

SAHARAN DUST LOADS OVER SOFIA, BULGARIA: LIDAR OBSERVATIONS ON WINTER AND SPRING DUST EVENTS

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Received on February 28, 2023

Presented by P. Atanasov, Member of BAS, on March 28, 2023

Abstract

Aerosols have significant impacts on the climate, ecosystems, and human health. Sahara Desert is the largest source of natural mineral aerosols (dust) on Earth. Enormous amounts of Saharan particulate matter are frequently transported to Europe through advection of warm air masses, being typical for spring and summer. Over the last years, winter Saharan dust load events have also been reported for various locations over Europe, including Sofia. In this work, we give a description of lidar observations of atmospheric aerosols present above Sofia, Bulgaria, during episodes of Saharan dust intrusions in periods of minimum (in winter) and maximum (in spring) activity of dust transport to the region. Measurements were conducted in February and April 2021, with the two aerosol channels (at 532 nm and 1064 nm) of the Nd:YAG-laser based lidar. Aerosol/dust layering and optical and microphysical properties are characterized. Colourmaps of the vertical aerosol distribution and its temporal dynamics were presented. Time-averaged vertical profiles of the aerosol backscatter coefficients and corresponding backscatter-related Ångström exponents were retrieved and analyzed. The Saharan origin of the aerosols detected

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This research was funded by the Bulgarian Ministry of Education and Science (support for ACTRIS BG, part of the Bulgarian National Roadmap for Research Infrastructure) and by the Bulgarian National Science Fund under grant No. KP-06-N28/10/2018. The financial support is acknowledged for EARLINET in the ACTRIS Research Infrastructure by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement no. 871115 (ACTRIS IMP).

DOI:10.7546/CRABS.2023.05.02

was identified using online available air/dust tracking and mapping web resources. Results obtained show that the considered here dust load events have affected significantly both the structure and aerosol composition of the local troposphere.

Key words: aerosol, Saharan dust, lidar, backscattering coefficient

Introduction. North Africa (particularly Sahara Desert) is recognized to be the widest dust-emitting region on Earth. Mineral dust is the most abundant type of atmospheric aerosols, influencing strongly the environment and human life in various aspects [1]. The mechanism of desert dust transport from North Africa to Europe has been subjected to extensive research for a long time [2].

The most intense transport of dust from Sahara Desert over the Mediterranean, including the Balkan Peninsula, happens mainly in spring and summer [3,4]. As a departure from this pattern, some winter events of Saharan dust intrusions over Europe have been observed in recent years [5,6].

The impacts of dust/aerosols on the environment are mainly determined by their optical, microphysical and topological properties [7–10]. Various measurement techniques are being utilized for atmospheric aerosol tracking, detecting and studying. The active remote sensing by lidars is a widely adopted efficient technique for carrying out observations of atmospheric aerosols, including desert dust [3–8]. Being particularly sensitive to changes in the atmospheric aerosol density, the lidar approach provides retrievals and vertical profiling of the aerosol/dust optical and microphysical characteristics, such as backscattering or extinction coefficients and the Ångström exponent. Lidars offer advantageous possibilities of observing the aerosol layer density stratification and dynamics in nearly real time, with high spatial and temporal resolution. Accordingly, they are recognized to be an efficient instrument for detecting and characterizing individual aerosol/dust events, as well as for incorporating them into the regional or global picture of the atmospheric aerosol transport in a climatological aspect. Saharan dust loadings over Europe have been regularly and extensively studied and documented in the framework of the European Aerosol Research Lidar Network (EARLINET) and in the pan-European Research Infrastructure for monitoring of aerosols, clouds and trace gases (ACTRIS) [7,9,11,12].

In this study, we report results of remote sensing observations of the troposphere over Sofia, Bulgaria, performed during Saharan dust episodes. The main objective of the work is to present in a comparative aspect two events of Saharan dust load over Sofia, in periods of minimum (winter) and maximum (spring) activity of dust transport to the region, by lidar characterization of the aerosol/dust stratification and properties, regarding their effects on the local troposphere and weather, in terms of seasonal specificity.

Measurement site, instrumentation, and methods. Bulgaria is located in Southeastern Europe, in the northeastern part of the Balkan Peninsula (Fig.

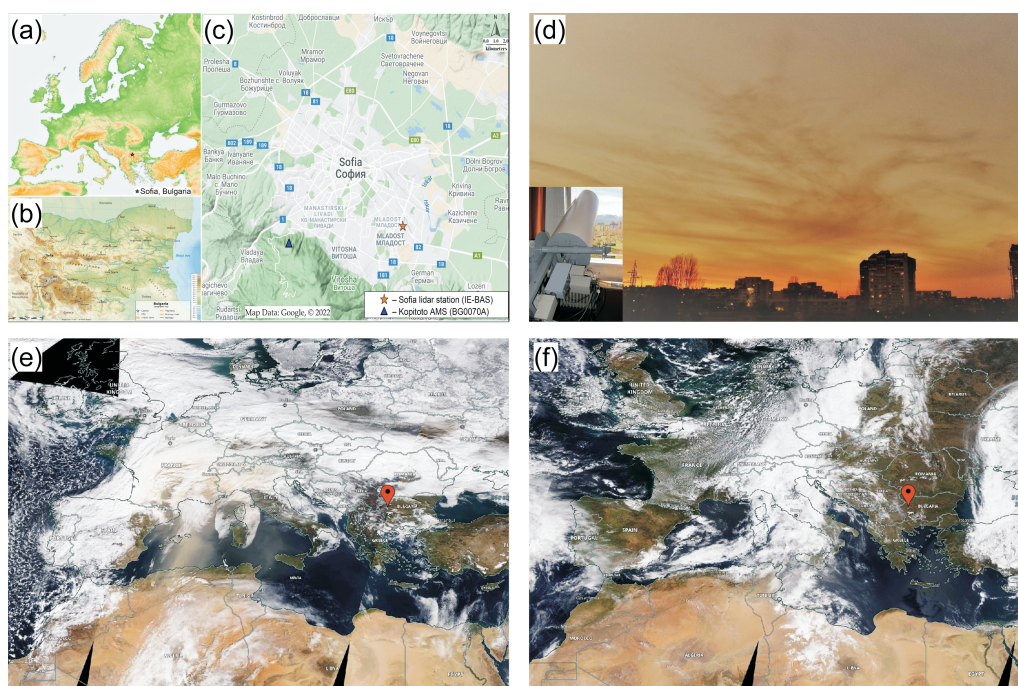


Fig. 1. Topographic maps of Europe (a), Bulgaria (b), and Sofia (c); Picture of Saharan dust veils in the sky over Sofia in the evening of 6 February 2021 (d) with a photo of the lidar system (inset); MODIS-Terra true-colour images of the dust-cloud plume spread for 6 February 2021 (e) and 12 April 2021 (f). The red symbol indicates the position of Sofia

1a). The capital Sofia is situated in the Sofia Valley, in the western part of the country (Fig. 1b). The valley is surrounded by mountains on all sides and has an average altitude above sea level (ASL) of about 550 m.

Sofia lidar station is located in the southeastern part of Sofia (42.65°N, 23.38°E, 600 m ASL), as marked in Fig. 1c. It is represented by the Laser Radars Laboratory (LRL) of the Institute of Electronics, Bulgarian Academy of Sciences (IE-BAS). The lidar measurements described in this work were carried out using an aerosol lidar designed and built in the LRL of IE-BAS [4,6], a photograph of which is shown as an inset in the lower left corner of Fig. 1d.

The lidar system is configured in a monostatic biaxial arrangement, pointing at an angle of 32° with respect to the horizon. The light source is a solid-state Q-switched frequency-doubled Nd:YAG laser (pulse energy: up to 600/80 mJ at 1064/532 nm; pulse duration: 15 ns FWHM; beam divergence: 3 mrad; repetition rate: 2 Hz). The light backscattered by atmospheric molecules and aerosol particles is received using classical Cassegrain telescope (aperture: 35 cm; focal distance: 200 cm). The lidar measures backscattered signals with time/range/height resolution of 100 ns/15 m/7.5 m.

For retrieving profiles of the aerosol backscatter coefficient (BSC), the widely adopted Klett–Fernald’s inversion algorithm [13,14] is applied, in particular its version regarding the case of constant lidar ratio (the ratio of aerosol extinction and backscatter coefficients). Here, we use a lidar ratio of 45 considered to be reasonable in cases of aerosols dominated by Saharan dust [4]. Applying this algorithm, we calculate the averaged aerosol BSC profiles, whereas using series of consecutively recorded range-corrected signals (RCS), colourmaps in height-time coordinates are constructed, illustrating the spatial distribution and temporal dynamics of the aerosol fields detected. The BSC profiles obtained at the two laser wavelengths (532 nm and 1064 nm) are then used to calculate the corresponding profiles of the backscatter-related Ångström exponent (BAE), which is regarded as an indicator of the dominant particle size fractions in the aerosol layers registered [15]. To make assumptions about the type and origin of the aerosols in the layers detected by the lidar, we use data and images provided by the SKIRON modelling system of the University of Athens [16,17], BSC-DREAM8b model of the Barcelona Supercomputing Center [18,19], as well as the NOAA HYSPLIT Model backward trajectories [20,21].

For further verification and validation of the lidar results regarding Saharan dust, reference data from in-situ measurements of aerosol mass concentration (PM_{10}) were used, provided by one of the air-quality automated measuring stations (AMSs) in Sofia, part of the National Automated System for Environmental Monitoring (NASEM) [22] – the elevated rural station for aerosol background measurements Kopitoto AMS deployed in Vitosha Mountain (1321 m ASL, $42^{\circ}38'13.2''\text{N}$, $23^{\circ}14'38.4''\text{E}$) (Fig. 1c).

Results and discussions. The remote sensing observations were performed on 6 February (Event 1) and 12 April (Event 2) in 2021, with the two aerosol channels (at 532 nm and 1064 nm) of the lidar system.

Figure 1d shows a photograph of the evening sky over Sofia, during the conducted lidar measurements on 6 February 2021. It clearly shows spreading veils of Saharan dust.

In Fig. 1e, f, true-colour images of the dust-cloud plumes spread for 6 February 2021 and 12 April 2021 are presented, obtained by the satellite MODIS-Terra [23]. The grey-yellowish dust plume is better distinguished in Fig. 1e, tracing an arcuate spreading pathway from North Africa over the Western Mediterranean and Central Europe to the Balkans. In Fig. 1f, the dust plume related to 12 April 2021 is not as well visible due to cloud masking, whereas the direction of propagation is rather directly to the northeast.

Figure 2 displays the vertical mass distribution and temporal dynamics of the aerosol fields detected in terms of colour-mapped time series of range-corrected lidar signals at 1064 nm. On the right-hand side of the maps, a colour bar of the aerosol density in arbitrary units is shown.

The colourmap for 6 February indicates an event of moderate, increasing dust

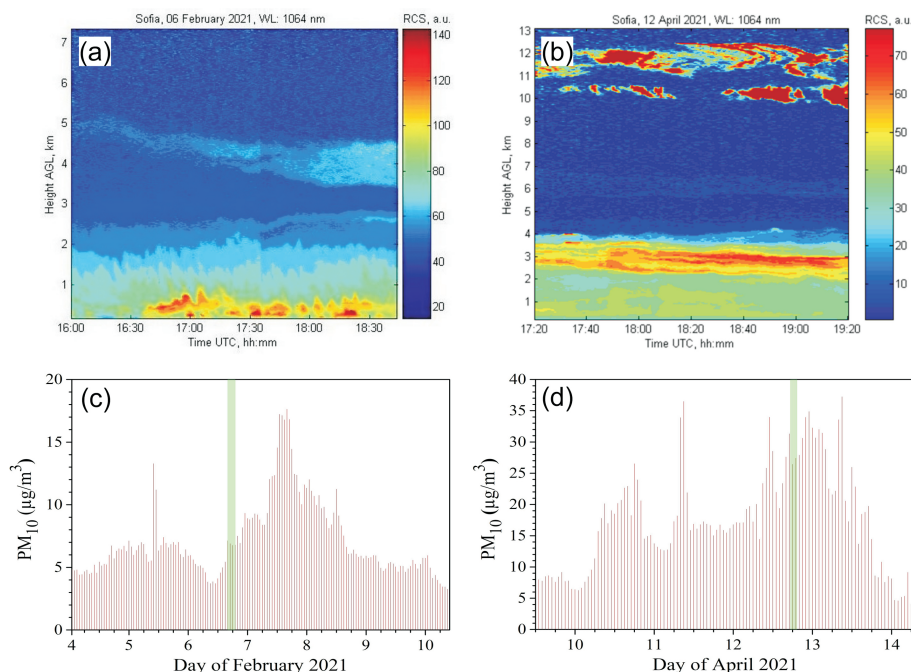


Fig. 2. Colour-coded time series of range-corrected lidar signals measured at 1064 nm on 6 February (a) and 12 April 2021 (b); Hourly mean values of the PM_{10} mass concentrations measured by the Kopitoto AMS on 6 February (c) and 12 April 2021 (d). The vertical green bars indicate the time intervals of the lidar measurements

load intensity, being in its initial stage. The registered dust layers are located both superimposed on the local atmospheric boundary layer (ABL) up to heights of 2.5 km above ground level (AGL) and also separately above the ABL, in the height range 3.5–5 km AGL. Hereinafter, all heights are given in their AGL values.

The colourmap for 12 April shows a high-density dust layer, extending in the height range 2–4 km, being mixed and superimposed with the local ABL, erasing its upper boundary. A much weaker aerosol layer can also be seen at altitudes between 5.5 and 6.8 km.

Figure 2c, d presents histograms of hourly mean values of the PM_{10} mass concentrations measured by the Kopitoto AMS in the periods 4–10 February and 9–14 April 2021, respectively. The time intervals during which lidar aerosol measurements were carried out within the two periods are highlighted with green vertical stripes. As can be seen in both histograms, the lidar observations on 6 February fall within the initial period of increasing intensity of the dust Event 1 having a local maximum on 7 February, whereas those on 12 April are in close proximity to the maximum of the dust Event 2, being in the late hours of 12 April and in the early hours of 13 April. In the first case, the highest exceedance of background aerosol concentrations for Kopitoto AMS (approximately $5 \mu\text{g}/\text{m}^3$) is

about 3–4 times, and in the second – more than 7 times, with values of 15–18 $\mu\text{g}/\text{m}^3$ and 30–35 $\mu\text{g}/\text{m}^3$, respectively.

Figure 3 presents the BSC-DREAM8b model vertical profiles of dust mass concentration above Sofia during the days in question, the corresponding SKIRON forecast colourmaps for Saharan dust spreading in the atmosphere over the Mediterranean Basin and Europe, and HYSPLIT-backward trajectories ending above Sofia within the height range 2–5 km, during the lidar measurement time intervals. According to the presented data, the dust transport on 6 February has been conditioned by a stable zone of high atmospheric pressure over the Central Mediterranean, determining a specific arcuate motion and distribution of the dust plume over large areas around it, covering almost the entire territory of Europe. Thus, the intrusion of dust-rich air masses from the Sahara over Bulgaria and, in particular, over Sofia, takes place from the West-Northwest, instead of, as is typical, from the Southwest. This specific Saharan dust distribution pattern predicted by the SKIRON model is confirmed by the actual MODIS dust plume image shown in Fig. 1e. According to Fig. 3a, the observed layers of desert aerosols are the result of long-range transport of dust originating mainly from North-West Africa (Mauritania, Western Sahara, Algeria and Morocco), as shown by the backward trajectories displayed in Fig. 3c.

On 12 April, the origin of desert aerosols is also from regions of the North-Western and Central Sahara. The dust transport is mostly direct, in the typical for the spring-summer period North-Eastern direction, as also confirmed by Fig. 3d.

Vertical profiles of the aerosol/dust optical and micro-physical parameters are displayed in Fig. 4. In the case of Event 1 (6 February), the height profiles of the aerosol backscatter coefficient at the two lidar wavelengths shown in Fig. 4a indicate a dust load of moderate intensity with well separated dust layer at a

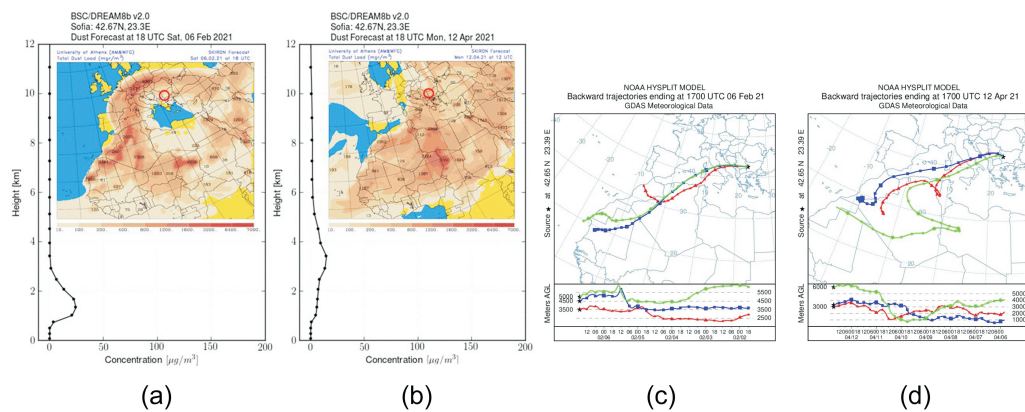


Fig. 3. BSC-DREAM8b model forecasts of the Saharan dust concentration profile above Sofia with regional SKIRON dust load maps (inset) for 6 February (a) and 12 April (b) 2021, respectively; HYSPLIT-backward trajectories ending above Sofia during the two measurements (c), (d)

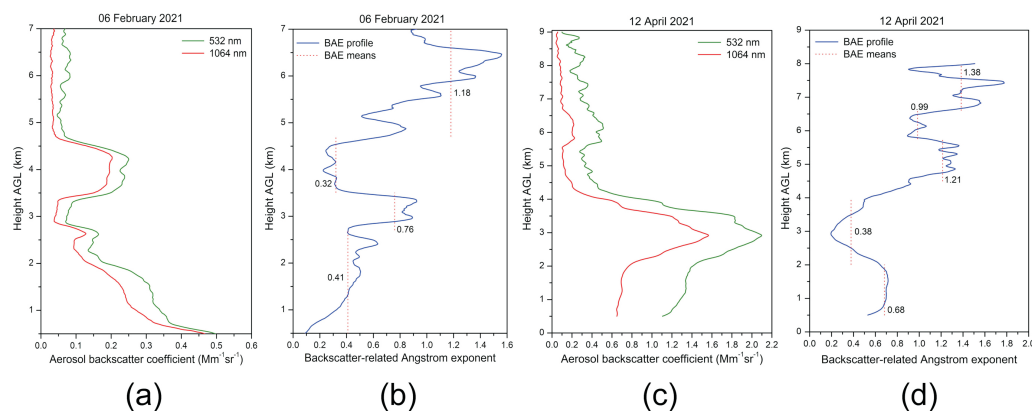


Fig. 4. Vertical profiles of the aerosol backscatter coefficient at the two laser wavelengths 532 nm and 1064 nm calculated from lidar data obtained on 6 February (a) and 12 April (c) 2021; The corresponding aerosol backscatter-related Ångström exponent derived from the lidar measurements (b), (d). Mean BAE values of characteristic profile parts are labelled and shown by dashed lines

height of about 4 km, in conformity with the dynamic lidar colourmaps in Fig. 2. In the detached layer, the BSC values at both lidar wavelengths are relatively low, about $0.2 \text{ Mm}^{-1} \text{sr}^{-1}$, corresponding to the very initial stage of the considered dust intrusion, as seen in Fig. 2a.

In the case of Event 2 (12 April), the vertical backscatter profiles displayed in Fig. 4c show much higher densities of the aerosol/dust layers, confined in the lower half of the troposphere, which is typical of dust intrusions over the Balkans, during the spring-summer season. They are peaked at the centre of the dense dust layer at heights of 2.5–3 km, just above the local ABL, reaching values of 1.5 and $2.1 \text{ Mm}^{-1} \text{sr}^{-1}$ for 1064 and 532 nm, respectively.

The weak aerosol layer in the height range 5.5–7 km, also visible in Fig. 2b, shows backscatter values of $0.2/0.5 \text{ Mm}^{-1} \text{sr}^{-1}$ for 1064/532 nm. Backward trajectories corresponding to this layer indicate the presence of mixed aerosols containing desert dust, mainly from the territory of Algeria (the green trajectory in Fig. 3d), together with extremely-long-range transported across the Atlantic aerosols from regions in the USA with active massive forest fires in the period preceding the measurements (corresponding trajectories not shown here).

Backscatter-related Ångström exponent profiles corresponding to Events 1 and 2 are presented in Fig. 4b and d, respectively. In the height zone of the local ABL (below 2 km), BAE in the two cases in question shows average values of 0.4 and 0.68, which are significantly below the typical values for the ABL, being normally of over 1. This is an indication of desert aerosol penetration into the ABL and mixing with the local ones, with dominance of the former. Differently, the BAE values in layers above the ABL (near 4 km in Fig. 4a and 3 km in Fig.

4b) are in the range 0.3–0.4, which are typical for Saharan dust particles in the size range around and above 1 μm . For the weak layer at 6 km in Fig. 4c, the BAE shows an average value of about 1. This is an indirect confirmation of the mixed composition of aerosols in this layer noted above, containing Saharan dust and fire smoke whose characteristic values are significantly above 1.

Conclusions. Lidar measurement carried out on 6 February 2021 (Event 1) presents a winter Saharan dust load over the whole of Europe, the frequency of which has been increasing in the last decade. The transport of dust is conditioned by a stable zone of high atmospheric pressure over the Central Mediterranean, determining a specific arcuate motion and distribution of the dust field over large surrounding areas. Registered dust layers are a result of a long-range transport from regions of Northwest Sahara, being in the initial stage. They are located both superimposed on the local atmospheric boundary layer and separately above it. Dynamic lidar maps and height profiles of the aerosol backscatter coefficient indicate an event of moderate, increasing intensity. Backscatter-related Ångström exponent profile show mixing of desert aerosols with those from the local ABL, with dominance of the former, as well as the presence of dust fractions with sizes well above a micron in the separated aloft dust layer.

Lidar measurement conducted on 12 April 2021 (Event 2) represents a spring Saharan dust load falling in the period of maximum dust transport activity over the Mediterranean and Europe. The origin of desert aerosols is from the north-western regions of the Sahara. The dust transport is direct, in the typical for the period northeastern direction. Dynamic lidar maps and height profiles of the aerosol backscatter coefficient show a dust layer of much higher density, mixed and superimposed with the local ABL, erasing its upper boundary. Backscatter-related Ångström exponent profile shows mixing of desert aerosols with those of the local ABL, with dominance of the former in the upper part of the mixed layer, with dust fractions in the over-micron size range. An aloft aerosol layer was also detected, identified as consisting of mixed Saharan dust and long-range trans-Atlantic-transported fire smoke.

The considered here dust load Events 1 and 2 have affected significantly both the structure and aerosol composition of the local troposphere. In the case of the wintertime Event 1, the local seasonal weather is also strongly influenced, manifested by significant increase in the air temperature and a reduction in relative humidity, as a result of the intrusion of warm and dry desert air masses into the cold local troposphere.

Acknowledgements. The authors would like to acknowledge data and images from the BSC/DREAM8b model operated by the Barcelona Supercomputing Center and from the SKIRON model operated by the University of Athens, the use of imagery from the NASA Worldview application (<https://worldview.earthdata.nasa.gov/>), part of the NASA Earth Observing System Data and Information System (EOSDIS), and the NOAA Air Resources Laboratory for the

provision of the HYSPLIT transport – and dispersion model and READY website used in this publication.

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