Identification of Saharan-Dust Intrusions over Sofia, Bulgaria, Using Near-Ground PM\textsubscript{10} and PM\textsubscript{2.5} Mass Concentration Measurements

Tsvetina Evgenieva*, Elena Vakareeva, Ljuan Gurdev, Tanja Dreischuh

Institute of Electronics, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria

ABSTRACT

Intrusions of Saharan dust (SD) in the atmosphere over Sofia City, Bulgaria, are not a rare phenomenon. Since it can significantly affect the Earth’s radiative balance, various atmospheric processes, the climate and the living conditions on the land and in the ocean, as well as the air quality, it has been the subject of large-scale studies of considerable societal and scientific interest. In the present work, results were analyzed of: concurrent measurements of near-ground aerosol PM\textsubscript{10} and PM\textsubscript{2.5} mass concentrations and the aerosol’s optical and microphysical characteristics as obtained by an AERONET Cimel CE318–TS9 sun/sky/lunar photometer, the MONARCH Saharan-dust forecasting model and the HYSPLIT air-mass back-trajectory-recovering model. Data on the weather conditions in Sofia Valley and the fires in Bulgaria and neighboring countries were also considered. It was shown that the strong increases in the daily-mean PM\textsubscript{10} mass concentration (> 50 \(\mu\)g m\textsuperscript{-3} or > 70 \(\mu\)g m\textsuperscript{-3}) measured by a mountain ecological station are most frequently (74% and 86% of the cases, respectively) indications of relatively intense SD passages over the station. It was shown as well that during very intense Saharan dust intrusions over the region of Sofia (with dust load > 0.15–0.20 g m\textsuperscript{-2}), the urban PM\textsubscript{10} and PM\textsubscript{2.5} mass concentrations noticeably increased, while the PM\textsubscript{2.5}/PM\textsubscript{10} mass concentration ratio dropped down as a rule to values around 0.2 and below. The peculiarities found in the behavior of the particulate PM\textsubscript{10} and PM\textsubscript{2.5} mass concentrations contact-measured near the ground would allow one to recognize or confirm intense SD transport over Sofia and Sofia Valley.

Keywords: Atmospheric particulate matter (PM), Atmospheric aerosols, Saharan dust transport, In-situ PM measurements, Sun photometer measurements

1 INTRODUCTION

The atmospheric aerosol field, including desert dust, is known to significantly influence the Earth’s radiative balance through absorption and scattering of radiation (Chand et al., 2009; Patel et al., 2017; Boiyo et al., 2019; Kaskaoutis et al., 2019); various atmospheric phenomena, such as cloud formation and precipitation (Solomos et al., 2011); the climate and the living conditions on the land and in the ocean, including the soil formation and fertilizing due to settling, and phytoplankton blooming (Seinfeld and Pandis, 2016; Aleksandropoulou and Lazaridis, 2013; Kaskaoutis et al., 2019; Richon et al., 2018; Goudie and Middleton, 2001); and, of course, the air quality and its impact on human health (Seinfeld and Pandis, 2016; WHO, 2013; Milford et al., 2020; Salvador et al., 2022; Querol et al., 2019b). Therefore, it has been the subject of extensive and diverse research worldwide using various contact-probing and active and passive optical and microwave remote sensing approaches, as well as different ground-based, ship-, air-, and space-borne experimental facilities and investigatory networks (Schmid et al., 2003; Yin et al., 2019; Pappalardo et al., 2014; Holben et al., 1998; Sugimoto et al., 2018; Vaughan et al., 2009). The situations with dominating Saharan-dust (SD) aerosol load in the atmosphere (SD events) are usually characterized by a relatively high aerosol optical depth (AOD > 0.2–0.3), prevalent
Aerosol and Air Quality Research | https://aaqr.org 2 of 21 Volume 24 | Issue 6 | 230304

AOD and volume-size-distribution (VSD) mode of the coarse particle fraction, and relatively low Ångström exponent (AE < 1) (Dubovik et al., 2002; Evgenieva et al., 2022). Since such situations can cause serious deterioration of the air quality due to sedimentation and serious health risks (Seinfeld and Pandis, 2016; WHO, 2013; Milford et al., 2020; Salvador et al., 2022; Querol et al., 2019b), it is important that they be recognized timely in order to prevent or mitigate air pollution-related health problems.

The SD events have usually been recognized on the basis of results from active optical remote sensing of the aerosol stratification by lidars (Liu et al., 2008; Tesche et al., 2009; Mona et al., 2012; Peshev et al., 2022), or from passive optical remote determination of column-averaged or column-integrated aerosol characteristics, such as AOD and AE, by ground-based sun/sky/lunar photometers or space-borne spectroradiometers (Kaufman et al., 2005; Pérez et al., 2006; Evgenieva et al., 2022). The conclusions thus drawn about the occurrence of SD events have most frequently been validated by using dust-intrusion forecasting models and air-mass back-trajectory recovery models, such as the Barcelona Supercomputing Center’s Multiscale Online Nonhydrostatic Atmosphere Chemistry model (MONARCH) v2.0 (Klose et al., 2021) and the USA National Oceanic and Atmospheric Administration’s (NOAA’s) HYbrid Single-Particle Lagrangian Integrated Trajectory model (HYPLIT) (Stein et al., 2015; Rolph et al., 2017). Clarifying information is obtainable as well from meteorological and satellite data concerning the weather conditions and fire activity.

A reliable approach to confirming occurrences of SD intrusions is also the one based on measuring the PM$_{10}$ and PM$_{2.5}$ mass concentrations near the ground using contact ground-based automatic measurement stations (AMSs) for air-quality monitoring. In case of an intensive SD intrusion, the contact-measured near-ground PM$_{10}$ mass concentration should increase significantly (Pederzoli et al., 2010; Aleksandropoulou and Lazaridis, 2013; Kaskaoutis et al., 2019; Milford et al., 2020; Çapraz and Deniz, 2021; Yang et al., 2021; Salvador et al., 2022; Gomes et al., 2022) due to sedimentation of the dust particulate matter, which contains mainly a coarse particle fraction (Kaskaoutis et al., 2019; Çapraz and Deniz, 2021; Yang et al., 2021; Salvador et al., 2022). Certainly, the PM$_{2.5}$ mass concentration should also increase, but to a lower extent because of the lower PM$_{2.5}$ content and settling rate (Milford et al., 2020; Çapraz and Deniz, 2021). Then, the PM$_{2.5}$/PM$_{10}$ mass concentration ratio, $\mathcal{R}$, should drop considerably because of the relatively reduced content of fine particles (Kaskaoutis et al., 2019; Yang et al., 2021). For instance, it has been found that under conditions of intense SD storms over the region of Athens, this ratio falls down to values of around 0.20–0.25, which are substantially smaller compared to those obtained in the absence of dust intrusions (Kaskaoutis et al., 2019). A similar situation was described in Yang et al. (2021), where during a severe desert dust storm in Northwest China, the ratio $\mathcal{R}$ dropped to minimum values of about 0.12–0.18 at the height of the storm.

Thus, one may expect that relatively deep declines in $\mathcal{R}$ should be one of the features and indicators of intense SD intrusions over Sofia. Therefore, one purpose of this work is to investigate the behavior of the ratio $\mathcal{R}$ depending on the intrusion intensity characterized by the dust load in the atmosphere.

The mountain AMSs are usually located outside and high above populated areas and measure the PM$_{10}$ and/or PM$_{2.5}$ mass concentrations of the natural aerosol particle background. Major increases of the PM$_{10}$ mass concentration measured in this case during the summer may be caused mainly by strong wildfire activity, adding mostly to the fine aerosol fraction (Evgenieva et al., 2022); mountain-valley wind circulations (Kolev et al., 2000), adding to both the fine and coarse aerosol fractions, and Saharan dust and marine aerosol (MA) intrusions, adding mostly to the coarse aerosol fraction (Evgenieva et al., 2022). Other factors that could also influence the PM$_{10}$ mass concentration are the planetary boundary layer (PBL) development and aerosol-capping temperature inversions (Kolev et al., 2000). During the winter, the ground is moist and the wind circulation cannot contribute appreciably to the measured PM$_{10}$ mass concentration. Also, the maximum achievable height of the PBL is lower compared to that in summer and warmer months (Evgenieva et al., 2008, 2009; Danchovski, 2019; Kirova et al., 2022). However, smoke of occasional wildfires and of fuel combustion, and Saharan-dust outbreaks may contribute to the fine and coarse aerosol fractions, respectively, and increase the PM$_{10}$ mass concentrations. Nevertheless, especially in the winter, one should expect that the SD events are the most probable factor for
increasing the PM$_{10}$ mass concentration (Koçak et al., 2007; Querol et al., 2009; Pey et al., 2013; Querol et al., 2019a; Buchunde et al., 2019; Clemente et al., 2023).

Since it is convenient to identify the occurrence of SD intrusions by only tracking the changes in the PM$_{10}$ mass concentration as measured by mountain AMSs, another purpose of this work is to study the behavior of this concentration during SD events and estimate the relative occurrence of its SD-due strong rises – above 30, 40, 50, 60, 70, and 80 $\mu$g m$^{-3}$. The relative occurrence is in fact the probability of predicting an SD event. A related additional objective arising at this point is to trace graphically the co-evolution of the PM$_{10}$ mass concentration measured in the mountain and the PM$_{10}$ and PM$_{2.5}$ mass concentrations measured in the city. In this way, one could estimate to what extent the natural-aerosol dynamics influences the dynamics of the aerosol situation in the city.

In the following Sect. 2, we briefly describe the research approach, the experimental facilities employed and their locations, the models employed, and the set of aerosol characteristics underlying the analyses performed. In Sect. 3, the results on the evolution of the PM$_{10}$ mass concentration measured at a mountain AMS and the corresponding Saharan dust load are described and discussed. Some specific aerosol events of interest are additionally characterized on the basis of their optical and microphysical properties, the fire situation in Bulgaria and the adjacent countries, the weather conditions, and the back trajectories of the air masses arriving over Sofia. Then, an analysis is performed of the co-evolution of the PM$_{10}$ mass concentration measured at a mountain AMS, the PM$_{10}$ and PM$_{2.5}$ mass concentrations measured at an urban AMS, the ratio $R$, and the Saharan dust load predicted for the Sofia region. The main results obtained and conclusions drawn in the work are briefly summarized in the final Sect. 4.

2 RESEARCH APPROACH, MEANS AND SITES

The investigations performed in this work concern the region of Sofia City, the capital and largest city of Bulgaria, with a population of 1 280 334 inhabitants as of 31 December 2022 (NSI, 2023). It is situated in a vast mountain valley in the western part of Bulgaria, the Sofia Valley, which is surrounded by several mountains, among them the Vitosha Mountain on the south and the Balkan Mountains on the north (Fig. 1).

The approach followed in the work consists in studying the interrelated behavior of the results from ground-based contact measurements of the PM$_{10}$ and PM$_{2.5}$ mass concentrations, from the MONARCH dust-intrusion forecasting model and the HYSPLIT air-mass back-trajectory-recovering model, and from the remote-sensing-based determination of aerosol optical and microphysical characteristics using a Cimel CE318–TS9 sun/sky/lunar photometer (CIMEL, 2023), the latter contributing to the NASA’s AERosol ROBotic NETwork (AERONET). Additional clarifying information was used as well on the weather conditions and the fires in Bulgaria and neighbouring countries. The meteorological data used in the paper are provided by the Sofia Central Meteorological Observatory (WMO Station 15614; 42.66°N, 23.38°E, 586 m ASL) at the Bulgarian National Institute of Meteorology and Hydrology (NIMH) and are accessible at Weather Data (2023). The fire information is provided by the NASA’s Fire Information for Resource Management System (FIRMS) (Earthdata, 2023), part of NASA’s Earth Observing System Data and Information System (EOSDIS), based on satellite observation from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua and Terra satellites, and the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the Suomi NPP and NOAA 20 satellites.

Remote sensing of the atmosphere is carried out by the Aerosol Remote Sensing (ARS) Station at the Institute of Electronics of the Bulgarian Academy of Sciences (Peshev et al., 2022; Evgenieva et al., 2022; Peshev et al., 2023). The Station is located in the southeast part of Sofia City (42.65°N, 23.39°E, 590 m ASL). It is involved in the activities of AERONET (Holben et al., 1998), the European Aerosol Research Lidar Network (EARLINET) (Pappalardo et al., 2014), and the Aerosol, Clouds and Trace Gasses Research Infrastructure (ACTRIS) (ACTRIS, 2023). The ARS Station is about 300 m away (Fig. 1) from the WMO Station 15614.

Data of two ground-based contact ecological AMSs for air-quality control were analysed. The first station (BG0070A), Kopitoto, is located on Vitosha Mountain (42.64°N, 23.24°E, 1321 m ASL,
Fig. 1. Map of Sofia Region (Google Maps image), where the locations are shown of Sofia ARS Station and WMO Station 15614 (blue and red asterisks, respectively) and Kopitoto and Hipodruma AMSs (orange and yellow triangles, respectively).

about 750 m above Sofia City, Fig. 1) and is considered as an elevated rural station for measuring the aerosol background as unaffected directly by anthropogenic aerosols. It provides data on PM₁₀ mass concentrations only. The excessive results measured at AMS Kopitoto are thought to be most frequently due to Saharan dust intrusions (Escudero et al., 2007; Aleksandropoulou and Lazaridis, 2013; Pey et al., 2013). The second station (BG0050A), Hipodruma, is located within the city (42.68°N, 23.30°E, 581 m ASL, Fig. 1), within an urban environment, and measures both PM₁₀ and PM₂.₅ mass concentrations. Both AMSs are part of the Bulgarian National Automated System for Environmental Monitoring at the Ministry of Environment and Waters, operated by the ministry’s Executive Environmental Agency (ExEA, 2023). The PM mass concentration data used here are available at https://www.eea.government.bg/kav/ (last accessed: 31 July 2023).

At both locations, the PM mass concentration measurements are performed by the following instruments: Thermo Scientific™ Model 5030 SHARP Synchronized Hybrid Ambient Real-time Particulate Monitor based on light scattering photometry and beta attenuation approaches, and TCR Tecora SENTINEL PM Sequential Module for Dust Sampling combined with the atmospheric sampler Charlie, based on a gravimetric approach; the measurement accuracy is ~5%.

The HYSPLIT and MONARCH models allowed us to obtain information about, respectively, the backward trajectories of the air masses arriving over Sofia at different altitudes and different times (in particular, at 12:00 UTC), and the occurrence and intensity of Saharan dust intrusions...
over the city. The intrusion intensity can be characterized through the dust load (DL, g m\(^{-2}\)) provided by the model MONARCH. The daily-mean DL considered below was determined by averaging eight three-hour-interval sampled data. Identification of SD situations was performed as well using a set of aerosol characteristics, namely, the aerosol optical depth at wavelength \(\lambda = 440\) nm (AOD\(_{440}\)), the total AOD and those of the fine and coarse aerosol fractions at wavelength \(\lambda = 500\) nm (AOD\(_{500}\) and AOD\(_{500}\), respectively), the Ångström exponent for the wavelength pair 440/870 nm (AE\(_{440/870}\)), as well as the particle VSD, single-scattering albedo (SSA), sphericity factor (SF) and linear depolarization ratio (LDR). These characteristics were estimated by AERONET (Version 3 Level 1.5 products) on the basis of measurement data from the Cimel CE318–TS9 sun/sky/lunar photometer [CIMEL, 2023] of the above-mentioned Sofia ARS Station (AERONET, 2023). The photometer is installed on the roof of the Institute of Electronics’ building at about 20 m above ground. It is automatically operating according to pre-defined scenarios and is annually calibrated following the AERONET protocols at AERONET-EUROPE operating within the ACTRIS Centre for Aerosol Remote Sensing at Laboratoire d’Optique Atmosphérique, Université de Lille, France (CARS-ASP-CNRS) (Evgenieva et al., 2022; Peshev et al., 2023). A more detailed description of the photometer operation and of the AERONET capabilities are given, e.g., in Holben et al. (1998), Barreto et al. (2016), Giles et al. (2019), and Sinyuk et al. (2020).

3 RESULTS AND DISCUSSION

Let us first track (Figs. 2(a) and 2(b), respectively) the evolution of the daily-mean and hourly-mean PM\(_{10}\) mass concentrations measured by AMS Kopitoto during the period from 2018 to 2022 (1826 days). The number of days with missing daily-mean data during this period is 125, i.e., 6.85%, and the annual mean PM\(_{10}\) mass concentrations vary from ~12 to ~17 µg m\(^{-3}\) (Table 1). The missing data are a consequence of absent data during a day or of rejected low-accuracy estimates of the daily-mean mass concentration, based on a too small number of hourly data available. Note that Table 1 contains also data on PM\(_{10}\) and PM\(_{2.5}\) and their ratio \(\mathcal{R}\) obtained from AMS Hipodruma. Because of the large number of missing data on PM\(_{2.5}\) mass concentrations from AMS Hipodruma for the years 2018, 2019, and 2020, the corresponding low-accuracy estimates of the annual-mean PM\(_{2.5}\) mass concentrations and ratios \(\mathcal{R}\) are not presented.

![Image](https://example.com/image1.png)

**Fig. 2.** Evolution of the (a) daily-mean and (b) hourly-mean PM\(_{10}\) mass concentrations measured by AMS Kopitoto during the period from 2018 to 2022.
relatively rare (120 cases of 1701 days with data available, 7%) and is frequently due to the presence of Saharan dust over Sofia (100 cases of 112, that is, ~89%), according to the model MONARCH forecast. Note that there are no MONARCH-predicted DL data for 8 of the 120 days mentioned above. The number of days with DL ≥ 0.05 g m⁻² is 68, that is, ~61% of all the 112 sample days. Thus, one may expect that when the daily-mean PM₁₀ mass concentration measured exceeds 30 µg m⁻³, the probability of this being due to SD transport over Sofia is ~89%, while that of a more intense SD transport is ~61%.

Further, the data on the daily-mean PM₁₀ mass concentrations exceeding 40 µg m⁻³ and the corresponding dates and DLs are given in Table 2. It is seen that of all 48 cases of measured PM₁₀ concentrations above 40 µg m⁻³ and available MONARCH DL data, 44 (92%) are accompanied by SD intrusions. The number of intrusions with DL ≥ 0.05 g m⁻² is 32, or ~67% of all 48 sampling days (Table 2). Thus, in this case, the predictabilities of any dust intrusions and of more intense dust intrusions are 92% and 67%, respectively.

The exceedances found over the DLV of 50 µg m⁻³ in cases of available MONARCH-derived DL values are 27, of which 25 (~93%) are accompanied by any SD intrusions, and 20 (~74%) are with DL ≥ 0.05 g m⁻² (see Table 2). In this case, the predictabilities of any SD intrusions and of more intense SD intrusions are 93% and 74%, respectively. Similarly, the number of days with mean PM₂₅ mass concentration above 60 µg m⁻³ is 15, of which (87%) with any SD present, and 10 (67%) with DL > 0.05 g m⁻² (Table 2). Thus, the predictabilities of any SD intrusions and of more intensive ones seem to decrease with respect to the preceding case to 87% and 67%.

### Table 1. Annual-mean PM₁₀ and PM₂₅ mass concentrations measured by AMSs Kopitoto and Hipodruma, and annual-mean PM₂₅/PM₁₀ mass concentration ratios R estimated from Hipodruma AMS’ data, from 2018 to 2022.

<table>
<thead>
<tr>
<th>Year</th>
<th>PM₁₀ (µg m⁻³) AMS Kopitoto</th>
<th>Days of no daily mean data available</th>
<th>PM₁₀ (µg m⁻³) AMS Hipodruma</th>
<th>PM₂₅ (µg m⁻³) AMS Hipodruma</th>
<th>R</th>
<th>Days of no daily mean data available</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>17.04 ± 12.49</td>
<td>17</td>
<td>39.15 ± 47.91</td>
<td>–</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>2019</td>
<td>13.96 ± 10.67</td>
<td>26</td>
<td>32.08 ± 31.16</td>
<td>–</td>
<td>–</td>
<td>8</td>
</tr>
<tr>
<td>2020</td>
<td>12.50 ± 12.93</td>
<td>45</td>
<td>30.71 ± 28.73</td>
<td>–</td>
<td>–</td>
<td>10</td>
</tr>
<tr>
<td>2021</td>
<td>13.16 ± 10.97</td>
<td>18</td>
<td>26.36 ± 19.30</td>
<td>8.91 ± 6.57</td>
<td>0.34 ± 0.38</td>
<td>10</td>
</tr>
<tr>
<td>2022</td>
<td>14.54 ± 11.61</td>
<td>19</td>
<td>31.51 ± 25.73</td>
<td>10.33 ± 9.47</td>
<td>0.33 ± 0.41</td>
<td>6</td>
</tr>
</tbody>
</table>

### Table 2. Days with mean PM₁₀ mass concentrations above 40 µg m⁻³ measured by AMS Kopitoto and the corresponding mean DLs.

<table>
<thead>
<tr>
<th>Date</th>
<th>PM₁₀ (µg m⁻³) AMS Kopitoto</th>
<th>Dust Load (g m⁻²)</th>
<th>Date</th>
<th>PM₁₀ (µg m⁻³) AMS Kopitoto</th>
<th>Dust Load (g m⁻²)</th>
<th>Date</th>
<th>PM₁₀ (µg m⁻³) AMS Kopitoto</th>
<th>Dust Load (g m⁻²)</th>
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<td>26.02.2018</td>
<td>57.01</td>
<td>0.02</td>
<td>30.03.2020</td>
<td>44.99</td>
<td>0.15</td>
<td>31.07.2021</td>
<td>45.70</td>
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<td>88.54</td>
<td>0.26</td>
<td>14.05.2020</td>
<td>94.11</td>
<td>0.92</td>
<td>02.08.2021</td>
<td>51.63</td>
<td>0.33</td>
</tr>
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<td>0.70</td>
<td>15.05.2020</td>
<td>111.18</td>
<td>1.20</td>
<td>05.08.2021</td>
<td>66.61</td>
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<td>0.58</td>
<td>16.05.2020</td>
<td>58.21</td>
<td>0.83</td>
<td>31.03.2022</td>
<td>41.56</td>
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<td>0.25</td>
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<td>29.07.2021</td>
<td>51.73</td>
<td>–</td>
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<td>29.03.2020</td>
<td>62.33</td>
<td>0.32</td>
<td>30.07.2021</td>
<td>55.23</td>
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<td>09.12.2022</td>
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<td>0.03</td>
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respectively. Such a departure from the trend of increasing the probability of identifying Saharan dust transport is due to a relative decrease in the volume of statistical data.

Further, the number of days with mean PM$_{10}$ concentrations above 70 µg m$^{-3}$ or 80 µg m$^{-3}$ is seven, with no days without SD and only one day with DL $< 0.05$ g m$^{-2}$ (Table 2). In this case, one may expect with 100% probability that all intrusions are SD ones. The probability of a more intense SD transport (with DL $\geq 0.05$ g m$^{-2}$) is 86%. As a whole, one may conclude that the exceedances of the daily-mean PM$_{10}$ mass concentration above the DLV of 50 µg m$^{-3}$ include any type of SD intrusions with a 93% probability, and more intense SD intrusions, with a 74% probability. At higher concentration values, say above 70 µg m$^{-3}$, the corresponding probabilities are 100% and 86%.

A significant increase in the measured PM$_{10}$ mass concentration in the absence of, or with a tiny content of Saharan dust in the atmosphere may be due mainly to an increased content of smoke from biomass burning (BB) in forest and field fires and from wood and coal heating accompanied by continental and marine aerosol passages. As it seems, such are 11 of the 16 cases (Table 2) of concentrations above 40 µg m$^{-3}$ and DL below 0.05 g m$^{-2}$. These 11 cases, having taken place on 26 February, 19 and 20 October and 10 November 2018, 29 and 30 October 2019, 17 August, 26 and 28 September and 8 and 16 October 2022 (Table 2), are seemingly related to strong fire activity around Sofia and/or an intense heating campaign in the city during the cold months. The corresponding values of $\cal R$ measured by AMS Hipodruma (see below) are relatively high ($\sim$0.4–0.8), exceeding the annual means for 2021 (0.34) and 2022 (0.33) and for the period 2021–2022 (0.33) (Table 1), which is an indication of a relatively high content of fine-fraction aerosol particles. Most of the HYSPLIT-derived back trajectories of the air masses arriving over Sofia at different heights (AGL) do not pass over Africa or include very short sections passing over North Africa. The only exceptions are the trajectories arriving at heights of 5000 m on 29 October 2019 and 4000 m and 5000 m on 30 October 2019 that have longer initial sections over Africa (Algeria and Libya). The SD mass concentrations at such heights were probably low, with their sedimentation being slow (Escudero et al., 2007), which led to low DL and small contribution to the near-ground PM$_{10}$ mass concentration. Note as well that the trajectory arriving on 28 October 2019 at 1500 m height has an initial section passing over Algeria, Tunisia and Libya. The possible SD transport at this height on 28 October might have enlarged to some extent the PM$_{10}$ mass concentration measured on 29 and 30 October via sedimentation. The available AERONET data on the aerosol properties are characterized by a prevalent optical influence (higher AOD) of the fine particle fraction, a relatively high AE$_{440/870}$ ($\sim$1.3–1.4, Evgenieva et al., 2022), a dominant VSD peak of the fine particle fraction, a wavelength-decreasing SSA, a particle high SF ($\sim$90–100%) and a low LDR ($\sim$0.001–0.005). The specifics of one of these aerosol events, which took place on 17 August 2022, with all the data needed for the analysis available, are illustrated in Fig. 3. Thus, in Fig. 3(a) (three-day FIRMS fire map) one can see a few outbreaks of fires around Sofia City. Dense fire outbreaks are also seen in Kosovo and Serbia to the west and northwest of Sofia, respectively. The HYSPLIT-provided 120-hour back trajectories of the air masses arriving over Sofia at heights of 500 m, 1500 m, and 2000 m (Fig. 3(b)) do not pass over Africa.

Such are, in general, the back trajectories of the air masses arriving over Sofia at heights of 3000 m, 4000 m, and 5000 m (Fig. 3(c)) with the exception of the trajectory at 3000 m that includes a very short section over Morocco. Note, however, that the trajectories arriving at heights of 4000 m and 5000 m have sections over the Atlantic Ocean, while those arriving at heights of 1500 m to 3000 m have traveled a long way over the Mediterranean Sea and Italy through a relatively dense SD layer. Therefore, one may expect that the corresponding air masses have been enriched with marine and some amounts of SD aerosols capable of influencing the daily aerosol evolution. In Figs. 3(d) and 3(e), it is seen, respectively, that the VSD peak of the fine particle fraction is strongly dominant, while in the wavelength interval between 440 nm and 1020 nm the SSA is alternately decreasing with $\lambda$ (BB aerosols, Dubovik et al., 2002) or having a maximum around $\lambda = 675$ nm (mixed aerosols, Evgenieva et al., 2022). The particle SF and LDR vary on this day from 6.55% to 99% (as almost half of the measured values are above 96%) and from 0.002 to 0.115, respectively. The other daily-mean characteristic parameters of importance are AOD$_{440}$ = 0.22, AOD$_{500}$ = 0.17, AOD$_{650}$ = 0.14, AOD$_{870}$ = 0.03, and AE$_{440/870}$ = 1.71; the mean PM$_{10}$ mass concentration at AMS Kopitoto is 66.39 µg m$^{-3}$, the mean DL = 0.03 g m$^{-2}$ (Table 2), and the ratio $\cal R = 0.47$. The weather conditions were fair, with a temperature of about 30°C, wind speed of
1–3 m s⁻¹ with a predominant W-NW direction, a relative humidity from 40% to 87% and a horizontal visibility of 18–20 km. So, the above-described impacts on and characteristics of the aerosol situation over Sofia on 17 August 2022 outline a BB aerosol event as a whole (Dubovik et al., 2002; Evgenieva et al., 2022). The alternately varying SSA shape and changeable SF during the day are indications of marine aerosol passages that have occurred periodically over Sofia Valley and Sofia ARS Station. Another reason for the measured PM₃₀ mass concentration increasing without a significant presence of SD is the increased content of mixed aerosols (Evgenieva et al., 2022) in the atmosphere. This reason underlies the remaining five (of the above 16) cases that took place on 25 and 26 February 2021, and 17 and 18 November and 9 December 2022. The mixed aerosol ensembles may consist of BB aerosols and/or continental aerosols (CA), including some amounts of SD and/or MA capable of influencing to some extent the ensemble characteristics. Mixed aerosols may also arise in the absence of fire activity around Sofia and contain CA and heating-due smoke as aerosol components rich in fine-fraction particles. The aerosol components (SD, MA) rich in coarse-fraction particles lead to some increase of AOD₅₅₀, a decrease of AE₄₄₀/₈₇₀ (below 1.40, Evgenieva et al., 2022), a domination of the VSD coarse-particle mode, a complicated dependence of SSA on λ, a decrease of the SF and an increase of the LDR of the particles. Some of the air masses arriving over Sofia in this case may have passed over North Africa, the Mediterranean Sea or the Atlantic Ocean. The available data from AMS Hipodruma on the ratio  \( \frac{\text{AOD}_{\lambda}}{\text{AOD}_{\lambda}} \) on these days
are \(-0.24 \sim 0.26\), which indicates some increase of the coarse-particle fraction. Let us consider, for instance, the characteristics of the aerosol situation that occurred on 26 February 2021, when nearly all data necessary for the analysis were available. In Fig. 4(a) (three-day FIRMS’ fire map), one can see numerous fires around Sofia. From the HYSPLIT-provided 120-hour back trajectories of the air masses arriving over Sofia at heights of 500 m, 1500 m, and 2000 m (Fig. 4(c)), only the one arriving at 1500 m has a short section over Morocco and Algeria. At the same time, all these trajectories pass over zones in western and central Europe with high DL as predicted by MONARCH, so that these air masses might have entrained some amounts of Saharan dust. The air masses arriving at the heights of 2000 m to 5000 m have not passed over Africa, but have traveled as a whole a long way over the Atlantic Ocean (Figs. 4(b) and 4(c)) and are expected to be enriched with marine aerosols. It is also worth noting here that the trajectories of the air masses arriving at heights of 2000 m to 5000 m over Sofia on 24 February 2021 pass over immense territories in Africa, entirely crossing Algeria. Therefore, one may suppose that the sedimentation of the desert dust these air masses brought on this date had also some contribution to the increase of the PM\(_{10}\) mass concentration measured by AMS Kopitoto on 25 and 26 February 2021. The VSD fine- and coarse-particle fraction mode peaks seen in Fig. 4(d) show the domination as a whole of the coarse-particle fraction modes. The dependence of SSA on \(\lambda\) is complicated (Fig. 4(e)), first increasing, at shorter wavelengths, and then decreasing, at longer wavelengths, as a result of the competition.

![Fig. 4. Three-day FIRMS’ fire map (a); HYSPLIT-provided 120-hour back trajectories of the air masses arriving over Sofia at 12:00 UTC, at (b) heights of 500 m, 1500 m, and 2000 m and (c) heights of 3000 m, 4000 m, and 5000 m; and (d) VSD and (e) SSA daily evolutions, on 26 February 2021.](image-url)
between the small and large particle absorption and scattering. The variation intervals of the particle SF and LDR during the day are, respectively, 0.64–92.34% and 0.0091–0.1113. The other important daily-mean characteristic parameters are AOD_{440} = 0.16, AOD_{500} = 0.13, AOD_{800} = 0.069, AOD_{1000} = 0.066, and AE_{440}/AE_{870} = 0.89. The mean PM_{10} mass concentration and DL at AMS Kopitoto are 46.63 µg m\(^{-3}\) and 0.02 g m\(^{-2}\) (Table 2), respectively; no data are available from AMS Hipodruma on PM_{2.5} and, correspondingly, \(\mathcal{R}\) on this day.

The meteorological conditions were as follows: a temperature of about 18°C, a wind speed of 1–2 m s\(^{-1}\) with a predominant SE direction, a relative humidity from 43 to 81% and a horizontal visibility of 20–28 km. The above-discussed characteristic parameters and environmental conditions concerning the aerosol field over Sofia on 26 February 2021 reveal a mixed aerosol situation with MA and SD making up the coarse-particle-rich aerosol component. Let us note that 25 and 26 February 2021 were days of a dust flow drop in the middle of a period of a massive transport to Europe of Saharan dust (Hoshyaripour, 2021; Szczepanik et al., 2022; Peshev et al., 2023), whose influence on the aerosol situation and especially on the concentration of PM_{10} through sedimentation was noticeable.

As mentioned in Sect. 1, another, complementary, approach to identifying SD events over Sofia is based on investigating the behavior of the daily-mean PM_{2.5} and PM_{10} mass concentrations (measured by AMS Hipodruma) and their ratio \(\mathcal{R}\). Such behavior, along with the evolution of the corresponding DL and PM_{10} mass concentration measured by AMS Kopitoto, is represented graphically in Figs. 5(a–d) concerning, respectively, the spring period from 28 March to 28 April 2022, the summer period from 25 July to 25 August 2021, the autumn period from 25 September to 25 October 2021, and the winter period from 25 January to 25 February 2022. To avoid cluttering the figures, the standard deviations of the PM mass concentrations, DL and \(\mathcal{R}\) are not represented there. The relative PM-concentration standard deviations (standard deviations normalized to their means) vary mainly from \(\sim 10\%\) to \(30–50\%\). The relative standard deviations of DL and \(\mathcal{R}\) vary mainly from \(-45\%\) to \(100–120\%\) and from \(-20\%\) to \(30\%\), respectively. An overview of the figures reveals generally synchronous variations of both PM_{10} mass concentrations (measured by AMSs Kopitoto and Hipodruma) and the PM_{2.5} mass concentration measured by AMS Hipodruma. Such synchronicity is evidence of a strong influence of the dynamics of natural aerosols on the dynamics of the overall aerosol situation in Sofia. According to our preliminary estimates for the period 28 March–28 April 2022, the values of the correlation coefficients between the fluctuations of the daily-mean mass concentrations of PM_{10} measured by AMSs Kopitoto and Hipodruma, PM_{2.5} and PM_{2.5} measured by AMSs Kopitoto and Hipodruma, and PM_{10} and PM_{2.5} measured by AMS Hipodruma are 0.99, 0.61, and 0.76, respectively. That is, the natural aerosols would influence mostly the PM_{10}, and to a lower extent the PM_{2.5} fraction that originates mainly from local sources (Koçak et al., 2007; Querol et al., 2019a, 2019b; Buchunde et al., 2019; Fan et al., 2021).

It is also seen in Fig. 5 that the PM_{10} mass concentration measured by AMS Hipodruma almost always exceeds that measured by AMS Kopitoto, which is due to numerous local urban aerosol sources. In Fig. 5(a) one may notice five peaks of the PM_{10} mass concentration measured by AMS Kopitoto, and corresponding peaks and maxima that are practically coincident in time, respectively, of the PM_{10} and PM_{2.5} mass concentrations measured by AMS Hipodruma. The PM_{10} peak values measured by both AMSs, Kopitoto and Hipodruma, are around and above 20–30 µg m\(^{-3}\) with only one exceedance of the European DLV on 1 April 2022. The PM_{2.5} maximum values are all below 10 µg m\(^{-3}\). All the mass concentration peaks and maxima are accompanied by almost simultaneous (two of them with \(\pm\) one day shift) peaks of DL with values from 0.15–0.20 to 1.01 g m\(^{-2}\), and declines in \(\mathcal{R}\) with depths around 0.10 and below at a mean value of \(-0.13\) for the period. The deepest decline in \(\mathcal{R}\) \(-0.05\) corresponds to the DL exceedance peak on 1 April 2022. The FIRMS’ fire images show a moderate fire activity in Bulgaria and a low one in the regions near Bulgaria. As a whole, one may conclude that during the period from 28 March to 28 April 2022, the air quality over Sofia was satisfactory with several peaks (only one above the DLV) of the PM_{10} mass concentration and corresponding declines in \(\mathcal{R}\) due mainly to desert (Saharan) dust intrusions. Thus, the peaks of the PM_{10} mass concentration and the declines in \(\mathcal{R}\) may indeed be considered as an indication of intense SD transport over the city. It would be interesting to compare the behavior of the PM_{10} and PM_{2.5} mass concentrations and their ratio \(\mathcal{R}\) observed here with the springtime behavior of the same quantities in other geographic areas south of Bulgaria and closer
to Sahara. Such an area is the basin of Athens (37.98°N, 23.73°E), at about 900 km from Sahara, while the city of Sofia is situated at about 1500 km from Sahara. In March 2018, under the conditions of intense Saharan-dust intrusions over Athens, the peak values of the varying-synchronously daily-mean PM$_{10}$ and PM$_{2.5}$ mass concentrations there rose up to 300 µg m$^{-3}$ and 65 µg m$^{-3}$, respectively, many times above the values obtainable in Sofia (Fig. 5(a)); the corresponding declines in $\mathcal{R}$ had depths of 0.20–0.25 at a monthly-mean $\mathcal{R}$ of 0.38–0.58 (Kaskaoutis et al., 2019). In April 2022, however, the declines in $\mathcal{R}$ during dust events in Sofia were deeper (with depths ~0.1 and below, Fig. 5(a)) than those in Athens despite the weaker SD effect. This means that the values of $\mathcal{R}$ depend not only on the intensity of the dust intrusion, but also on the

**Fig. 5.** Evolution of the daily-mean PM$_{10}$ mass concentrations measured by AMS Kopitoto, along with the corresponding daily-mean DLs, and daily-mean PM$_{10}$ and PM$_{2.5}$ mass concentrations and ratios $\mathcal{R}$ determined by AMS Hipodruma, during the periods (a) 28 March–28 April 2022, (b) 25 July–25 August 2021, (c) 25 September–25 October 2021, and (d) 25 January–25 February 2022.
accompanying fine-fraction particles and, especially, on the local urban aerosol emissions with dominating submicron particles (Koçak et al., 2007; Talbi et al., 2018; Querol et al., 2019a; Fan et al., 2021). For instance, in non-dusty days, the values of \( R \) in Athens exceeded 0.7 and sometimes even approached 1.0, while in Sofia they were well below 0.4 indicating a relatively lower content of fine-fraction aerosols. Different seasonal sources of submicron particles, such as intense fires in the summer and the domestic heating in the winter, will also cause increases in the level of \( R \) (Querol et al., 2019b; Buchunde et al., 2019). As it seems, the lowest values of \( R \) are obtainable mainly in the spring (see, e.g., in this work and in Koçak et al. (2007)).

The characteristics of the PM over Sofia during the summer period from 25 July to 25 August 2021 are represented graphically in Fig. 5(b). The situations seen in these figures are a little different from those shown in Fig. 5(a). The level of the ratio \( R \) is now higher in general (with a monthly mean value of ~0.21) compared to that during the spring period 28 March–28 April 2021 (with a
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monthly mean value of ~0.13). This may be due to a higher content of fine-fraction particles in the atmosphere as a consequence of more intense fire activity in the summer as confirmed by the FIRMS' images of the Balkan and southeastern European region. The wind speed during the period is from 1–2 m s⁻¹ to 3 m s⁻¹ with a variable direction. During this summer period, there are 6–7 pairs of peaks of the PM₁₀ mass concentration measured by AMSs Kopitoto and Hipodruma that are coincident in time. The values of the first three peak pairs exceed the European DLV of 50 µg m⁻³, and other three ones are above 25–30 µg m⁻³. The PM₂.₅ mass concentration is everywhere around and below 10 µg m⁻³. The three peak pairs rising above 50 µg m⁻³ and two more pairs rising above 25–30 µg m⁻³ on 30 July, 2 August and 5 August 2021, and 10 and 17 August 2021, respectively, are accompanied by peaks of the DL. The first DL peak is three days prior to the mass concentration peak, whereas the second and the third ones are coincident in time with the mass concentration peaks. The fourth and fifth DL peaks occur one day after the mass concentration peaks. The corresponding peak DLs are ~0.39 g m⁻², 0.33 g m⁻², 0.49 g m⁻², 0.29 g m⁻², and 0.06 g m⁻². It is important to note here that the first three concentration peak pairs are accompanied by declines in ℛ with depths of ~0.12, 0.20 and 0.16. The decline corresponding to the fourth peak is two days late with a depth of ~0.19, while the one coincident in time with the fifth peak is ~0.22. Thus, a relatively intense dust transport in the atmosphere over Sofia City gives rise to a sharp increase of the PM₁₀ mass concentration (measured by urban and rural AMSs) along with characteristic deep declines in the ratio ℛ. The remaining two concentration peaks occurred on 21 and 25 August 2021 under conditions of negligible dust load and no clear-cut deep declines in ℘. As explained above, e.g., the discussion on the situations on 17 August 2022 and 26 February 2021, the PM₁₀ mass concentration increases in such cases should be due to an increased content in the atmosphere of smoke from fires or a mixture of smoke and marine aerosol and desert dust. Certainly, urban and continental aerosols (UA and CA) should always be present over and around AMSs Hipodruma and Kopitoto, respectively. Apart from the aforementioned seasonal fire activity, in the period from 17 to 25 August 2021, no noticed HYPLIT back trajectories passed over Africa except those ending at heights of 4000 m and 5000 m at 12:00 UTC on 25 August. The latter trajectories have passed over the northern part of Morocco and crossed (along with that ending at 3000 m) SD-loaded zones over Mediterranean Sea. The effect on the DL over Sofia in this case is too weak. The AERONET data concerning the peak days indicate in general a high AOD₄₄₀ ~0.38–0.64 and an AE₄₄₀/₈₇₀ ~1.84–1.89. Also, we have AOD₄₄₀ ~0.30–0.53, AOD₅₀₀ ~0.28–0.51, AOD₅₅₀ ~0.02–0.04, SF ~93.27–99.00%, and LDR ~0.0021–0.0045. The fine-fraction mode of the VSD is strongly prevailing over that of the coarse aerosol fraction, and the SSA decreases sharply with ℛ. Thus, the AERONET data outline in fact BB aerosol situations (Dubovik et al., 2002; Evgenieva et al., 2022).

During the autumn period from 25 September to 25 October 2021, there is only one peak zone of the PM₁₀ and PM₂.₅ mass concentrations, around 27–28 September, accompanied by a relatively high DL peak with a height of ~0.25 g m⁻² (Fig. 5(c)). The peak values of the PM₁₀ concentrations are around (a little above and below) 30 µg m⁻³, and that of the PM₂.₅ mass concentration is a little below 10 µg m⁻³. This is in fact a situation of satisfactory air quality. The decline of the ratio ℛ in this case is not so deep, ~0.27 at a monthly mean value of ~0.30, which suggests that the PM₁₀ and PM₂.₅ mass concentrations measured are a result of settling of not only SD, but of UA and even of biomass-burning (BB) aerosols as well. Such a supposition has been additionally proved by the HYPLIT model, showing long sections over Africa (all the territory of Algeria) of the 120-hour back trajectories of the air masses arriving over Sofia on 27 and 28 September at 12:00 UTC at heights of 500 to 6000 m; by the FIRMS' images, showing a strong fire activity in Bulgaria and the neighbouring countries; and by the AERONET data indicating mixed-aerosol characteristics (Evgenieva et al., 2022), that is, AOD₄₄₀ = 0.38, AE₄₄₀/₈₇₀ = 1.07, AOD₅₀₀ = 0.33, AOD₅₅₀ = 0.20, AOD₅₅₀ = 0.13, SF = 0.59–98.83%, and LDR = 0.0025–0.1943. The modes of fine and coarse aerosol fractions are equally pronounced in the volume size distribution, and the SSA is increasing with ℛ in the visible spectral region and is nearly constant at longer wavelengths. A deeper and steeper drop in ℛ, with a depth of ~0.22, occurs 4–5 days later, on 1–2 October, due to a delayed massive settling of, probably, SD particles. The remaining 3–4 peak concentration zones, around 4–6, 13, and 19–23 October, are characterized by a zero or negligible (~0.05 g m⁻³) DL and the absence of ℛ declines. One may expect in these cases that the main reason for increasing the PM
concentration is the urban sources of pollutants and, especially, the domestic heating with wood and coal. Indeed, it is seen in Fig. 5(c) that at the end of October, when the home heating begins, the urban PM$_{10}$ mass concentration peaks increase significantly, approaching the DLV of 50 µg m$^{-3}$. The PM$_{2.5}$ maxima also increase. Almost all considered 120-hour HYSPLIT-provided back trajectories of the air masses arriving over Sofia at different heights during the days discussed do not pass over Africa. Most of them, however, have long sections over the Atlantic Ocean and Mediterranean Sea, where marine aerosols may have been entrained by the air masses. The FiRMS' images indicate weak-to-absent fire activity in Bulgaria and neighboring countries. The weather conditions are typical for the autumn in Bulgaria, with ambient temperatures of 4.0–8.4 to 11.2–12.4°C, wind speed of 0–2 to 3 m s$^{-1}$ with a variable direction, variable visibility of 8–12 to 20–25 km, and rare mists and short rain showers. The AERONET data outline urban aerosol characteristics, that is, a higher AOD and a major VSD mode of the fine aerosol fraction, a relatively high value of AE ($>1.4$), an SSA decreasing with the radiation wavelength $\lambda$, a high particle sphericity and a small LDR (Evgenieva et al., 2022). For instance, for the aerosol situations on 5, 13, 20 and 22 October, we have AOD$_{440} \sim 0.15–0.21$, AE$_{440/870} \sim 1.62–1.78$, AOD$_{500} \sim 0.12–0.18$, AOD$_{550} \sim 0.09–0.17$, AOD$_{5500} \sim 0.01–0.02$, SF $\sim 85.49–99$%, and LDR $\sim 0.0021–0.0064$. The SSA on 13, 20, and 22 October is decreasing with $\lambda$, and the pronounced major mode of VSD is that of the fine particle fraction. On 5 October, some of the hourly SSA vs. $\lambda$ curves are increasing up to 675 nm and decreasing at longer wavelengths, while the corresponding VSD modes of the fine and coarse particle fractions become comparable. Such a daily dynamics of the SSA, VSD, and SF behavior is likely due to passages of marine aerosol bunches over Sofia.

During the winter period from 25 January to 25 February 2022, there is one only PM peak zone from 14 to 17 February (with the maximum PM$_{10}$ mass concentration at AMS Hipodruma exceeding 50 µg m$^{-3}$) accompanied by a DL peak of about 0.18 g m$^{-2}$ on 16 February (Fig. 5(d)). A related decline in $\mathcal{R}$ is seen in this case, with a depth of $\sim 0.22$, on 18 February, at a monthly mean value of 0.27. A sharp and deep decline in $\mathcal{R}$ with a depth of $\sim 0.12$ characterizes the situation on 31 January, when DL = 0. This decline accompanies a PM$_{10}$ mass concentration peak with a height of $\sim 50$ µg m$^{-3}$ as measured by AMS Hipodruma on 1 February, again in the absence of DL. The remaining peaks of the PM$_{10}$ mass concentration measured by AMS Hipodruma on 26 and 28 January and 5, 11, 19–20, and 25 February are accompanied by fluctuating $\mathcal{R}$ without any specific declines, under conditions of an absent or negligible dust load. Two of these peaks (on 5 and 11 February) exceed 70 µg m$^{-3}$, one peak (on 15–16 February) exceeds 50 µg m$^{-3}$, the other two (on 19–20 and 25 February) exceed 40 µg m$^{-3}$, and the peaks on 26 and 28 January exceed 30 µg m$^{-3}$. The daily-mean PM$_{10}$ mass concentrations measured by AMS Kopitoto and the PM$_{2.5}$ such concentrations measured by AMS Hipodruma are all close to and below 20 µg m$^{-3}$. The period is characterized by winter weather conditions typical for Bulgaria; i.e., temperatures from $\sim 5.1$–3 to 4.5–7.8°C, a wind speed from 0–1 and 0–2 to 2–4–5 m s$^{-1}$ and a variable direction (most often WNW and ESE), a visibility from 6–14 to 18–26 km, a snow cover from 2–5 to 9–20 cm, snowfalls and mists, and rare short rain falls. The additional information provided by HYSPLIT, FiRMS and AERONET, respectively, on the 120-hour back trajectories of the air masses arriving over Sofia, the fires in Bulgaria and the adjacent countries, and the optical and microphysical properties of the aerosol ensembles on these peak days led us to the following conclusions: First, during the considered period, the generally weak fire activity goes through periods of some intensification, partially or completely coinciding in time with the peak PM-concentration zones described above. Besides, the winter season is characterized by intense domestic heating. Thus, the smoke from fires and domestic heating should be a significant reason for increasing the urban PM mass concentration. Marine aerosols from the Atlantic Ocean and the Mediterranean Sea and continental and polluted urban aerosols from Europe could also increase the measured PM mass concentration. For instance, on 26 and 28 January and 5 and 10–11 February, the 120-hour back trajectories considered of the arriving air masses have not passed over Africa; they have passed mainly over the Atlantic Ocean and Europe. Correspondingly, the optical and microphysical properties of the aerosol ensembles on these days indicate urban and biomass-burning aerosol situations (Evgenieva et al., 2022) with a slight influence of marine aerosols, that is, prevalent VSD mode and AOD of the fine aerosol fraction, an AE$_{440/870}$ $\sim 1.42–1.74$, a wavelength-decreasing SSA, a high SF ($\sim 81.92–99$%) and a low LDR ($\sim 0.0021–0.0140$). The second conclusion concerns
the peak zone around 14–17 February, when the 120-hour HYSPLIT-provided back trajectories have sections passing over Africa (Libya, Algeria and Tunisia), the USA and the Atlantic Ocean, West and East Europe and the Mediterranean Sea. The fire activity is intensive and the AERONET-provided optical and microphysical aerosol characteristics indicate a complicated UA, BB-smoke, SD and MA containing mixed aerosol situation (Evgenieva et al., 2022) with prevalent VSD mode and AOD of the fine aerosol fraction, an alternating, decreasing and increase-decreasing (with \( \lambda \) ) SSA behavior during the days, and a rather high SF (~87.99–99%) and a low LDR (~0.0013–0.0069).

A third interesting conclusion concerns the aerosol situation on 31 January 2022 (Fig. 6). Then the PM concentration peaks are accompanied by a deep decline in \( \mathcal{R} \), in the absence of any DL, at a high sphericity (99%) of the aerosol particles having a fine mode peak at 0.26 \( \mu m \) particle size and a major coarse mode peak at 2.24 \( \mu m \) particle size (Fig. 6(d)). The other AERONET-provided aerosol characteristics are: AOD\textsubscript{440} = 0.08, AOD\textsubscript{500} = 0.07, AOD\textsubscript{5500} = 0.03, AOD\textsubscript{500} = 0.04, AE\textsubscript{440/870} = 0.62, and LDR = 0.0029; SSA is increasing from 0.64 at \( \lambda = 440 \text{ nm} \) to 0.93 at \( \lambda = 1020 \text{ nm} \) (Fig. 6(e)). The only possible explanation of such a combination of characteristics is the presence of aged polluted urban and BB aerosols over the region of Sofia (Eck et al., 2003; Müller et al., 2007; Ortiz-Amézcua et al., 2017; Noh et al., 2017; Ansmann et al., 2021; Janicka et al., 2023).

Indeed, in this case there are no established 120-hour HYSPLIT back trajectories of arriving air masses that have passed over Africa. Instead, these trajectories have long sections over North America (USA and Canada), the Atlantic Ocean and the whole of Europe (Figs. 6(b) and 6(c)), which may have enriched the air masses with marine aerosols, but mostly with aged polluted urban and BB aerosols. Note that the FIRMS image (Fig. 6(a)) reveals many fire outbreaks in North America, southwestern Europe and the Balkan Peninsula at the end of January 2022. So, one may conclude in general that as a rule the SD events over Sofia would most often lead to an increase in the PM mass concentration and a decrease in the value of \( \mathcal{R} \); however, such an effect, although much less often, can also be caused by other types of aerosols with a predominant coarse fraction.

Finally, let us briefly consider for completeness the aerosol situation on 19–20 February 2022 characterized by an increased fire activity around Sofia and Bulgaria. In this case, the back trajectories of the arriving air masses have long sections over the Atlantic Ocean and Europe and very short ones over Algeria and Tunisia. Correspondingly, the AERONET data, e.g., on 19 February, outline a mixed aerosol situation, containing seemingly mainly urban, continental and marine aerosols, with AOD\textsubscript{440} = 0.06, AOD\textsubscript{500} = 0.05, AOD\textsubscript{5500} = 0.03, AOD\textsubscript{500} = 0.02, AE\textsubscript{440/870} = 1.23, SF ~58.93–77.51, and LDR ~0.0146–0.0248. The VSD is three-modal, with an intermediate aerosol fraction mode that is lower compared to the comparable modes of the fine and coarse aerosol fractions. The SSA increases with \( \lambda \) in the visible and decreases in the infrared spectral regions. The case on 25 February is similar, but with the VSD being bimodal.

### 4 CONCLUSIONS

The main objective of the present study was to assess the possibility of recognizing Saharan dust transport events over Sofia, Bulgaria, based on data on ground-level PM\textsubscript{10} and PM\textsubscript{2.5} mass concentrations from a mountain (background) station and an urban station measuring the air quality. A wide range of additional data from other instruments and models were also used as necessary in the course of the research. These data concerned the optical and microphysical characteristics of the aerosol ensembles over Sofia, the back trajectories of the air masses arriving over Sofia at different altitudes and times, the corresponding Saharan dust load, and the impacts of the fire activity and the weather conditions.

It was shown that considerable increases of the daily-mean PM\textsubscript{10} mass concentration (above 50 \( \mu g \text{ m}^{-3} \) or 70 \( \mu g \text{ m}^{-3} \)) measured at the mountain AMS were commonly due, in 74% and 86% of all cases, respectively, to relatively intense SD events over Sofia, with a DL > 0.05 g m\textsuperscript{-2}; thus, one may estimate with 74% and 86% probability the occurrence of such events.

It was shown as well that the cases when the PM\textsubscript{10} mass concentration had peaks above and well above 25–30 \( \mu g \text{ m}^{-3} \) in combination with simultaneous deep declines in the PM\textsubscript{2.5}/PM\textsubscript{10} mass concentration ratio \( \mathcal{R} \) down to and below 0.1–0.2 were as a rule indications of relatively strong SD events with dust loads above and well above 0.15–0.20 g m\textsuperscript{-2}. 


Some cases were also established when the PM$_{10}$ mass concentration was high, exceeding, e.g., 40–50 µg m$^{-3}$ at a DL $< 0.05$ g m$^{-2}$. The concentration increases in such cases were shown to
be due to an increased content of smoke of fires in the summer or domestic heating in the winter, or to mixtures of smoke and marine aerosols with some amounts of desert dust.

The fact was confirmed that in a region (Athens) located closer to the Sahara Desert with higher achievable PM$_{10}$ and PM$_{2.5}$ mass concentrations during intense SD intrusions, the declines in $ℛ$ can be shallower than those obtainable in Sofia (farther away from the desert) during in general weaker SD intrusions and lower PM concentrations peaks measured. This is due to the fact that the depth of the declines is determined to a large extent by the level of the local urban aerosol pollutions that have a prevalent fine particle fraction.

The analysis of the co-evolution of the PM$_{10}$ mass concentration measured by the mountain AMS and the PM$_{10}$ and PM$_{2.5}$ mass concentrations measured by the urban one showed that the natural PM$_{10}$ influences mainly the urban PM$_{10}$ fraction, and to lower extent, its PM$_{2.5}$ fraction.

On the basis of the peculiarities established in the work in the behavior of the near-ground in-situ measured PM$_{10}$ and PM$_{2.5}$ mass concentrations under conditions of intense SD intrusions, with a high degree of confidence one can identify and confirm the occurrence of such intrusions over the region of Sofia City and Sofia Valley.

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