A multi-instrument approach for characterizing the atmospheric aerosol optical thickness during the STAAARTE/DAISEX-99 campaign

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Received 6 June 2001; revised 27 September 2001; accepted 13 November 2001; published 28 February 2002.

[1] This work deals with the retrieval of the aerosol optical thickness (AOT) needed to carry out the atmospheric correction of remote sensing data measured in Barra (Spain) on 4 June 1999 in the framework of 1999 Digital Airborne Imaging Spectrometer Experiment (DAISEX'99). The AOT was estimated through three approaches based on: spectral extinction of direct solar irradiance at ground level, airborne nephelometer measurements at different altitudes, and backscatter lidar in the lower troposphere. We found extremely low AOT values due to a cold Atlantic front that swept across the Iberian Peninsula from west to east producing light rain over the test area on 2 June 1999. The results were solar irradiance extinction: 0.085±0.018; nephelometer: 0.063±0.020; lidar: 0.083±0.030. Nephelometer- and lidar-derived values account for both extinction and absorption, assuming a single scattering albedo value of 0.90. Errors values include measurements and retrieval uncertainties as well as statistical variability. INDEX TERMS: 0305 Atmospheric Compositions and Structure: Aerosols and aircraft. POLDER were operating simultaneously on board the ARAT (STAAARTE) Program, also participated in DAISEX'99. Both Aircraft for Atmospheric Research Throughout Europe within the framework of the Scientific Training and Access to uncertainties as well as statistical variability.

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1. Introduction

[2] In the framework of the 1999 Digital Airborne Imaging Spectrometer Experiment (DAISEX'99), which took place during 3, 4 and 5 June 1999, two imaging spectrometers (DAIS-7915 and HyMap) operating on the aircraft DLR/Dornier Do228 were used as airborne demonstrators to simulate data to be acquired during the Land Surface Processes and Interactions Mission (LSPIM) of the European Space Agency (ESA) Earth Observation Preparatory Program [Berger et al., 2001].

[3] In addition to the DLR/Do228, a second airborne platform, the multi-agency (INSU/CNES/IGN/Météo-France) Avion de Recherche Atmosphérique et de Télédetection (ARAT), accessible within the framework of the Scientific Training and Access to Aircraft for Atmospheric Research Throughout Europe (STAAARTE) Program, also participated in DAISEX'99. Both the backscatter lidar LEANDRE and the imaging radiometer POLDER were operating simultaneously on board the ARAT aircraft.

[4] Simultaneously to aircraft measurements, a combination of radio soundings and ground solar spectral irradiance measurements were made to collect the atmospheric data necessary for performing atmospheric correction of the remote sensing data.

[5] The above measurements had a double objective: on one hand (general purpose) to study the radiative forcing of aerosols and their climatic impact; on the other hand (specific purpose) to retrieve the parameters needed to carry out the atmospheric correction of remote sensing data measured during the DAISEX'99 campaign. The results presented in this paper deal with the second objective. The aerosol optical thickness (AOT) estimated over Barrax on 4 June 1999, from independent measurements are compared. The analysis focuses in that day because both the imaging spectrometers were in use simultaneously. Three (direct and indirect) approaches are undertaken, based on a) spectral extinction of direct solar irradiance at ground level; b) nephelometer measurements made on board the ARAT at different altitudes, and c) zenith and nadir pointing lidar measuring atmospheric reflectivity in the lower troposphere.

2. Instrumentation and Measurements

[6] Flights were made at midday on 3 June 1999, in the morning and afternoon of 4 June 1999 and on the morning of 5 June 1999. On 1 and 2 June 1999 a cold Atlantic front swept across the Iberian Peninsula from west to east producing light rains over the test area on 2 June 1999. Two-day back trajectories computed with HYSPLIT4 (Hybrid Single-Particle Lagrangian Integrated Trajectory) Model (courtesy of NOAA Air Resource Laboratory, http://www.arl.noaa.gov/ready/hysplit4.html) ending at 0800 UTC in Barrax on 4 June 1999 indicated that the air masses arriving over the test site had traveled for at least 2 days over the Iberian Peninsula (Figure 1).

2.1. Ground Based Measurements

[7] For this experiment we used Vaisala RS80 soundings including ozone sensors. Two soundings reaching heights of over 32 km were carried out on June 4. Spectral solar irradiance measurements, direct and global, were obtained using two Licor 1800 spectroradiometers. The Licor 1800 is a spectroradiometer provided with a simple monochromator that allows to obtain measurements in the range 300–1100 nm with a FWHM (Full Width at Half Maximum) of 6 nm approximately and a wavelength step of 1 nm. For the direct irradiance measurements a radiance limiting tube (collimator) was used with a FOV (Field Of View) of 4.7°, and so the diffuse-light effects can be neglected [Cannon, 1986]. Several papers have studied the sensitivity of this spectroradiometer which varies with the spectral range considered [Cachorro et al., 1998]. In the visible range the measurement accuracy, governed mainly by the calibration uncertainty, is 3%. Spectral solar measurements were made every 15 minutes from 0600 to 1600 ST at the point located at 39.060 N and 2.103° W, and 700 m above sea level.

2.2. Aircraft Measurements

[8] The ARAT aircraft carried the backscatter Nd-YAg lidar LEANDRE-1 [Flamant and Pelon, 1996]. The plane was also

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0094-8276/02/2001GL013585$05.00

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shown in Figure 2. During those time periods as evidenced by nadir measurements the lower troposphere was observed not to change significantly between 0749 and 0820 UTC. Fortunately, the aerosol structure of between 0645 to 0711 UTC, while nadir profiles were acquired (see next section) could not be computed from nadir pointing measurements only, but rather had to be derived from composite lidar-derived optical depths between 350 and 1000 m AGL and (iii) an elevated aerosol layer between 0 and 350 m AGL overlaid by (ii) a residual layer troposphere to be composed of 3 layers: (i) a nocturnal boundary layer peak to peak variability is approximately 0.025 km regardless of the level considered, so that the error can reach 30% at the highest level while being less than 15% at the lowest level. The largest resulting quadratic error accounting for measurements uncertainties and statistical variability is 32%. [14] The total optical thickness derived from the profile shown in Figure 4 is equal to 0.09. The AOT obtained by subtracting the molecular optical thickness between 0 and 3 km is equal to 0.054±0.017 for the entire flight. Note that, because of the instrument design, the AOT corresponds to that aerosol having a negligible absorption component. This issue is further discussed later in the paper.

3.3. Aerosol Optical Thickness from Lidar Measurements

[15] Particulate extinction coefficients are derived from the lidar signal via an inversion procedure [Klett, 1985; Flamant et al., 1998, 2000]. It requires the knowledge of the particulate backscatter-to-extinction ratio (BER) profile and a reference value of the extinction coefficient, which is obtained from nephelometer measurements.

Figure 2. Atmospheric reflectivity at 532 nm derived from nadir LEANldre 1 measurements between 0759 and 0818 UTC on 4 June 1999.
In the present case, the aerosols in the lower 2 layers (the nocturnal and residual layers, see previous section) are presumed to be of continental origin. Therefore, below 1000 m AGL, the BER was taken constant with height and equal to 0.02 sr/C0 for continental aerosols for an average relative humidity (as inferred from soundings) of 40% [Ackermann, 1998]. On the other hand, the aerosols in the elevated (1000–3000 m AGL) layer could, to some extent, be decoupled from the lower layers. As shown by the back-trajectory ending at 2500 nm AGL the aerosols in that layer could be of maritime origin. Nevertheless, Flamant et al. [1998] found that for similar relative humidities, the BER characterizing the aerosols above the marine atmospheric boundary layer (mainly water-soluble and sea-salt of diameter less than 0.6 μm) was on the order of 0.0225 sr/C0 or less. As a result, the extinction coefficient profiles in the lower troposphere have been obtained after inversion of the lidar equation using a BER equal to 0.02 sr/C0 over the entire atmospheric column sampled by lidar.

From zenith and nadir measurements we have derived an average composite (molecular + particular) extinction profile and compared to the total extinction profile derived from nephelometer measurements (Figure 4). The agreement between the two type of retrievals is excellent, except close to the surface. However, such discrepancies are expected as integrating nephelometers are known to have a truncation problem where forward scattered light is not detected. The presence of large particles could be an explanation for the differences observed between the lidar and nephelometer derived extinction profiles in the nocturnal layer. Another explanation could be that the BER value of 0.02 sr/C0 is too small and is not representative of the nature of the aerosol in the nocturnal layer. However, in order for the lidar-derived AOT to match the nephelometer-derived AOT, the value of the BER in the nocturnal layer would need to be of the order of 0.1 sr/C0, which is an unrealistically high value for continental aerosols [Ackermann, 1998].

For the lidar-derived AOT, taking into account the statistical variability of the lidar signal and the error associated with the inversion method and the uncertainty on the backscatter to extinction ratio, the quadratic error is 35%. So the average AOT derived from this profile is 0.068±0.024 for the entire flight.

### 3.4. Discussion

The solar irradiance extinction measurements are representative of any light absorption that takes place in the column. The nephelometer measurements are presented assuming no absorption, and may also be a reason why this measurement exhibits the lowest AOT. The lidar measurements are dependent on the BER and a significant absorption component would tend to lower this ratio (i.e. k_{a}=k/\omega_{0}) and increase the AOT. However many parts of Europe have soot as a significant component of their aerosols, with single scattering albedos in the 0.8–0.9 range [Russell and Heintzenberg, 2000; and references therein].

The sensitivity of both lidar- and nephelometer-derived AOTs to the single scattering albedo is presented in Table 1. Table 1 evidences that for a value of \omega_{0}=0.9, the lidar-derived AOT is in good agreement with the solar irradiance AOT (0.08±0.03). Nevertheless, the same value could be obtained while using a BER value of 0.018 sr/C0 instead of 0.02 sr/C0 the former value being commonly used to characterize continental aerosols. A value of \omega_{0}=0.9 leads to a nephelometer-derived AOT of 0.068±0.024 for the entire flight.

### Table 1. Lidar and Nephelometer Derived AOTs Obtained After Correction of the Absorption by Aerosols for 5 Values of the Single Scattering Albedo. BER in sr^{-1}

<table>
<thead>
<tr>
<th>\omega_{0}</th>
<th>1.00</th>
<th>0.95</th>
<th>0.90</th>
<th>0.85</th>
<th>0.80</th>
</tr>
</thead>
<tbody>
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<td>BER</td>
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<td>0.019</td>
<td>0.018</td>
<td>0.017</td>
<td>0.016</td>
</tr>
<tr>
<td>Lidar</td>
<td>0.068</td>
<td>0.073</td>
<td>0.080</td>
<td>0.086</td>
<td>0.094</td>
</tr>
<tr>
<td>Neph</td>
<td>0.054</td>
<td>0.057</td>
<td>0.060</td>
<td>0.063</td>
<td>0.068</td>
</tr>
</tbody>
</table>

Figure 3. AOT derived from spectroradiometric measurements in the range 400–670 nm on 4 June 1999 at 0800 UTC.

Figure 4. Average lidar-derived composite (molecular and particular) extinction profile (solid line) and total extinction profile derived from nephelometer measurements (dotted line) in the morning of 4 June 1999. The vertical line represents the molecular contribution to the total extinction coefficient.
AOT of 0.06±0.02, which is still to low in comparison to the AOTs obtained from lidar and solar irradiance measurements.

4. Conclusions

[21] The AOT values obtained in this paper were extremely low, in the same range than those reported by Martínez-Lozano et al. [2001] for similar conditions during a campaign carried out in the surroundings of Valencia, 150 km from Barrax. These results obtained in the two campaigns evidence exceptionally low AOT values in this area despite the presence of small continental aerosols. These low values present the difficulty of being affected by large relative uncertainties, specially those obtained from irradiance extinction measurements at ground level. This is caused by the relative weight acquired by the other atmospheric constituents under these conditions in the calculation of the AOT value.

[22] Nevertheless, given the uncertainties associated with the AOT retrievals for each instrument, the agreement found is encouraging. At the time of the flight, the AOT retrieved from the ground is approximately 0.085, on the order of the lidar-derived AOT (0.080) but larger than the obtained from nephelometer measurement (0.060). The lidar and nephelometer-derived AOTs are obtained for a single scattering albedo of 0.9 characteristic of European pollution outbreaks over the Iberian Peninsula. The difference between the nephelometer AOT and the other AOTs is due to the truncation problem of the integrating nephelometer in the presence of large particles in the nocturnal boundary layer. The relatively lower AOTs derived from airborne in situ nephelometers in this study have been reported in similar comparisons. In the framework of the ACE-2 experiment, Schmid et al. [2000] have found differences of 10–17% (at 525 nm) between the AOT measured in situ with the CIRPAS Pelican nephelometer and the derived from sunphotometer measurement. Ross et al. [1998] found an agreement within 20% between AOTs derived from ground-based sun photometer measurements and airborne nephelometer measurements. Hartley et al. [2000], in the framework of the Tropospheric Aerosol Radiation Forcing Observational Experiment (TARFOX), also reported smaller AOT values (by 12–15%, on average) as derived with an airborne nephelometer when compared to sun photometer derived AOT.

[23] Bearing in mind that these instruments can measure properly only up to 3 km above the ground level we have applied to the results obtained a correction of vertical distribution for higher altitudes. With this aim, and given the backtrajectories shown in Figure 1, we have chosen a vertical model for maritime aerosols [D’Almeida et al., 1991], which yields a value of 0.003 for the AOT above 3 km AGL. Using this correction, the results obtained for the different methods employed in this case study are: a) nephelometer: 0.063±0.020; lidar: 0.083±0.030; solar irradiance extinction: 0.085±0.018. Future campaigns to be programmed by the ESA in the same zone, specifically on summer 2002, will allow for the re-evaluation of these results taking into account further-more periods of several days.

Acknowledgments. This work was supported by the European Space Agency (ESA) through the Observation Preparatory Program and the European Commission through STAAARTE. The authors thank Jost Heitzemberg and an anonymous reviewer for their helpful comments on the manuscript.

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