OPTICAL PROPERTIES OF FREE TROPOSPHERIC AEROSOL FROM MULTI-WAVELENGTH RAMAN LIDARS OVER THE SOUTHERN IBERIAN PENINSULA

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ABSTRACT

Two cases of free tropospheric aerosol layers observed with multi-wavelength Raman lidars over Évora (Portugal) and Granada (Spain) were investigated. Optical properties, both, columnar and vertically-resolved, of a forest fire smoke plume from North America on 13 June 2011, and of mineral dust layers on 27 June 2011 are presented. The aerosol optical depth and Ångström exponents derived from lidar data were compared to sun photometer measurements. The aerosol optical depth at 355 nm of the free tropospheric smoke layers were about 25 to 30% of the columnar aerosol optical depth found from sun photometer measurements at both sites. The lidar ratio at 355 nm was 46±14 sr and 48±16 sr, over Évora and Granada, respectively. The lidar ratio at 532 nm over Évora was 66±19 sr. The investigation of the dust plume showed larger differences in the aerosol optical properties observed at the two sites. This was due to different transportation paths and intrusion of other aerosol types, namely anthropogenic and marine aerosols.

Key words: atmospheric aerosol profiling; multi-wavelength Raman lidar; long range transport; Saharan dust; forest fire smoke.

1. INTRODUCTION

Atmospheric aerosols have an impact on solar and terrestrial radiation. As they influence the Earth's climate, better knowledge about aerosol properties would improve climate modelling.
One of the key problems is the large variety of aerosol optical properties due to different aerosol sources, microphysical properties and chemical compositions. Depending on the aerosol type, their properties are also influenced by ageing processes during the transportation of the aerosols.
Lidars enable vertically resolved measurements of aerosol optical properties. In connection with the analysis of back-trajectories or tracer models, the transport of aerosol plumes can be estimated. The combination of ground based lidar measurements at different sites allows the detection of the aerosol distribution not only on the vertical and temporal, but also on the horizontal scale.
In the framework of EARLINET (European Aerosol Research Lidar Network) [3] various joint studies for the investigation of different aerosol types were conducted before, e. g. by Balis et al. [2], Sicard et al. [7]. For this study, measurements of the multi-wavelength Raman lidars at the EARLINET stations CGE (Évora Geophysics Center), Évora, Portugal (38.57° N, 7.91° W, 290 m above sea level (asl)) and CEAMA (Andalusian Center for Environmental Research), Granada, Spain (37.16° N, 3.6° W, 680 m asl) were combined. The distance between both stations is about 410 km.

2. INSTRUMENTATION AND METHODOLOGY

The lidars at CGE and CEAMA have similar capabilities. The lidar at CGE is of the type Polly^{XT} [1] and the one at CEAMA is a model LR331D400 from Raymetrics S.A., Greece. Both instruments are emitting at the wavelengths 355, 532 and 1064 nm. They detect elastically backscattered photons at those wavelengths as well as inelastically backscattered photons at 387 and 607 nm. Thus, the backscatter coefficients at 355, 532 and 1064 nm and the extinction coefficients at 355 and 532 nm can be determined. Additionally, both lidars detect the cross polarised component at 532 nm (cross polarised with respect to the polarisation orientation of the emitted beam). The vertical resolution of the raw data from CGE and CEAMA lidars are 30 m and 7.5 m, respectively. The lidar data was averaged over 30 min.
From the profiles of the particle extinction and backscatter coefficients (α and β, respectively), the profiles of the extinction-to-backscatter ratio (or lidar ratio) S, the extinction- and backscatter-related Ångström exponents

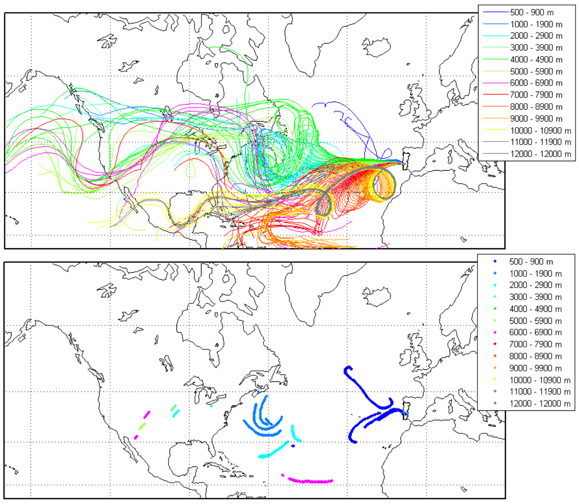

Figure 1. Ten-day HYSPLIT back-trajectories arriving over Évora at 21 UTC on 13 June 2011. Upper plot: Entire trajectories for every 100 m between 0.5 and 12 km asl. Lower plot: Fractions of the same trajectories within the boundary layer.

k_α and k_β as well as the aerosol optical depth τ were calculated. From the information on the polarisation of the detected signal and the backscatter coefficient, the linear particle depolarisation ratio δ_p was determined.
Both, CGE and CEAMA, are operating CIMEL sun photometers in the framework of AERONET (Aerosol Robotic Network)[5]. By means of a power fit, the columnar τ at 355 and 532 nm were determined. Hence, aerosol optical depths and Ångström exponents obtained from lidar measurements could be compared to sun photometer data.
Various sources of information were used to determine the origin of the free tropospheric aerosol layers. HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) [http://ready.arl.noaa.gov/HYSPLIT.php, May 2012] back-trajectories over 10 days were calculated and combined with information on the boundary layer height. The procedure is illustrated in figure 1 by means of back-trajectories arriving over Évora at 21 UTC on 13 June 2011. Back-trajectories were calculated for every 100 m between 0.5 and 12 km asl over Évora and Granada. In the upper plot in figure 1 they are colour coded according to the height asl over Évora. In the lower plot, only the fractions of the back-trajectories which are inside the boundary layer are shown. Those trajectories are more likely to pick up aerosols than trajectories without boundary layer contact. Furthermore, the aerosol models NAAPS (Navy Aerosol Analysis and Prediction System) [http://www.nrlmry.navy.mil/aerosol_web/Docs/globaer_model.html, May 2012] and DREAM (Dust Regional Atmospheric Model) [http://www.bsc.es/projects/earthscience/DREAM, May 2012] as well as satellite images from MODIS (Moderate Resolution Imaging Spectroradiometer) [http://modis.gsfc.nasa.gov, May 2012] and Landsat [http://landsat.gsfc.nasa.gov, May 2012] were used for aerosol source identification.

3. OBSERVATIONS

Two different cases of free tropospheric aerosol layers observed over the southern Iberian Peninsula in June 2011 were investigated. On 13 June 2011 an aerosol layer was advected towards Portugal and Spain from west, presumably smoke from North America. Mineral dust from the Sahara was detected by both lidars on 27 June 2011. Both events lasted several days. However, the analysed periods were selected according to correlative measurements at both stations, Évora (EV) and Granada (GR). Measurements in temporal coincidence were analysed. Therefore, different fractions of the aerosol plumes were observed. This can give information about the horizontal homogeneity of the layers in terms of vertical distribution and aerosol optical properties.

3.1. Forest fire smoke from North America, 13 June 2011

On 13 June 2011 aerosol layers were observed by lidars from 4.75 to 6.64 km asl (EV) and from 5.42 to 7.01 km asl (GR). The data was averaged from 20:30 to 21:00 UTC. The back-trajectories with boundary layer contact ending over Évora at 21 UTC on 13 June 2011 are shown in figure 1 (lower plot). The back-trajectories arriving over Granada in the considered height range, were similar to those over Évora. Regarding the layer heights, aerosol was transported to Évora by back-trajectories plotted in green, light green and pink. The back-trajectories had boundary layer contact over the Atlantic Ocean between the Cape Verde Islands and the Caribbean Sea. Besides, back-trajectories with boundary layer contact over the south-west of the USA were arriving at the aerosol layer height over both stations after five to seven days. According to the NAAPS model, smoke was the most prominent aerosol source in this region. A very large smoke contribution in eastern Arizona, USA, was given by the model. The fire detection provided from MODIS data showed active fires in this area. Data from 5 June 2011 was investigated considering the length of the back-trajectories. Furthermore, images of the visible composite from MODIS were screened for smoke plumes. A large plume was found starting in Arizona and drifting north-eastward. The burning area was also captured by Landsat.
Optical aerosol properties obtained from lidar and sun photometer measurements over Évora and Granada on 13 June 2011 are given in table 1. Lidar and sun photometer data was averaged over 30 min, respectively. As night time lidar measurements were analysed, the sun photometer data just before sunset was used for comparison.
Over Granada, the free tropospheric aerosol layer was wider than over Évora. The lower layer observed over Évora, was not detected over Granada. The particle extinction coefficients could not always be determined, due to a low signal-to-noise ratio in optically thin layers at the

wavelengths 387 and 607 nm. The total aerosol optical depth at 355 nm of the layers was about 25 to 30% of the columnar aerosol optical depth found by sun photometer measurements at both measurement sites. The columnar k_τ from sun photometer measurements were higher over Granada, which is reasonable, as it is an urban station, whereas Évora is a rural site. More anthropogenic aerosol within the boundary layer at Granada would increase the columnar k_τ. The smaller values over Évora agreed with k_α found from lidar measurements there. Both k_β, at the pair of wavelengths 355 and 532 nm as well as 532 and 1064 nm, of the lower layer over Évora were larger than of the higher layer. The columnar k_τ was smaller than k_β in the free tropospheric layers. Over Granada, k_β(355, 532 nm) was higher than over Évora. This could be due to the observation of different fractions of the aerosol plume. However, the lidar ratio S at 355 nm was very similar at both sites. Over Évora, S at 355 nm was significantly smaller than S at 532 nm. This agrees well with findings by Müller et al. [6] for aged smoke particles. The linear particle depolarisation ratio over both stations was low (between 2 and 6%), indicating mainly spherical particles.

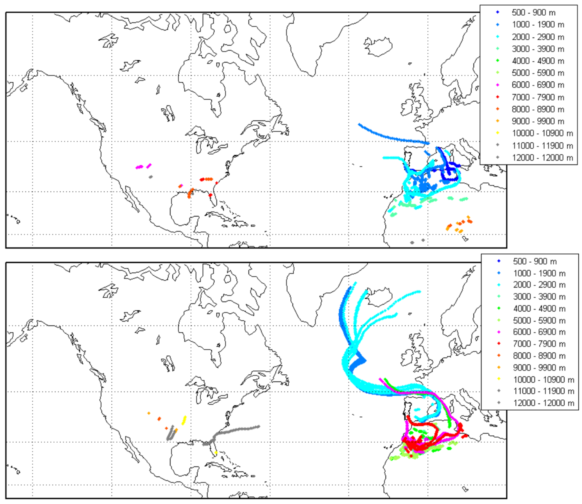

Figure 2. Fractions within the boundary layer of the 10-day HYSPLIT back-trajectories arriving over Évora (upper plot) and Granada (lower plot) at 00 UTC on 27 June 2011.

3.2. Saharan dust, 27 June 2011

A Saharan dust episode was predicted by DREAM starting on 24 June 2011. The dust plume was approaching the Iberian Peninsula from south-west. The lidar measurements were averaged from 00:10 to 00:40 UTC (EV) and from 00:00 to 00:30 UTC (GR) on 27 June 2011. Free tropospheric aerosol layers from 1.74 to 5.02 km asl (EV) and from 1.73 to 4.73 km asl (GR) were analysed. The respective nocturnal residual layer heights were 1.59 km asl (EV) and 1.52 km asl (GR).
The back-trajectories with boundary layer contact arriving at 00 UTC on 27 June 2011 are shown in figure 2. The back-trajectories plotted in light blue, cyan, green and light green are indicating the aerosol source region. At both sites the main source according to the back-trajectories was the Saharan desert, with some additional contributions from the coastal areas of the Mediterranean Sea. The back-trajectories from the Sahara to the measurement sites were about two to five days long. Over Granada, the aerosol in lower altitudes might be additionally influenced by the Atlantic Ocean. Air masses from the Sahara also arrived in higher altitudes over Granada. However, no aerosol was observed in those height ranges. Profiles of the optical properties are shown in figure 3. Layer mean values and standard deviations of the plotted optical aerosol properties are given in table 1. No sun photometer data from Évora exist from the afternoon of 26 June 2011 due to the presence of clouds. Because of the long time difference to sun photometer data from the morning of 27 June 2011 no sun photometer values are presented for this case.
The altitudes of the aerosol layer boundaries were very similar at both sites. The optical depths at 355 and 532 nm of the higher free tropospheric layer were slightly smaller over Évora. The mean lidar ratios at both wavelengths were lower than those over Granada. At both stations k_α and k_β were low, indicating a strong contribution of large particles. This is typical for Saharan dust [8].
The linear particle depolarisation ratio was larger over Évora, with layer mean values of (17±2)% (EV) and (11±1)% (GR). Those values are lower than what would be expected for pure Saharan dust [4]. This is probably due to the intrusion of anthropogenic and marine air masses from the Mediterranean Sea and its coastal areas, as can be seen in figure 2. The differences in δ_p and S at 355 and 532 nm found at both sites were probably caused by different transportation paths and thus different mixtures of aerosol types.

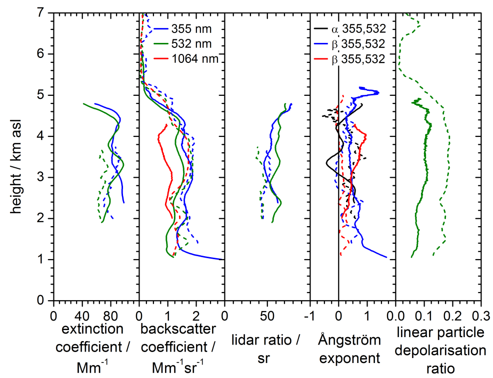

Figure 3. Profiles of the particle extinction and backscatter coefficients, lidar ratios, extinction- and backscatter-related Ångström exponents and linear particle depolarisation ratios shortly after midnight on 27 June 2011; over Évora (dashed, EV) and Granada (solid, GR).

Table 1. Layer heights and layer mean values and standard deviation of optical aerosol properties.

site	height / km (asl)	τ 355 nm	τ 532 nm	S / sr 355 nm	S / sr 532 nm	k_α, k_τ 355, 532 nm	k_β 355, 532 nm	k_β 532, 1064 nm
13 June 2011: 20:30 to 21:00 UTC								
EV	column*	0.15±0.005	0.09±0.005			1.13±0.02		
EV	4.75 – 5.50	0.01±0.002					1.6±0.2	1.8±0.2
EV	5.77 – 6.64	0.03±0.007	0.02±0.005	46±14	66±19	0.9±0.5	1.3±0.5	1.4±0.3
GR	column*	0.14±0.005	0.08±0.01			1.50±0.01		
GR	5.42 – 7.01	0.04±0.01		48±16			2.3±0.2	
27 June 2011: 00:00 to 00:30 UTC								
EV	1.74 – 2.18	0.04±0.001	0.03±0.001	45±1	43±1	0.5±0.1	0.2±0.2	0.2±0.1
EV	2.51 – 5.02	0.16±0.04	0.14±0.04	44±9	39±5	0.4±0.3	0.2±0.2	0.1±0.1
GR	1.73 – 2.21		0.03±0.001		58±2		0.7±0.1	0.2±0.1
GR	2.40 – 4.73	0.21±0.01	0.19±0.02	55±7	61±4	0.2±0.3	0.4±0.1	0.6±0.2

* Columnar data from sun photometer measurements averaged over 30 min before sunset on 13 June 2011. The Ångström exponent k_τ was calculated from τ at the wavelengths 355 and 532 nm.

4. SUMMARY AND CONCLUSIONS

Free tropospheric aerosol layers were monitored simultaneously by lidars at two EARLINET stations on the southern Iberian Peninsula. Long range transported forest fire smoke from North America was detected on 13 June 2011 and desert dust from the Sahara on 27 June 2011. In both cases, the vertical extends of the investigated aerosol layers were very similar at both sites. This is probably due to the small distance between the two stations, compared to the length of the transport path of the aerosols. However, it hints a uniform vertical distribution over the southern Iberian Peninsula.
Back-trajectories of the forest fire plume arriving at both sites were very similar and the aerosol optical depths and lidar ratios at 355 nm agreed well at both sites.
The optical properties of the dust layer varied at the two sites. Reason for those differences were different transportation paths and mixing of the dust with anthropogenic and marine aerosols.

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