Characterization of an Aerosol Situation over Sofia, Bulgaria, Influenced by Wildfire Smoke from Canada Based on Lidar and Sun Photometer Measurements

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Abstract: The aerosol situation over Sofia, Bulgaria, on 3 October 2023 was investigated on the basis of lidar and ceilometer data on the atmospheric aerosol stratification, and of sun/sky/lunar photometer-measurement-based AERONET data on the aerosol optical and microphysical characteristics. Validation data were used as well from satellite observations of fire outbreaks around the world, air mass transport and dispersion models, desert-dust spread forecasting models, and weather information. The data obtained on the optical and microphysical aerosol properties, the extreme fire activity worldwide, and the long-range (mainly from Canada and less often from northern and central Africa) and shorter-range (mainly from Europe and Atlantic Ocean) backward trajectories, showed that the situation on 3 October 2023 was rather an aerosol event with prevailing content of aged and fresh biomass burning smoke, urban and continental aerosol, and possibly a lower content of marine aerosol and Saharan dust.

1. Introduction

The biomass-burning (BB) aerosol situations are consequences of long-range or short-range smoke transport from forest, grassland or bush fire active areas, smoldering combustion areas, or areas with wood and coal home heating. Because of its relatively high absorptivity of radiation, the smoke may significantly influence the exchange of solar and terrestrial radiative energy [1]. Moreover, it is a heavy air pollutant that can lead to fatal health problems [2]. It is to be noted as well that biomass burning releases into the atmosphere not only carbonaceous particles, but also greenhouse gasses causing unfavorable climate changes [2].

The fresh (minutes-to-hours old) smoke particles are characterized by dominating optical influence of the fine submicron aerosol fraction, a high aerosol optical depth $AOD_{440} > \sim 0.3$ at wavelength $\lambda = 440$ nm, a high Ångström exponent $AE_{440/870} > 1.5 - 1.7$ for the wavelength pair 440/870 nm, a high sphericity factor $SF > \sim 0.8 - 0.9$, and a low particle linear depolarization ratio $LDR_{440} \sim 0.002 - 0.005$ at $\lambda = 440$ nm [3–5]; the real n_r and imaginary n_i parts of the particle refractive index for λ from 440 nm to 1020 nm are $\sim 1.41 - 1.59$ and $0.0005 - 0.0256$, respectively [3,6,7]. In the cases of aged aerosols of this type, the $AE_{440/870}$ may fall down to values around unity [7]. The SF should then remain high with the LDR not exceeding several percent in the visible range (see below and [8,9]). However, some results were recently reported [8–10], indicating high LDRs, ~ 30 %, of Canadian aged BB aerosols over Europe at altitudes of 15 – 20 km. Note that some decrease of AE and SF may be caused as well by small amounts of desert dust or marine aerosol admixtures [5].

The aim of the present work was to study in more detail the peculiarities of the aerosol situation over Sofia, Bulgaria, on 3 October 2023 by using data characterizing the aerosol stratification and its optical and microphysical properties. The interest in this aerosol event was due to the extreme fire activity worldwide during 2023 [11], including the last decade of September and first decade of October, and to the fact that most of the long-range back trajectories of arriving air masses on that day originated from or passed over areas of powerful fire outbreaks in Canada.

2. Site, Instruments and Data

The experimental measurements were performed using a Raymetrics 8-channel depolarization Raman lidar LR332-D300 (3β-2α-2δ), a Lufft ceilometer CHM 15k „NIMBUS“, and a CE318-TS9 Cimel sun/sky/lunar photometer. The three devices are installed on the roof of the Institute of Electronics at the Bulgarian Academy of Sciences and are part of the instrumentation of the Sofia Aerosol Remote Sensing station (42.65° N, 23.39° E, 590 m ASL) that is contributing to EARLINET [12], AERONET [13,14], E-Profile [15], and ACTRIS [16]. The aerosol characteristics of interest are: AOD_{440}; $AE_{440/870}$; AODs of the fine and coarse aerosol fractions at $\lambda = 500$ nm (AOD_{f500} and AOD_{c500}, respectively); the particle single-scattering albedo (SSA), LDR_{440}, n_r and n_i; particle the volume size distribution (VSD) and the corresponding inflection radius R_i, effective radii (total, R_{effT}, of the fine fraction, R_{effF}, and of the coarse fraction, R_{effC}) and SF. Complementary data were also used on the fire outbreaks worldwide from the NASA’s FIRMS satellite system maps [17], on the back trajectories of the air masses arriving over Sofia from the NOAA’s model HYSPLIT [18], on the desert-dust spread from the predicting model SKIRON [19], and on the weather conditions from the Bulgarian National Institute of Meteorology and Hydrology [20].

3. Results and discussion

The lidar and ceilometer data reveal a multilayer aerosol stratification on 3 October 2023 and outline the daily evolution of several aerosol layers, including the planetary boundary layer (PBL), and layers at altitudes between 1850 – 1990 m AGL, 2200 – 2700 m AGL, and 4700 – 4900 m AGL descending with time as the lower one mixes with the PBL in the course of the day (Fig. 1(a,b)). The aerosol backscatter coefficient lidar profiles at wavelengths 355, 532 and 1064 nm in the time interval 07:13 – 08:15 UTC are represented in Fig. 1(c).

The column averaged and integrated AERONET data outline: a relatively high daily-mean $AOD_{440} = 0.28 \pm 0.03$; a moderate daily-mean $AE_{440/870} = 1.22 \pm 0.04$; daily-mean $AOD_{f500} = 0.23 \pm 0.02$ and $AOD_{c500} = 0.02 \pm 0.01$; comparable during the day fine and coarse fraction modes of the particle VSDs (Fig. 2(a)) with R_{effT}, R_{effF}, and R_{effC} of 0.28 – 0.56 µm, 0.14 – 0.24 µm and 2.52 – 3.34 µm, respectively, and R_i of 0.76 – 0.99 µm; and complicated increasing-decreasing behavior with λ of the SSA indicating a noticeable aerosol absorption of radiation (Fig. 2(b)). In 73 % of the daily measurements, the $LDR_{440} \sim 0.009 – 0.002$ corresponds to the high SF ~ 92 – 99%, and n_r and n_i for 440 nm ≤ λ ≤ 1020 nm vary between 1.4 and 1.6 and 0.004 and 0.02, respectively.

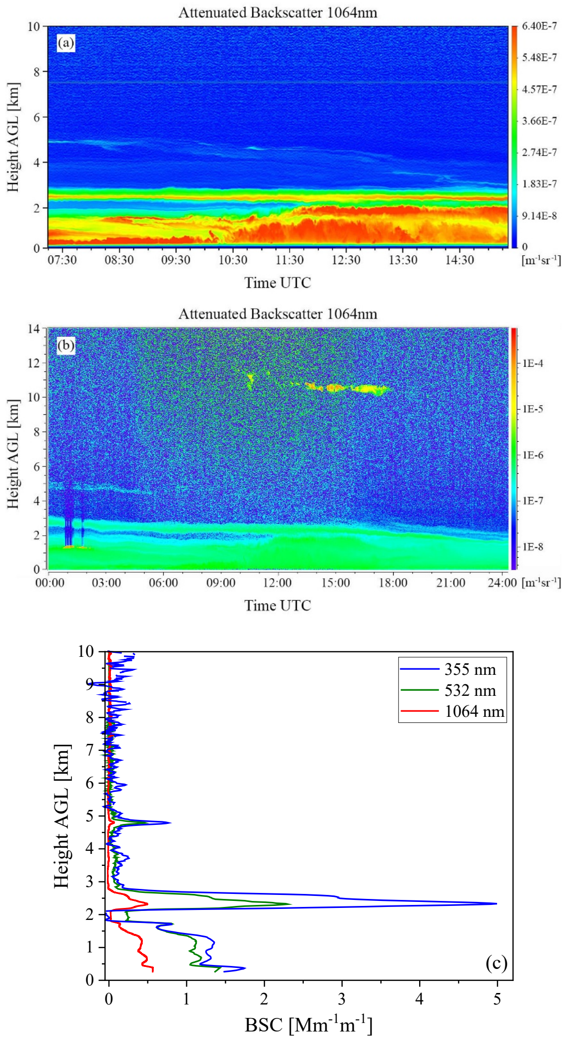

Figure 1. Time evolution of the attenuated backscatter coefficient vertical distribution measured by lidar (a) and ceilometer (b) at 1064 nm, and aerosol backscatter coefficient height profiles at 355, 532 and 1064 nm in the time interval 07:13 – 08:15 UTC (c) on 03 October 2023

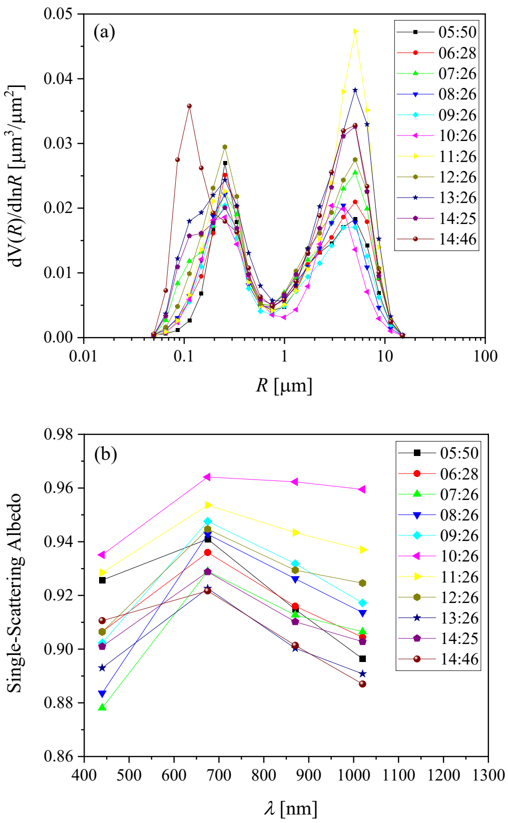

Figure 2. VSD (a) and SSA (b) obtained from sun photometer data on 03 October 2023

Very high fire activity during the period of concern was observed all over the world (Fig. 3), including Bulgaria and adjacent countries, Europe, North America (USA and Canada), South America, Equatorial and South Africa, etc.

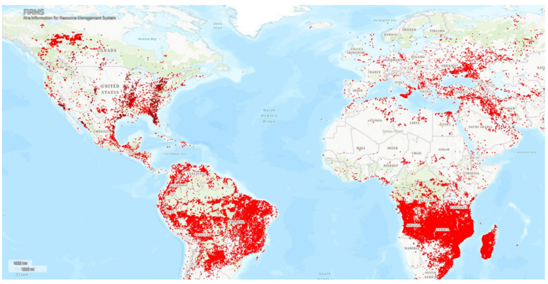

Figure 3. NASA's FIRMS worldwide fire map for the period 21–23 September 2023

The long-range (120 to 240 hrs) back trajectories of the air masses arriving over Sofia at different times and heights (including those of the observed aerosol layers) begin mainly from Canada, and less often (ending at altitudes about 7000 m) from arid North and fire-covered Equatorial Africa and pass over the Atlantic Ocean and all of Europe (Fig. 4). The shorter-range (24 and 48 hrs) back trajectories begin mainly from the Atlantic Ocean and closer and more distant European countries, and include North Africa only slightly. Some of the back trajectories passing over dust-loaded zones in Europe could entrain some amounts of dust particles [19].

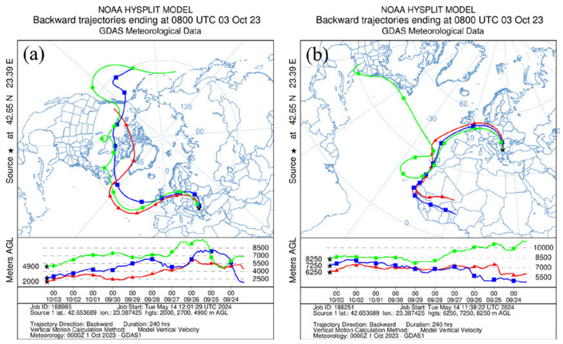

Figure 4. HYSPLIT model 240-h back trajectories of the air masses arriving over Sofia at 08:00 UTC at heights of 2000 m, 2700 m and 4900 m AGL (a) and at 6250 m, 7250 m, and 8250 m AGL (b) on 03 October 2023

The weather was fair with temperature of 7.3 – 21 °C, SSE wind with speed of 1 – 2 m/s, relative humidity of 27 – 96 %, and visibility of 15 – 25 km.

The above-listed optical and microphysical aerosol characteristics on 3 October 2023 are intrinsic in general to an aerosol situation with prevailing fresh and aged smoke particles accompanied by urban/industrial and continental aerosols [3–5,7]. The presence of some amounts of Saharan dust and marine aerosols is also possible. Such an aerosol picture over Sofia is also consistent with the HYSPLIT back trajectories of the air masses and the corresponding FIRMS fire maps and SKIRON predictions. In comparison with the cases of fresh BB aerosol, lowering $AE_{440/870}$ down to 1.22, increasing the effective and inflection radii of VSD and complicating the behavior of SSA with λ are usually due to the presence of aged smoke particles and, possibly, desert dust and sea salt particles [5,7].

4. Conclusion

Taking into account the optical and microphysical properties of the aerosol situation over Sofia on 3 October 2023, the intense fire activity worldwide, the dust transport over Europe and the back trajectories of the air masses arriving from Canada at heights corresponding to the layers observed by lidar and ceilometer, one may conclude that it was rather a biomass burning aerosol event with prevailing content of aged and fresh smoke along with urban/industrial and continental aerosols, and possibly some content of marine aerosols and Saharan dust.

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