Lidar observations of massive Saharan dust intrusion above Sofia, Bulgaria, in April 2019

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Abstract. A large-scale massive transport of Saharan dust over all of Europe was observed in the last third of April 2019. As part of the European Aerosol Research Lidar Network (EARLINET) and the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS), Sofia lidar station conducted lidar observations of the atmospheric aerosol load in this period. Some of the results obtained are described in this work. Remote measurements were implemented using two elastic-scatter lidar channels (1064 nm/532 nm). The paper presents results of studying and analyzing the optical and microphysical properties of the aerosols detected, as well as the topological and dynamical features of the aerosol/dust layers observed. The height profiles of the atmospheric aerosol backscattering coefficient are retrieved and discussed. The microphysical properties of aerosol/dust particles are characterized qualitatively based on an analysis of the backscatter-related Ångström exponents profiles and distributions obtained for particular aerosol layers. Dust mixing with other aerosol types of local origin or such captured during the transport is also considered and discussed based on local meteorological radiosonde data and air-transport modeling and forecasting data. Conclusions are drawn concerning the experimentally ascertained and the possible impacts of the massive dust intrusion event on the local tropospheric aerosol structure and meteorological conditions.

1. Introduction

Airborne Saharan dust, due to its usual huge amount and large scale of spreading, is one of the key factors determining the atmospheric thermal and radiative parameters and conditions, and thus, the impacts they have on regional and global heating or cooling climate processes [1]. Driven by the air circulation systems in North Africa and the Mediterranean Basin, enormous air masses carrying dust from the Sahara Desert often head to the northeast and cover large regions of Europe, mostly in its southern parts [2]. Although such events of long-range Saharan dust transport are observed with increasing frequency in all seasons of the year, even atypically in winter [3, 4], their heaviest manifestation is in spring [5]. The near-surface thermal low-pressure system of Saharan heat low [6] plays an important role in the West African monsoon system [7] in spring and summer, combining with and strengthening the moist south-westerly monsoon flow from the Atlantic Ocean and the dry dust-rich north-easterly Harmattan flow. The powerful Sharav cyclones, being also mainly active in the spring period, can mobilize large masses of desert dust to move them eastward along the North African coast and, subsequently, northward near the South-Eastern Mediterranean [8]. Some of the dust transport events in the period April-May are so intense and massive that they load the atmosphere over all of Europe with high concentrations of desert aerosols, reaching even the northermost
continental parts. Such events have a very strong effect on the meteorological conditions and aerosol composition of the atmosphere, as well as on the climatic processes in the region. The coordinated lidar observations within the European Aerosol Research Lidar Network (EARLINET) allow for a comprehensive characterization of these events and their impacts on the climate, air-quality and human health [9].

A large-scale long-distance transport of Saharan dust took place over Europe in the last ten days of April 2019 [10]. The Sofia lidar station, being a part of EARLINET and ACTRIS (Aerosol, Clouds and Trace Gases Research Infrastructure), monitored the atmospheric aerosol loads in this period.

In this work, we report results of two-wavelength (1064 nm/532 nm) lidar observations carried out in the evening of 24 April 2019 – the day of the peak load of the troposphere over the city of Sofia with desert aerosols for the time of the event in question.

2. Aerosol/dust distribution dynamics and meteorological state of the atmosphere

The remote observations are implemented using the two aerosol channels of a lidar based on a frequency-doubled Nd:YAG laser [11].

Figure 1 displays color-mapped time series of range-corrected lidar signals at 1064 nm (a), and 532 nm (b), as well as vertical profiles of meteorological parameters (air temperature, dew point, and relative humidity) from radiosonde data obtained at 12:00 UTC on 24 April 2019 (c), up to a height of 7 km above ground level (AGL). Hereafter, the values cited of elevation (height or altitude) are as measured AGL, unless it is explicitly noted that they are above sea level (ASL).

The color maps show the presence of aerosols from the surface to heights slightly above 4 km distributed in three distinct layers. The near-ground layer up to heights of 1-1.5 km coincides with the seasonal local atmospheric boundary layer (ABL). The main aerosol layer is located upward to heights of about 3 km and has a maximum density at 2-2.5 km. A secondary aerosol layer with a significantly lower density is observed in the height range 3-4 km. Above 4.5 km, there are no noticeable indications for the presence of significant amounts of aerosol.

The meteorological diagram in figure 1 (c) shows a typical course of the air temperature, with a ground value of 20 °C and the presence of a slight inversion at an altitude of just over 1 km, as well as moderate values (30-75%) of the atmospheric relative humidity in the atmospheric domains occupied by aerosols. Accordingly, the dew point profile as a whole remains detached from that of the temperature, indicating relatively low probability for condensation processes. Nevertheless, episodic clouds are present in figures 1 (a) and 1 (b) at the upper end of the main dust layer near 3 km, which may likely be nucleated by dust particles. Previously, a substantial reduction in the atmospheric relative humidity due to Saharan dust intrusions has been observed, even in cases of transport events much weaker than the one considered here [4]. Therefore, the moderate levels of RH, in combination
with the presence of water clouds within the dust layer, suggest that the air masses transferred from North Africa to the measurement site may likely have contained moisture.

3. Air-mass and dust transport modelling and forecasts

Figure 2 presents forecast data of the Barcelona Supercomputing Center (BSC), via its NMMB/BSC-Dust model, including Saharan dust concentration profile up to 12 km ASL with regional dust load map (inset) for 24 April 2019 (a) and NOAA ARL HYSPLIT-model diagrams of backward trajectories ending above Sofia at 18:00 UTC on the same day at 2.4 km in ensemble mode (b) and at 3.8 km in normal mode (c).

![Figure 2](image_url)

**Figure 2.** (a) NMMB/BSC-Dust model forecasted Saharan dust concentration profile with regional dust load map (inset) for 24 April 2019 and NOAA ARL HYSPLIT-model backward trajectories ending above Sofia at 18:00 UTC on the same day (b) at 2400 m and (c) at 3800 m AGL.

As can be seen from the map in figure 2 (a) (inset), at 18:00 UTC on 24 April 2019, the region of Sofia (marked by a red circle) was invaded by a massive dust plume transported from the Sahara Desert with a density of about 1-2 g/m². The vertical profile of the dust mass concentration shows a Saharan dust load in the lower half of the troposphere above Sofia up to an altitude of about 6 km, with a peak near 3 km, where the concentration exceeds 600 µg/m³. The forecast profile agrees well with the aerosol density distribution in figures 1 (a) and 1 (b) obtained from the lidar measurements.

Figure 2 (b) shows a HYSPLIT diagram containing an ensemble of backward trajectories with 72-hour duration ending in the region of Sofia at 18:00 UTC on 24 April 2019 at an altitude of 2.4 km AGL. As can be seen from the diagram, virtually all backward trajectories are located for the most part above the Sahara Desert, passing close to its surface or in the lower half (up to 3 km) of the Saharan ABL.

Figure 2 (c) displays three backward trajectories of 288-hour duration, ending over Sofia at altitudes near 3.8 km AGL, corresponding to the upper sublayer in figures 1 (a), (b). These trajectories pass in close proximity to the surface of the North Atlantic for a period of six days (April 13-19), indicating a high probability of catching coarse marine aerosols; whereafter they also cross areas over North Sahara, making capturing of desert dust possible.

The analysis of the BSC maps for the dynamics of dust transport and winds over North Africa in the days prior to the measurement (20-23 April) shows unequivocally that a south-westerly air current from the Atlantic Ocean, after a cycle of rounds over Western Mediterranean, South-West Europe, the East Atlantic and North-West Africa, already carrying desert dust and, probably, moist marine air, pushed powerfully and rapidly the dust-rich plume present over Algeria and Libya northeastward to Europe [10] and, particularly, to Bulgaria. In confirmation of this, the backward trajectories in figure 2 (b) passing over North-West Africa have a characteristic curvature correlating with the above-mentioned air-current track. These features, combined with the presence of moisture in the dust-
containing air masses, as it was ascertained in the previous section, are convincing indications allowing one to reasonably assume that the powerful air current mobilizing these masses northeastward is the mentioned earlier moist south-westerly monsoon flow from the Atlantic Ocean, which has its maximum activity during the spring season.

From the above comments on the diagrams shown in figure 2 and the air transport history, it can be concluded that in the time period 17:30-19:42 UTC on 24 April 2019, in which the lidar measurements described here were performed, the air masses present in the lower and middle troposphere above the city of Sofia contained significant amounts of Saharan dust, likely enriched with marine aerosols and moisture.

4. Lidar characterization of the aerosol/dust optical and microphysical properties

Results of the lidar studying and profiling the optical and microphysical parameters of the detected aerosols and desert dust are presented in figure 3.

Figure 3 (a) shows the time-averaged vertical profiles of the aerosol backscatter coefficient (BC) at the two lidar wavelengths up to a height of 7 km. The profiles were retrieved using the Klett-Fernald inversion method [12, 13] at a constant lidar ratio of 45 (the ratio of the aerosol extinction and backscattering coefficients) considered appropriate for the aerosol types registered. Applying a Rayleigh fitting procedure [14, 15] to the total range-corrected lidar signal profiles at each wavelength and the corresponding attenuated molecular backscatter profile from the standard atmosphere (SA) model [16], the altitude interval of pure molecular (aerosol free) atmospheric content is determined to be 8.2-9.5 km ASL. In this interval, at an altitude of 8.6 km ASL, the SA values of the molecular BC coefficient at 532 nm and 1064 nm were determined to be 6.07×10^{-7} m^{-1} sr^{-1} and 3.79×10^{-8} m^{-1} sr^{-1}, respectively, being used as reference ones in the retrieval of the BC profiles in figure 3 (a).

The profiles show the presence of significant amounts of aerosols up to 4.6 km distributed in a main dense layer extending up to 3.2 km with a pronounced peak at 2.35 km, and another one with a significantly lower density located immediately above the first one and centered at about 3.8 km. In general, the shapes and height distribution of the BC profiles correspond well to those of the dust concentration profile in figure 2 (a), with the exception of the smaller upper layer, which is much more pronounced in figure 3 (a).

The maximum BC values obtained of 6.5/4.5 M m^{-1} sr^{-1} at 532 nm/1064 nm exceed many times the ones typically measured at these heights in the absence of dust transfer, in accordance with the high concentrations of Saharan dust predicted by the BSC and seen in figure 2 (a).

Figure 3. Vertical profiles of (a) aerosol backscatter and (b) backscatter-related Ångström exponent; (c) Histograms of the total and characteristic partial BAE distributions; SD – standard deviation.
In order to characterize qualitatively the microphysical properties of the registered aerosols, profiling of the backscatter-related Ångström exponent (BAE) and statistical analysis of BAE arrays is performed. Note that the values of the BAE are inversely proportional to the dominant size of the aerosol particles. Figure 3 (b) shows a vertical profile of the BAE based on the BC profiles in figure 3 (a). The dotted lines and the numerical values indicate the mean BAE for the separated aerosol/dust layers and the free troposphere. Within the main dust layer, the BAE varies from 0.4 to 0.7 with a mean value of 0.54±0.06 indicating a dominance of relatively large aerosol fractions. Given the massive transport of dust and the small heights above the Sahara Desert from which it originates, the dominance of larger aerosol modes is reasonable. In the range of the upper sublayer, the BAE changes slightly around a mean value of 0.44±0.04 showing the predominance of even larger aerosol particles. The mixing of Saharan dust with marine aerosols and moisture, as discussed in section 3, may explain the lower BAE values for this layer. Regarding the altitudes above 5.5 km, the BAE reaches a mean value of 1.26±0.19, which is common for the residual background aerosols of low density that could be present in the free troposphere [11,16]. In the transition interval of 4.5-5.5 km, the BAE has expectedly an intermediate mean value of 1.00±0.26.

Figure 3 (c) shows the BAE distribution histograms characterizing the total BAE profile (panel 1) and its particular parts corresponding to the aerosol types and layers identified (panels 2-4). The displayed histograms result from a statistical analysis of the BAE occurrences when scanning the BAE values with a bin window of 0.02. SD stands for the standard deviation of the individual BAE values from the BAE mean value, being the square root of the BAE variance. We note that the BAE distributions are qualitative mirror-image analogues of the real aerosol particle size distributions.

5. Conclusions

Based on the results presented in this paper, the following conclusions can be drawn.

The lidar measurements described characterize an event of extremely strong, massive and fast large-scale transport of dust-rich air masses from the Sahara Desert northeastward over the Mediterranean Basin and almost all of Europe, with Bulgaria being located in the central zone of the densest dust plume.

The dynamic color maps corresponding to the lidar measurement time interval show the presence of a relatively monolithic dense dust layer in the height range 1.8-3.1 km with low penetration into the local ABL, which we attribute to the intensive rapid course of dust advection.

The retrieved profiles of the aerosol backscatter for the dust-rich layer show BC values considerably higher than those traditionally measured in ABL and the low troposphere above Sofia, including in numerous cases of Saharan dust intrusions.

The shape of the aerosol BC profiles correlates well with the forecasted dust concentration profile of the Barcelona Supercomputing Center NMMB/BSC-Dust model for Sofia for the time of the lidar measurements.

The calculated BAE values (with a mean of 0.54) for the main dust layer show the predominance of coarse aerosol fractions likely sized well above 1 μm. The corresponding BAE distribution is fairly narrow, indicating a nearly uniform aerosol composition.

For the sublayer observed in the altitude range 3.2-4.2 km, the lower BAE values obtained (with a mean of 0.44) are ascribed to the formation of a mixture of Saharan dust and large marine aerosols captured close to the ocean’s surface, as based on the air-mass transport history.

The influence of the dust-load event considered on the local meteorological conditions is expressed mainly in the formation of a temperature inversion near the lower limit of the main dust layer and in the moderate values of relative humidity. Given what has been observed before, namely, a more significant reduction in the relative humidity caused by Saharan dust intrusions, we attribute the weaker decrease of the relative humidity in the case under consideration here to the probable major role of the moist south-westerly monsoon flow from the Atlantic Ocean in the dust transport enriching the dry desert air masses with moisture.
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