruments nicely show the clean air slot near 3 km. The CPL shows a third weak aerosol layer centered at 7 km (above the Convair-580 profile top).

[42] Figure 10 shows the comparison over Senanga on 6 September. The inversion of the CPL data was constrained to match the  $\tau_a(\lambda)$  observed simultaneously at the Senanga AERONET site ( $S_a = 72.2$  sr and 32.2 sr). As shown in Figure 3g, the  $\tau_a(\lambda)$  measured by AATS-14 are slightly less than the AERONET results, which we attribute to the fact that the lowest Convair-580 flight altitude was 150 m above ground level. The CPL and AATS-14  $\tau_a(\lambda)$  and  $E_a(\lambda)$  agree well in general but with larger differences at the 0.532  $\mu\text{m}$  wavelength near the ground. The CPL shows the massive, thick aerosol layer topping out near 5.8 km a.s.l.

[43] The shaded area depicts the altitude above sea level of the underlying terrain.

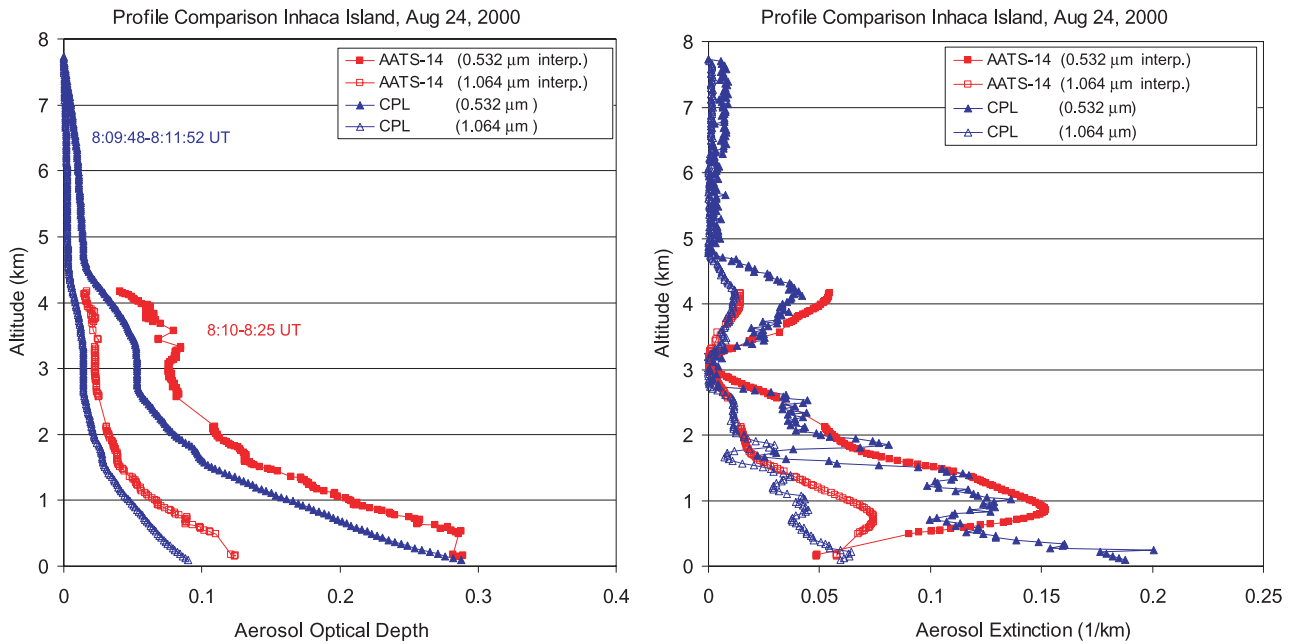
[44] Figure 11 shows the comparison over Mongu also on 6 September. The inversion of the CPL data was constrained to match the  $\tau_a(\lambda)$  observed simultaneously at the Mongu AERONET site ( $S_a = 70.5$  sr and 33.7 sr). As shown in

Figure 3h, the  $\tau_a(\lambda)$  measured by AATS-14 agrees well with the Sun/sky radiometer when flying 30 m above ground near the AERONET site, but are slightly lower when flying 120 m above the AERONET instrument (Figure 3i). The CPL and AATS-14  $\tau_a(\lambda)$  and  $E_a(\lambda)$  profiles agree reasonably well at all altitudes. The CPL shows the massive, thick aerosol layer extending to 6 km a.s.l.

[45] Figure 12 shows the comparison over water off the Namibian Coast on 11 September. Since there was not an AERONET site the inversion of the CPL data was constrained to match the AATS-14  $\tau_a(\lambda)$  observed at the lowest Convair-580 flight altitude ( $S_a = 79.9$  sr and 38.8 sr). The CPL and AATS-14  $\tau_a(\lambda)$  and  $E_a(\lambda)$  profiles agree very well at almost all altitudes. CPL shows the aerosol layer extending downward from 6 km altitude with a strong maximum near 5.3 km, and a nearly continuous decrease in extinction until  $\sim 600$  m where the lidar beam hits a low cloud with no returns from below the cloud. The AATS-14 measurements obtained after completion of the vertical profile confirm the existence of the cloud. The spectral parameters  $\alpha^*$  and  $\gamma$  indicate the dominance of small particles throughout the profile especially above 2.5 km. This suggests that the elevated aerosol layer consists of biomass burning aerosol advected off the continent, whereas, most of the marine boundary layer aerosol is masked by the presence of the low cloud.

### 3.5. TOMS $\tau_a$ Comparison

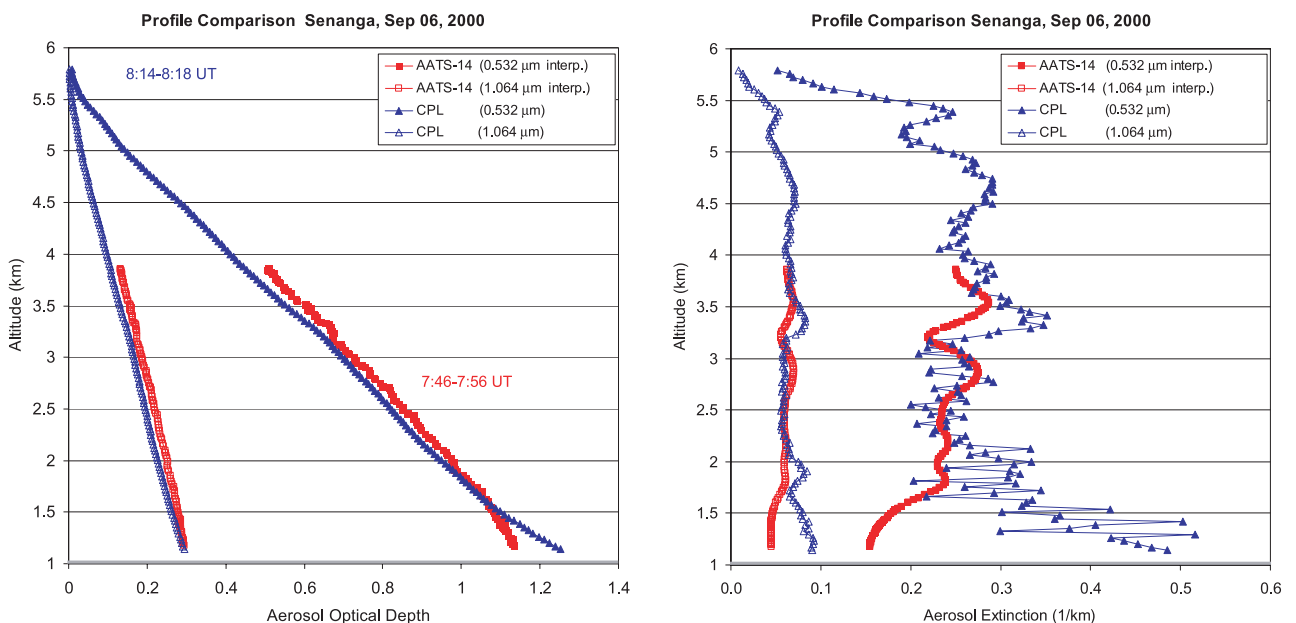
[46] During SAFARI 2000, several Convair-580 flights were coordinated with overpasses of the Earth Probe satellite. This resulted in three successful match-ups where the TOMS aerosol retrievals can be compared with AATS-14 column and profile measurements. Figure 13 shows the TOMS retrieved  $\tau_a$  at 0.38  $\mu\text{m}$  compared to  $\tau_a(\lambda)$  obtained from AATS-14 during low-altitude passes performed within or near a TOMS pixel.



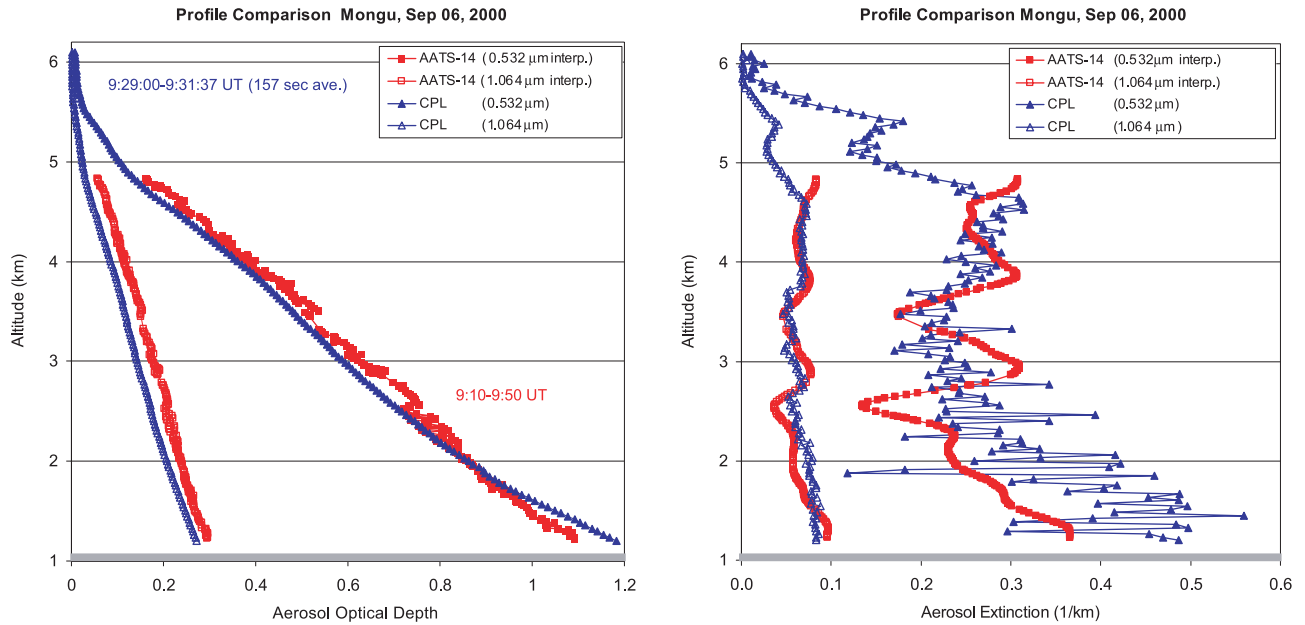
**Figure 9.** Comparison of aerosol vertical profiles from AATS-14 on the Convair-580 aircraft, CPL on the ER-2 aircraft over Inhaca Island, Mozambique, 24 August 2000.

[47] On Sep 2, 2000 the Convair-580 flew a downward spiral, followed by a low-altitude horizontal leg over the instrumented tower at Maun, Botswana. This entire flight segment lasting from 9:53 until 10:12 UT was located within one  $40 \times 40 \text{ km}^2$  TOMS pixel acquired at 9:48 UT. Figure 13a shows the  $\tau_a(\lambda)$  comparison obtained during the low-altitude leg. The agreement is within the TOMS predicted error bar for absorbing aerosols. The AATS-14 vertical profile obtained during the downward spiral is shown in Figure 7. The extinction at  $0.5 \mu\text{m}$  wavelength

increases gradually from  $0 \text{ km}^{-1}$  at 4.3 km to  $0.22 \text{ km}^{-1}$  near the surface. It should be noted that the TOMS retrieval algorithm for absorbing aerosols assumes that the UV-absorbing aerosols are concentrated in a single layer represented by a Gaussian distribution centered at 2.9 km above sea level. Throughout the entire AATS-14  $E_a(\lambda)$  profile we find  $\alpha^* \cong 2$  and  $\gamma \cong 0$  indicating the dominance of small particles (likely from biomass burning), which is consistent with the fact that TOMS retrieved an absorbing aerosol with  $\omega_0(0.38 \mu\text{m}) = 0.925$ .



**Figure 10.** Same as Figure 9 but for Senanga, Zambia, 6 September 2000. The shaded area depicts the altitude above sea level of the underlying terrain.

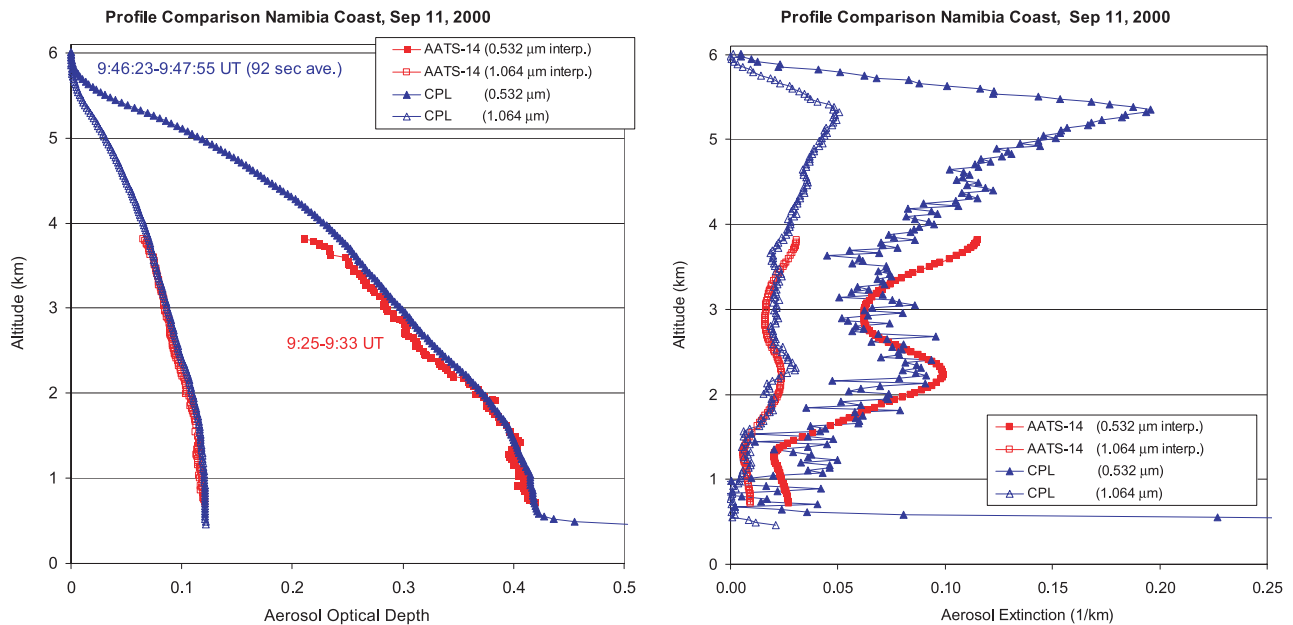


**Figure 11.** Same as Figure 9 but for Mongu, Zambia, 6 September 2000. The shaded area depicts the altitude above sea level of the underlying terrain.

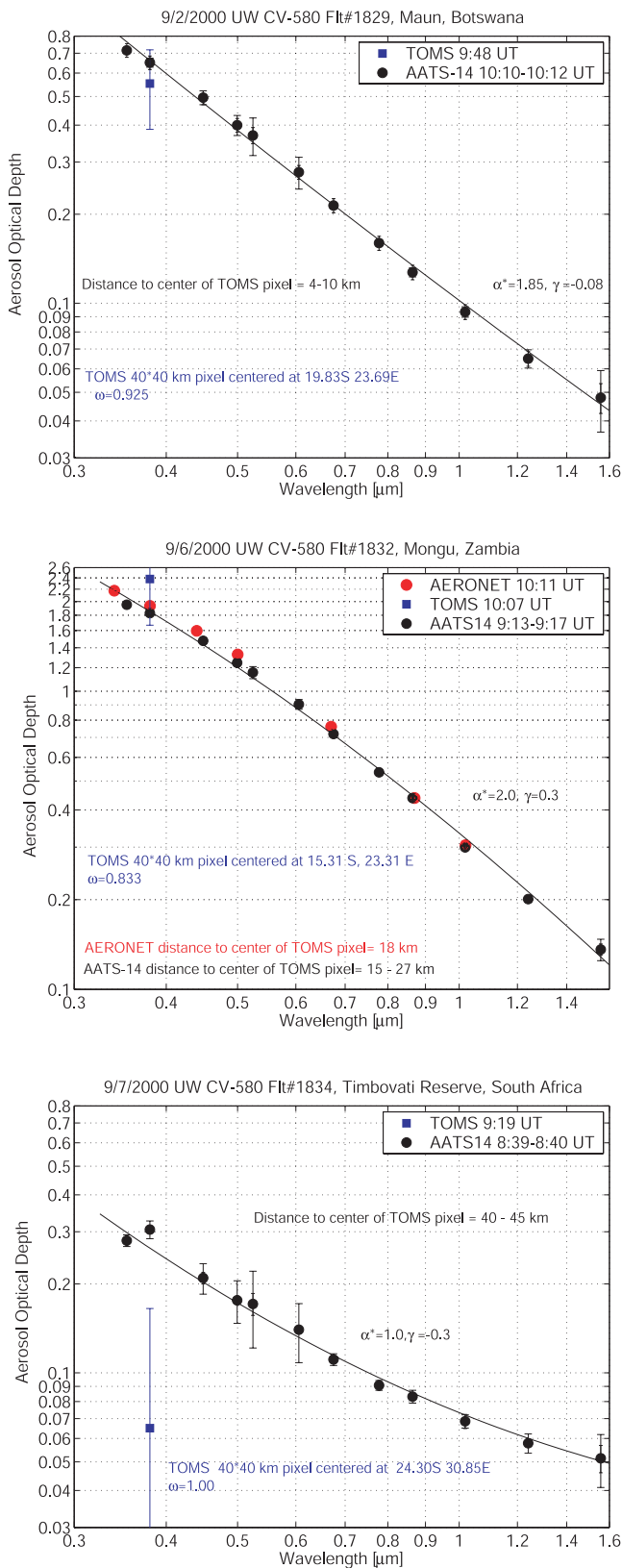
[48] On Sep 6, 2000 the Convair-580 flew several vertical profiles and low-altitude legs near Mongu Zambia. The AATS-14  $\tau_a(\lambda)$  obtained during a low-altitude leg and  $\tau_a(\lambda)$  obtained from the Maun AERONET site were located within the same TOMS pixel acquired at 10:07 UT. The  $\tau_a$  agreement (Figure 13b) is again within the TOMS predicted error bar for absorbing aerosols. Most of the AATS-14 vertical profile shown in Figure 7 is also contained in that same TOMS pixel. From the  $E_a(\lambda)$  profile we find  $\alpha^* \cong 2$  to  $2.4$   $\gamma \cong 0$  to  $0.6$  indicating an even stronger dominance by small particles. In accordance with that,

TOMS retrieved a strongly absorbing aerosol with  $\omega_0(0.38 \mu\text{m}) = 0.833$ . However, the actual aerosol vertical profile (see Figure 11) is markedly different from the idealized profile assumed in the TOMS retrieval.

[49] Figure 11 is markedly different from the idealized profile assumed in the TOMS retrieval. On Sep 7, 2000 the Convair-580 flew several low-altitude horizontal legs in and near a large prescribed fire in the Timbavati Game Reserve, South Africa. The prescribed fire was ignited around 8:20 UT. TOMS overpass time was one hour later. It is unlikely that the resulting smoke would fill an entire TOMS pixel



**Figure 12.** Same as Figure 9 but off Namibian Coast, 11 September 2000.



**Figure 13.** (opposite) Comparison of TOMS retrieved  $\tau_a$  at 0.38  $\mu\text{m}$  with AATS-14 during low-altitude passes of the Convair-580 within or near a TOMS pixel.

only one hour after ignition. Hence we decided to compare the cleanest AATS-14 low-altitude pass away from the fire with the closest TOMS pixel (Figure 13c). The AATS-14 total column  $\tau_a(\lambda)$  spectrum is relatively flat ( $\alpha^* = 1.0$ ) indicating few if any small (smoke) particles. This is consistent with the fact that TOMS retrieved a nonabsorbing aerosol ( $\omega_0(0.38 \mu\text{m}) = 1$ ). However, the TOMS retrieved  $\tau_a(0.065)$  was significantly smaller than the AATS-14 measurement ( $\sim 0.3$ ). The TOMS retrieval at another comparable close location (23.8S, 30.75S) was 0.057, consistent with the previous one. This suggests that either the AATS-14 spectrum was still influenced by smoke or that TOMS underestimates  $\tau_a(\lambda)$  in this situation.

### 3.6. MODIS $\tau_a(\lambda)$ Comparison

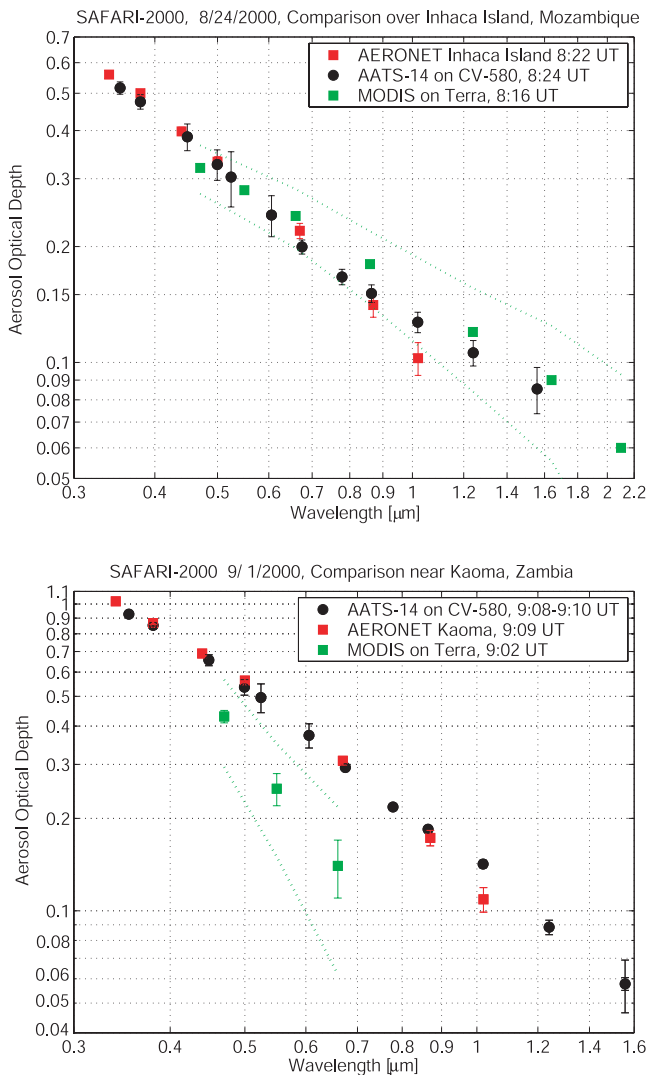
[50] During SAFARI 2000, numerous Convair-580 flights were coordinated with overpasses of the Terra satellite (Appendix A by P. V. Hobbs in the work of *Sinha et al.* [2003]). However, factors such as timing, surface brightness (MODIS requires dark surfaces such as water or vegetation), sunglint, and statistical validation criteria allowed for only two successful match-ups with AATS-14.

[51] Figure 14 (top) shows an over-water comparison near Inhaca Island off the coast of Mozambique west of the city Maputo. The timing was almost perfect with Terra passing over at 8:16 UT, a surface based AERONET Sun/sky radiometer measurement at 8:22 UT and the Convair-580 carrying AATS-14 reaching a flight altitude of 170 m a.s.l. at a distance of 7 km from the AERONET site at 8:24 UT. The MODIS  $\tau_a(\lambda)$ , representing a  $10 \times 10 \text{ km}^2$  area, agrees with AERONET and AATS-14 at all wavelengths within the retrieval error. To our knowledge, this is the first validation of MODIS  $\tau_a$  at the 1.24 and 1.64  $\mu\text{m}$  wavelengths. The vertical profiles from AATS-14 and CPL obtained in the same area are shown in Figure 7 and Figure 9 and are discussed in sections 3.3 and 3.4.

[52] An over-land comparison obtained near the Kaoma AERONET site in Zambia is shown in Figure 14 (bottom). Although separated by more than 30 km (see Table 1), the AERONET and AATS-14 results agree closely. The MODIS retrieved  $\tau_a(\lambda)$  is considerably less, and the disagreement is larger than the retrieval error. The MODIS  $\tau_a(\lambda)$  spectrum is also much steeper than the other two spectra.

[53] This result is consistent with recent findings that the MODIS-derived aerosol optical depths in Zambia are consistently lower than AERONET. In the MODIS  $\tau_a(\lambda)$  validation done by *Chu et al.* [2002] the southern African region was represented only by the permanent AERONET sites at Skukuza (in South Africa) and Mongu (in Zambia). Combining the results of these two sites in a plot of MODIS versus AERONET  $\tau_a(\lambda)$ , *Chu et al.* [2002] obtained a best fit line slope of 0.90 and 0.92 at 0.47 and 0.66  $\mu\text{m}$ , respectively. However, if the stations had been separated in the analysis the slopes would have been near 1 for Skukuza and 0.7 for Mongu (D. A. Chu, personal communication, 2002). Furthermore, [*Hao et al.*, 2003] find that  $\tau_a(\lambda)$  measured with 38 hand-held Sun photometers (and intercompared with AERONET) in western Zambia between 11 June and 6 October exceed MODIS retrieved  $\tau_a(\lambda)$  by more than 40%. Possible reasons for the difference





**Figure 14.** Comparison of MODIS retrieved  $\tau_a(\lambda)$  over water (top) and over land (bottom) with AERONET Sun/sky radiometers and with AATS-14 during low-altitude passes of the Convair-580 within or near a MODIS pixel. Dashed lines indicate the expected MODIS  $\tau_a(\lambda)$  retrieval error.

are currently under investigation. Using AERONET measurements, *Eck et al.* [2003] find that the aerosol properties measured in Zambia differ from those observed at Skukuza (South Africa).

### 3.7. MISR $\tau_a(\lambda)$ Comparison

[54] Since MISR is a new type of instrument, validation is especially important for the first algorithms used to interpret the data. The AATS team is engaged in a continuing effort with the MISR team to help in the validation effort. This section reports part of that work.

[55] Careful inspection of SAFARI 2000 AATS-14 total column  $\tau_a(\lambda)$  data and MISR  $\tau_a(\lambda)$  retrievals led to successful match-ups at three sites and dates. None of these match-ups coincides with the match-ups between MODIS and AATS-14 discussed above, although both

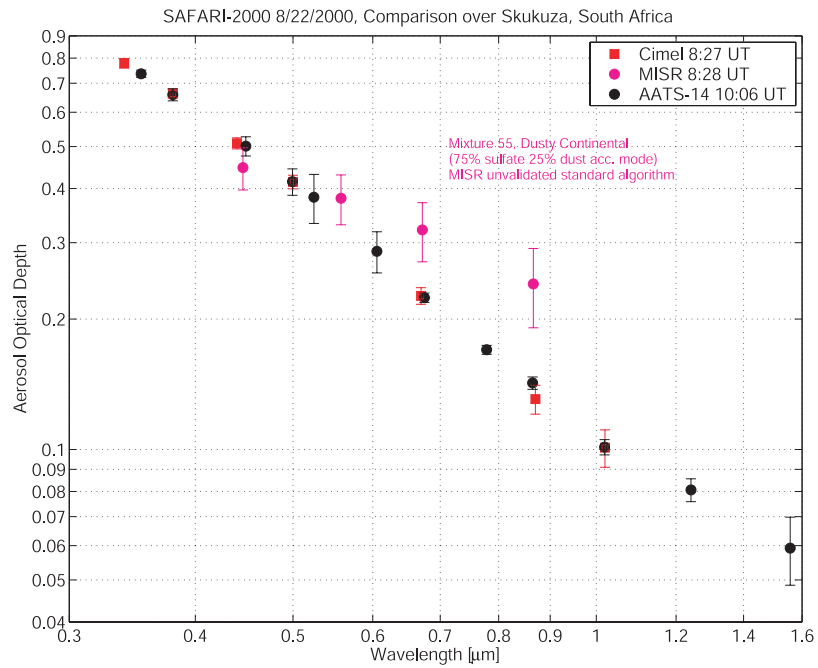
instruments fly aboard the Terra satellite. (The two instruments do not always have overlapping coverage because MODIS has a much wider swath than MISR, whereas, most MISR cameras are glint-free in regions where the single-angle MODIS view is glint-contaminated.)

[56] It is important to stress that all MISR  $\tau_a(\lambda)$  retrievals shown in this paper come from the “beta” version of the standard retrieval, which is an early post launch, unvalidated version of the algorithm. This retrieval is based on a list of prescribed aerosol mixture models. Each mixture is tested in terms of how well it reproduces the MISR-measured path radiances [*Martonchik et al.*, 1998; *Kahn et al.*, 2001]. In their comparison of MISR aerosol retrievals with AERONET observations, *Diner et al.* [2001] reported Regional Mean Optical Depth (RMOD) at the MISR standard wavelength of 0.558  $\mu\text{m}$ . The RMOD is the average of the  $\tau_a$  resulting from all aerosol mixture models that pass a certain goodness-of-fit threshold. Here we present  $\tau_a(\lambda)$  at all four MISR wavelengths for the single best fitting or second best fitting mixture.

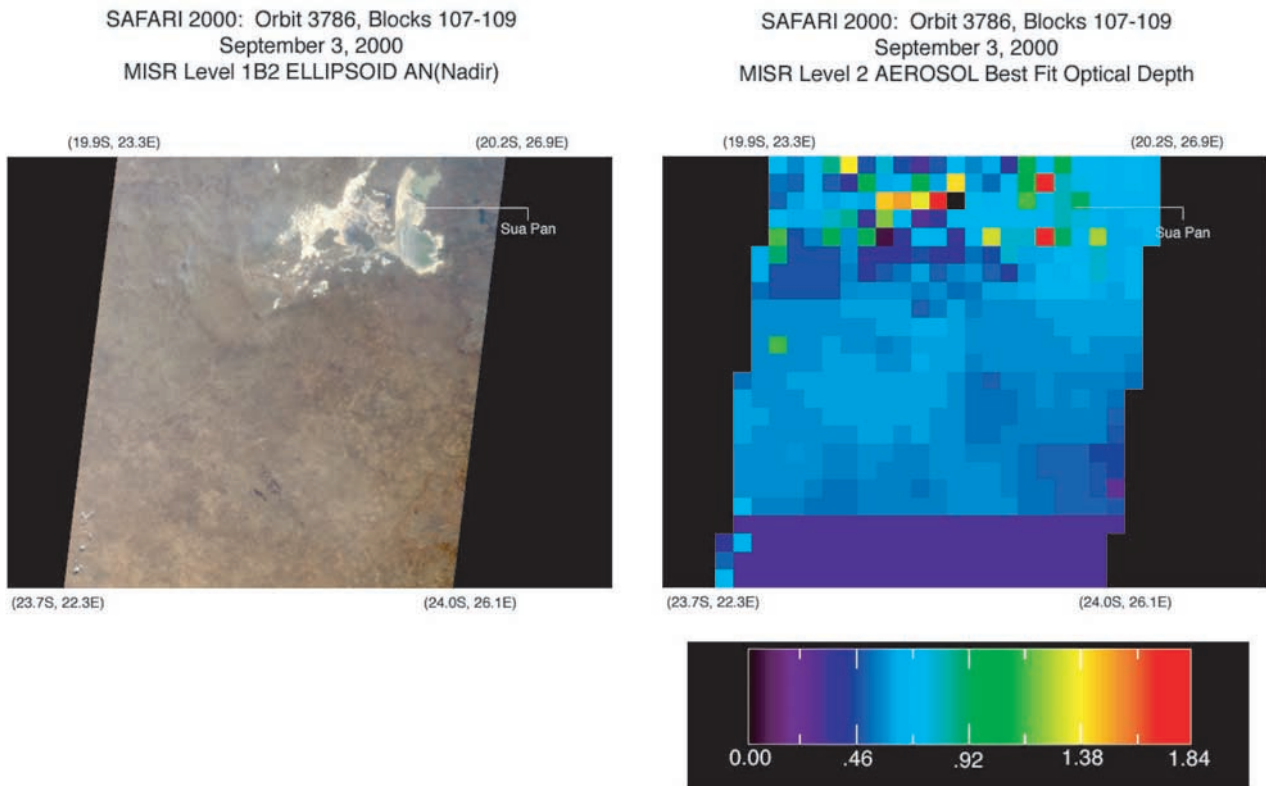
[57] Figure 15 shows the comparison of MISR retrieved best fit  $\tau_a(\lambda)$  with the Skukuza AERONET Sun/sky radiometer and with AATS-14 during a low-altitude horizontal pass of the Convair-580 within one  $17.6 \times 17.6 \text{ km}^2$  MISR region on 22 August 2000. The agreement is very good at the two shorter MISR wavelengths, but MISR  $\tau_a(\lambda)$  exceed AATS-14 and AERONET values at the two longer wavelengths. Given the limited range of particle mixtures in the “beta”-version algorithm’s climatology, the best fitting MISR  $\tau_a(\lambda)$  spectrum is too flat. This mixture is “Dusty Continental,” containing 75% sulfate and 25% dust accumulation mode aerosol. Indeed, the AATS-14  $E_a(\lambda)$  profile over Skukuza yields  $\alpha^* \cong 1.5$ , indicating the presence of larger particles; by contrast, most of the profiles in Figure 7 seem to be dominated heavily by small biomass burning aerosols. This spectral  $\tau_a(\lambda)$  comparison and others analyzed by the MISR team indicate that the “beta” version of the MISR algorithm does not contain enough small particles.

[58] Figure 16 shows MISR data acquired over northwestern Botswana on 3 September 2000 (Terra Orbit 3786). The left image is a red, green, blue (RGB) composite of radiometrically calibrated, geolocated data from the nadir camera. The right image shows best fit  $\tau_a$  at 0.558  $\mu\text{m}$ ; the pixellation shows individual  $17.6 \times 17.6 \text{ km}^2$  regions. Because the MISR aerosol retrievals are also used for atmospheric correction of surface parameters, the “beta” version of the algorithm fills in the aerosol field with neighboring successful retrievals for regions where the aerosol retrieval fails, and labels the product accordingly. For this study, we use only regions that are not in this category. The bright features in the northwestern quadrant of the RGB picture are the dry lakebeds of the Makgadikgadi Pans. During SAFARI 2000, Sua Pan (marked in Figure 16) was the location of extensive ground-truth measurements made by M. Helmlinger et al. for MISR and AirMISR [*Diner et al.*, 1998] validation. The suite of instruments used included an AERONET station (#59).

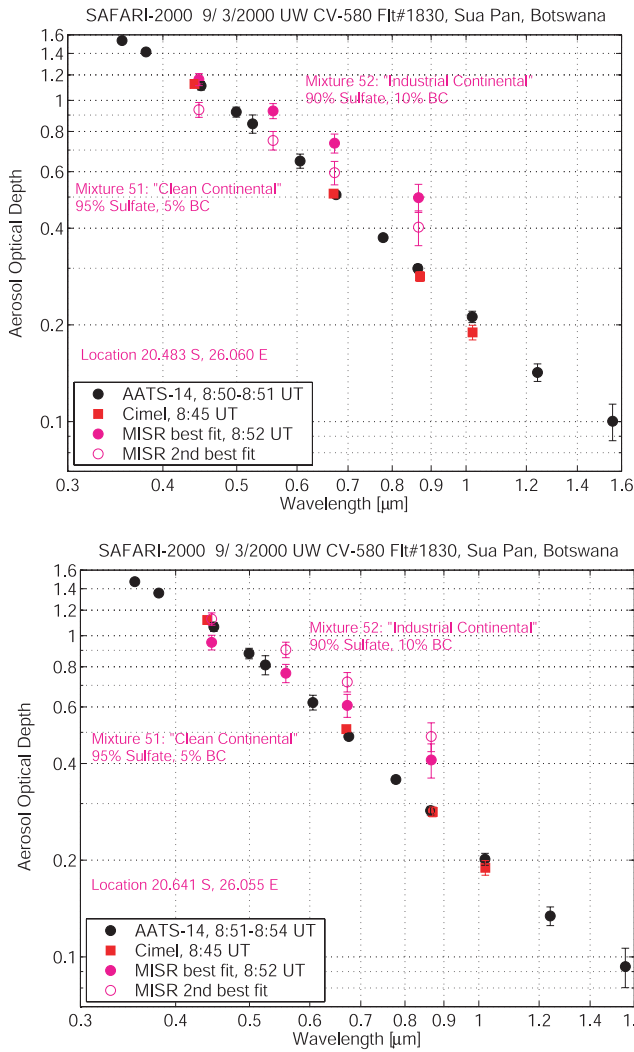
[59] Figure 17 shows the comparison of MISR retrieved  $\tau_a(\lambda)$  with the Sua Pan AERONET Sun/sky radiometer and with AATS-14 during a low-altitude pass of the Convair-



**Figure 15.** Comparison of MISR retrieved  $\tau_a(\lambda)$  with the Skukuza AERONET Sun/sky radiometer and with AATS-14 during a low-altitude pass of the Convair-580 within one  $17.6 \times 17.6 \text{ km}^2$  MISR region on 22 August 2000.



**Figure 16.** MISR data over northwestern Botswana acquired on 3 September 2000 (Terra Orbit 3786). Left image is a red, green, blue (RGB) composite of radiometrically calibrated, geolocated data from the nadir camera, right image shows best fit  $\tau_a(0.558 \text{ μm})$ ; the pixellation shows individual  $17.6 \times 17.6 \text{ km}^2$  regions.



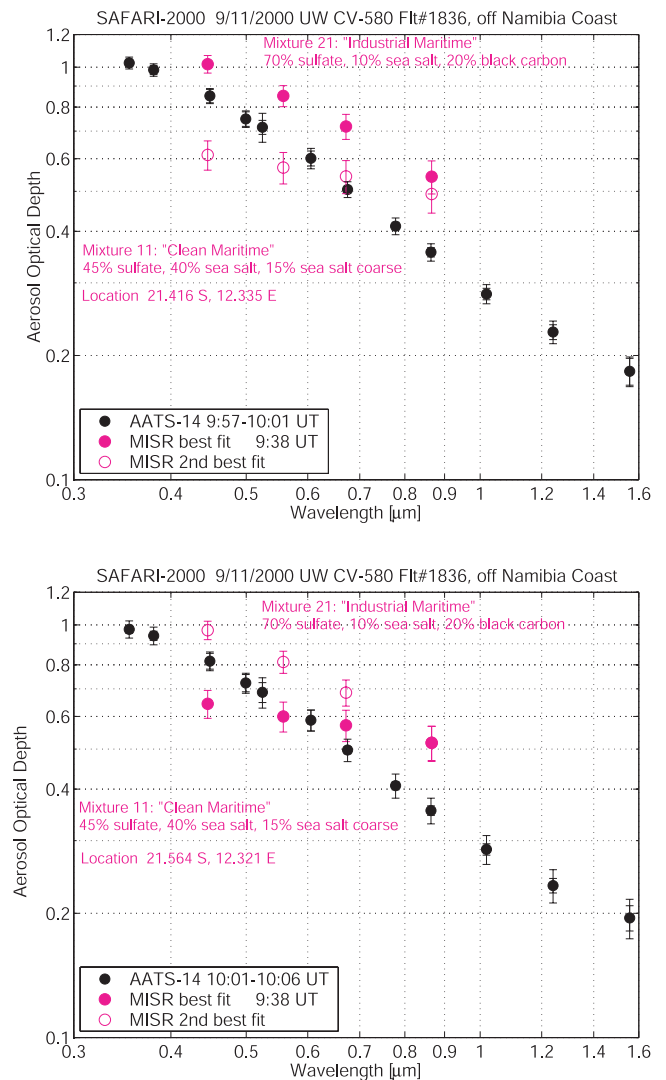
**Figure 17.** Comparison of MISR retrieved  $\tau_a(\lambda)$  with the Sua Pan AERONET Sun/sky radiometer and with AATS-14 during a low-altitude pass of the Convair-580 within two adjacent  $17.6 \times 17.6 \text{ km}^2$  MISR regions on 3 September 2000. The AERONET instrument was located in the  $17.6 \times 17.6 \text{ km}^2$  MISR region shown in the top plot, but the data are repeated in the bottom plot for reference purposes.

580 within two adjacent  $17.6 \times 17.6 \text{ km}^2$  MISR regions on 3 September 2000. The AERONET instrument was located in the  $17.6 \times 17.6 \text{ km}^2$  MISR region shown in the top plot, but the data are repeated in the bottom plot for reference purposes. The Convair-580 track actually crossed three adjacent MISR  $\tau_a(\lambda)$  pixels but only the first two have successful aerosol retrievals.

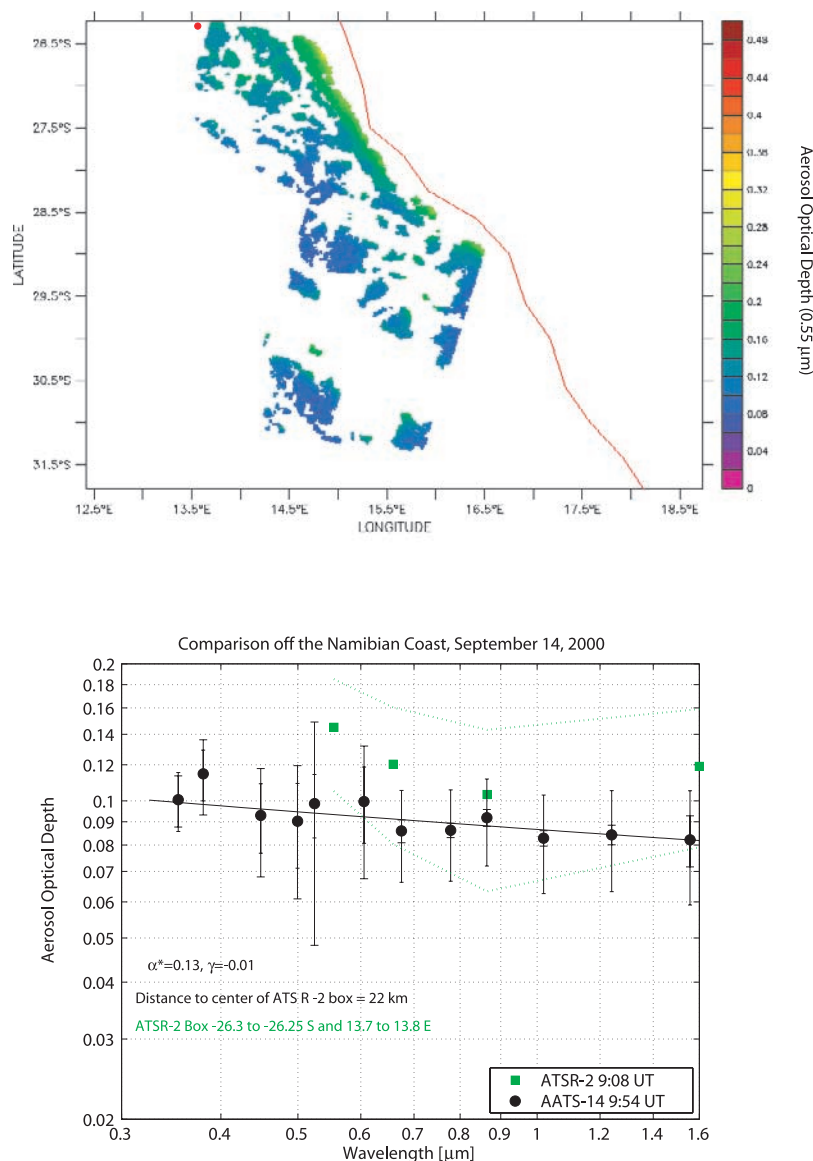
[60] From Figure 17 we see that for both pixels the “Clean Continental” mixture (95% sulfate and 5% black carbon) leads to good agreement at the  $0.558\text{-}\mu\text{m}$  standard wavelength. The “Industrial Continental” mixture (90% sulfate and 10% black carbon) leads to higher  $\tau_a(\lambda)$  values. Both spectra are too flat with respect to AERONET and AATS-14, but the Clean Continental is flatter. It is also evident from Figure 17 that  $\tau_a(\lambda)$  does not change significantly when AATS-14 is flown from one MISR  $17.6 \times 17.6$

$\text{km}^2$  region to the next one, because the agreement between AATS-14 and the stationary AERONET instrument remains. However, between the two regions the MISR algorithm switches best fit mixtures, which leads to a change in best fit  $\tau_a(\lambda)$ . The “beta” version of the MISR algorithm contains only one small-sized component particle: black carbon (characteristic radius 0.012 microns). The smallest spherical, nonabsorbing particle is sulfate, having a characteristic radius about seven times larger. Since smaller particles produce steeper slopes, the algorithm is forced to choose between small particles that are too dark, producing too high an optical depth, or lighter particles that are too large, giving too shallow a slope.

[61] Figure 18 shows the comparison of MISR retrieved  $\tau_a(\lambda)$  with AATS-14 during a low-altitude pass of the Convair-580 within two adjacent  $17.6 \times 17.6 \text{ km}^2$  MISR regions off the Namibian Coast on 11 September 2000. In both regions, the “Clean Maritime” mixture (45% sulfate,



**Figure 18.** Comparison of MISR retrieved  $\tau_a(\lambda)$  with AATS-14 during a low-altitude pass of the Convair-580 within two adjacent  $17.6 \times 17.6 \text{ km}^2$  MISR regions off the Namibian Coast on 11 September 2000.



**Figure 19.** (top) Map of  $\tau_a(0.555 \mu\text{m})$  from ATSR-2 off the Namibian Coast on 14 September 2000. Red line marks coastline. Red filled circle marks approximate position of Convair-580 carrying AATS-14, slightly outside ATSR-2 swath. White patches show areas identified as clouds. (bottom) Comparison of ATSR-2 retrieved  $\tau_a(\lambda)$  with AATS-14 during a low-altitude pass of the Convair-580 at the position marked in the upper figure. Wide AATS-14 error bars show measurement error, narrow error bars show  $\tau_a(\lambda)$  variability ( $2\sigma$ ). Green dotted lines indicate predicted uncertainty of ATSR-2 retrieved  $\tau_a(\lambda)$ .

40% sea salt and 15% sea salt coarse) leads to good agreement at  $0.558 \mu\text{m}$  and  $0.672 \mu\text{m}$ ; however, the MISR  $\tau_a(\lambda)$  spectrum is again too flat. The “Industrial Maritime” mixture (70% sulfate, 10% sea salt, 20% black carbon) leads to a spectral slope agreeing with AATS-14 but the MISR  $\tau_a(\lambda)$  values are then too high. As in the previous case, the MISR algorithm finds a different best fit mixture in the two adjacent regions, leading to a large change in best fit  $\tau_a(\lambda)$ , whereas, AATS-14 indicates very little change in  $\tau_a(\lambda)$ .

[62] At the time of writing, the MISR team is in the process of revising the aerosol retrieval algorithm, based on a variety of validation and calibration tests, including those presented here, along with AERONET studies and MISR-AirMISR intercomparisons. The new algorithm’s climatol-

ogy has a finer size grid of spherical, nonabsorbing aerosols, and includes smaller sizes.

### 3.8. ATSR-2 $\tau_a(\lambda)$ Comparison

[63] A map of  $\tau_a(0.555 \mu\text{m})$  from ATSR-2 aboard the ERS-2 satellite off the Namibian Coast on 14 September 2000 is shown in Figure 19. The red line marks the coastline. The white patches show areas identified as clouds. The ATSR-2 map shows fairly clean conditions in general but increasing  $\tau_a$  toward the coast.

[64] On this same day, the Convair-580 carrying AATS-14 flew a low-altitude horizontal leg just barely outside the ATSR-2 swath. The red filled circle in Figure 19 marks the approximate position of that leg. The distance to the closest pixels is less than 20 km, and the satellite overpass occurred

46 min before the aircraft leg. The comparison of ATSR-2 retrieved  $\tau_a(\lambda)$  with AATS-14 during the low-altitude leg is also shown in Figure 19. The wide AATS-14 error bars show measurement error, whereas, the narrow error bars show  $\tau_a(\lambda)$  variability ( $2\sigma$ ) in the low-altitude leg (3.4 km and 45 s long, at height 95 m). The green dotted lines indicate the predicted uncertainty of ATSR-2 retrieved  $\tau_a(\lambda)$  derived from comparison with various AERONET Sun photometers in Europe [Robles-Gonzalez *et al.*, 2003]. The agreement is within error bars. AATS-14 shows a remarkably flat spectrum ( $\alpha^* = 0.13$ ) with no curvature. This slope is consistent with the ATSR-2 results.

[65] The measurements were made over the ocean, and weather maps indicate along-shore flow; hence, the aerosol is expected to have a strong sea salt component. The observed offshore  $\tau_a$  gradient is likely due to the decreasing influence of offshore advection of continental aerosol. The slightly higher ATSR-2 values as compared to the AATS-14 may result from this gradient.

#### 4. Conclusions

[66] During the dry season campaign of the Southern African Regional Science Initiative (SAFARI 2000) (August–September 2000), coordinated observations were made of massive, thick aerosol layers. Aerosol optical depth from  $\lambda = 0.354$  to  $1.557 \mu\text{m}$  ( $\tau_a(\lambda)$ ), columnar water vapor (CWV), and vertical profiles of aerosol extinction, ( $E_a(\lambda)$ ), and water vapor density ( $\rho_w$ ) were obtained from the NASA Ames Airborne Tracking 14-channel Sun photometer (AATS-14) aboard the University of Washington's Convair-580 research aircraft.

[67] From 10 August to 9 September the Convair-580 was based in Pietersburg, South Africa, for the purpose of carrying out flights over South Africa, Botswana, Zambia and Mozambique. From 10 to 18 September, the Convair-580 was based in Walvis Bay, Namibia, for flights over Namibia and off the Namibian coast. In this paper we have discussed a subset of the AATS-14 results from 24 data flights, and we have shown all valid comparisons with independent ground-based, airborne and spaceborne measurements.

[68] The Convair-580 made eleven low-altitude flybys of seven AERONET sites, allowing comparison of  $\tau_a(\lambda)$  derived from the AATS-14 and the ground-based Sun/sky radiometers measurements. The RMS differences in  $\tau_a(\lambda)$  ranged from 0.023 to 0.075 (6 to 15%). We presented a detailed study of an individual smoke plume from a grass fire, for which  $\tau_a(\lambda)$  exceeded 6 in the ultraviolet. We have also presented and discussed vertical profiles of  $\tau_a(\lambda)$ , aerosol extinction, columnar water vapor, and water vapor density, for nine different locations and times. For virtually all of the profiles we found the spectral dependence of the aerosol optical depths indicated the dominance of small particles, presumably from biomass burning.

[69] Excellent coordination between the high-flying ER-2 and the Convair-580 aircraft, with the Convair-580 flying vertical profiles as the ER-2 passed overhead, led to five aerosol vertical profile comparisons between the downward pointing Cloud Physics Lidar CPL on the ER-2 and the AATS-14. One of the comparisons was carried out over a ground-based Micro Pulse Lidar (MPL) at Skukuza, South

Africa. At most altitudes  $E_a(\lambda)$  from AATS-14, CPL and MPL agree within  $0.02 \text{ km}^{-1}$  (at  $0.532 \mu\text{m}$ ) or  $0.01 \text{ km}^{-1}$  ( $1.06 \mu\text{m}$ ). In the lowest 1 km of the profiles there is tendency for the CPL retrieved  $E_a(\lambda)$  to be larger than those from AATS-14. Also, it is important to restate that the lidar extinction retrieval for the cases shown here relies on (and thus is forced to be consistent with) the AERONET (or AATS-14) measurement of total column  $\tau_a(\lambda)$ .

[70] Finally, we have shown comparisons between aerosol optical depths measured by the AATS-14 and AERONET retrieved over land and over water, and four spaceborne sensors (TOMS, MODIS, MISR and ATSR-2). For TOMS, two out of three of these comparisons were within the error bars of the measurements. A comparison between AATS-14 and MODIS over water led to excellent agreement, but in a case study over land in Zambia the MODIS algorithm significantly underestimated the aerosol optical depth. Three detailed comparisons of the measurements from the airborne AATS-14 and MISR led to the conclusion that to reproduce the spectral slope of the aerosol optical depth, as measured by AATS-14 and AERONET, the MISR algorithm needs a finer size grid of spherical, nonabsorbing aerosols, and it also needs to include smaller particles. One comparison between the AATS-14 and ATSR-2 over water showed agreement (within the error bars) at all wavelengths. The MODIS and ATSR-2 cases shown here represent the first published comparison of aerosol optical depths at 1.2 and  $1.6 \mu\text{m}$  wavelengths.

[71] **Acknowledgments.** Thanks are due to the dedicated efforts of the University of Washington's Convair-580 team, without whom the measurements described here would not have been obtained. We also express our thanks to the Pietersburg airport personnel, and to the local SAFARI 2000 organizers. We also would like to thank the Ozone Processing Team at NASA Goddard Space Flight Center for making available TOMS EP data. This research was conducted as part of the Southern African Regional Science Initiative (SAFARI 2000). Funding to NASA Ames was provided by NASA's Earth Observing System Inter-Disciplinary Science (EOS-IDS) Program, Radiation Sciences Program, and Total Ozone Mapping Spectrometer (TOMS) Program (Program Codes 291-01-91-45, 622-44-75-10, and 621-14-01-00, respectively). Funding to the University of Washington was provided by NASA (grants NAG5-9033, NAG5-7075) and NSF's Division of Atmospheric Science (grant ATM-9901624). Work of CRG and GdL is supported by the Netherlands Space Research Foundation (SRON), under contract EO-037. The ATSR-2 data were provided by the European Space Agency (ESA-ESRIN), contract AO03.280.

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