Bulgarian Geophysical Journal, 2014, Vol. 40
National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences

LIDAR REGISTRATION OF THE VERTICAL STRATIFICATION OF SAHARAN DUST INCURSIONS OVER SOFIA

A. Deleva

Institute of Electronics, 72 Tsarigradsko Chaussee blvd., 1784 Sofia, Bulgaria, e-mail: adeleva@ie.bas.bg

Abstract. Atmospheric particles (aerosols) and mainly mineral dust particles affect life on Earth in several ways. Key parameters for determining the impacts of aerosols to climate forcing and the ecological state of the environment are their optical parameters (backscatter and extinction coefficients), as well as their spatial distribution. In this study, the results are analyzed of the vertical remote sounding of several Saharan dust outbreaks above Sofia. The investigations were carried out by a aerosol LIDAR (*LI*ght *D*etection *A*nd *R*anging) based on a Nd:YAG laser. The examples presented illustrate that the detected aerosol/dust layers differ in their altitude, density, thickness and height stratification. Some of the results show that aerosols can reach up to and persist in the unusual 14 km altitude region in the troposphere. Experimental data are presented in terms of atmospheric backscatter coefficient profiles and 2D-color maps of the aerosol stratification time evolution. The DREAM (*D*ust *RE*gional *A*tmospheric *M*odel) forecasts and HYSPLIT (*HY*brid *S*ingle-*P*article *L*agrangian *I*ntegrated *T*rajectory) backward trajectories for the days of measurements were employed to draw conclusions about the atmospheric aerosol's origin.

Key words: lidar, atmospheric aerosols, Saharan dust, troposphere.

Introduction

Dust plumes, both of natural and anthropogenic origin, frequently cover huge areas of the Earth and represent one of the most prominent and commonly visible features in satellite imagery (Yoram J. Kaufman et al., 2002). Dust (mineral aerosols) is one of the major components of the atmospheric aerosol loading (Duce, R., 1995; Maria Raffaella Vuolo et al., 2009; Ina Tegen, 2003). The main sources of dust are the large arid areas of the world. Dust is transported in suspension at a wide range of heights above the surface and can rapidly cover considerable distances. Like all aerosol types, dust particles can alter the Earth radiation budget directly by scattering and absorption or indirectly by modifying the formation and properties of clouds (J. E. Penner et al., 2001; Natalie M. Mahowald et al., 2003; U. Pöschl, 2005; R. L. Miller and I. Tegen, 1998). Also, they affect the air quality, reduce visibility, and pose risks to human health (Perez L. et al., 2008; U. Pöschl, 2005). These effects of dust/aerosols on the environment strongly depend on their optical properties, altitude of location in the atmosphere and the vertical repartition of the particles (E. Hamonou et al., 1999; P. Kishcha, 2005; F. Immler and O. Schrems, 2003; Gian Paolo Gobbi et al. 2000; De Tomasi F. et all., 2003). The latter is transport dependent. Indeed, during the transport the vertical structure may be modified by mechanisms such as convective erosion of the dust layer and gravitational setting of particles.

North Africa, especially Sahara desert, is the largest source of dust of natural origin (Prospero M. Joseph, 1999; Vukmirović Z. M. et al., 2004). The desert aerosols captured by the wind at the surface are raised to considerable altitudes by the strong convective processes that develop over the desert and, under certain weather conditions, they can reach the European, Asian and American continents (Albert Ansmann et al., 2003; Albert Ansmann et al., 2009; Joseph M. Prospero, 1999; A.S. Goudie, 2001; Alpert P., 1993; Yoram J. Kaufman, 2005; J. Barkan, 2008; Chiapello J., 1997). The Mediterranean region, and particularly the Balkan Peninsula, have been under the influence of Saharan dust transport and deposition over millennia. Every year huge amounts [200-500 million tons (De Tomasi F. et all., 2003; Mitsakou C., 2008)] of Saharan dust are transported over the Mediterranean Sea to most of Europe.

In recent years, a number of studies have been focused on understanding the different phases of the Saharan dust process (mobilization, transport, deposition and climate interactions) over Europe based on lidar monitoring, in situ measurements, satellite imaging; these have often been organized as observational networks (L. Mona,2012; I. Mattis, 2008).

The lidar techniques for atmospheric studies are recognized as the most powerful tools for investigating the vertical structure of the atmosphere through its major advantage of real-time observation with high resolution both in time and space. Lidars have attained a high degree of reliability and have been used by regional networks to produce long-term and well-calibrated measurements of aerosol properties. These include the European Aerosol Research Lidar Network (EARLINET), a federation of 27 European lidar research groups (http://www.earlinet.org). The aim of EARLINET is to establish a quantitative data base of both horizontal and vertical distributions of aerosols on a continental scale. Systematic observations of Saharan dust transport events over Europe began in May 2000 by EARLINET (A. Papayanis, 2005; A. Papayanis, 2009; Papayannis A., 2008).

The only lidar station in Bulgaria is located in the Laser Radar Laboratory of the Institute of Electronics of the Bulgarian Academy of Sciences. Since March 2003, it has been involved in systematic measurements on a regular basis – three times per week according to the schedule of the EARLINET. When Saharan dust presence is forecast, more observations are conducted in view of obtaining as full as possible an image of the Saharan dust transport event.

Lidar measurements described below are obtained within the frame of the EARLINET. A large database is created accumulating the aerosol backscatter profiles which are uploaded on the common EARLINET-server in Germany.

In this study we present some results selected from the regular lidar investigations of the atmosphere. The backscatter profiles and height-time color maps included illustrate laser remote observations on the vertical mass distribution of relatively stable aerosol layers situated at different altitudes. The lidar measurements were conducted on Saharan-dust-affected days; we therefore infer that desert dust loadings in the air above Sofia were detected.

Equipment and data processing

The results presented in this paper are based on measurements by an aerosol elastic backscatter lidar located in the Laser Radar Laboratory, IE-BAS (A. Deleva, 2010; Atanaska D. Deleva, 2008). It is configured in a mono-static biaxial alignment pointing at a maximum slope angle of 32º with respect to the horizon, as determined by its position in the lab. Thus, despite that signals from as far as a 30-km distance are recorded, the maximum sounding height is limited to 16.4 km**.**

The lidar transmitter is based on a high-power Nd:YAG laser providing output pulse energy of up to 600 mJ at 1064 nm and 80 mJ at 532 nm, with a pulse duration of 15 ns FWHM at a repetition rate of 2 Hz. The laser beam divergence is 2.2 mrad. The receiver’s optical part consists of a Cassegrain-type telescope (aperture 35 cm; focal distance 200 cm) and a spectrum-analyzer based on narrowband interference filters (1-3 nm FWHM). The electronic part of the lidar receiving system is formed by compact photo-electronic modules, each comprising a photo-detector, a 10-MHz 14-bit analog-to-digital converter (ADC), a high-voltage power supply, and controlling electronics. The receiving modules are connected to a PC via high-speed USB ports. The received signals are digitized every 100 ns by an ADC, resulting in a 15-m range resolution (about a 7.5-m altitude resolution). Thus, the lidar measures the temporal evolution of the atmospheric aerosol backscatter with high time and range resolutions. The acquisition system is equipped with specialized software for accumulation, storage, and processing of lidar data. The vertical atmospheric backscatter coefficient profiles are retrieved using the Klett-Fernald inversion algorithm (J. D. Klett, 1981; F. G. Fernald, 1984). Since the magnitude of the backscatter coefficient value is proportional to the aerosol density, the changes in the calculated lidar profiles in time and space illustrate the temporal evolution and the stratification of the aerosol field observed. Usually, each lidar measurement lasts for 1-3 hours. The lidar signal is accumulated for 5-10 min (corresponding to data accumulation of 600-1200 different raw profiles received at each laser pulse). The parameters of the laser, telescope, photo-receiving modules and software make it possible for the lidar to be utilized for carrying out fast remote measurements of the atmosphere from 130 m above ground level (AGL) (approximately 700 m above sea level, ASL) to the tropopause.

To draw conclusions about the type and origin of the aerosol layers detected by the lidar, we use additional information provided by DREAM-forecast maps of dust load and concentration in the atmosphere for the Euro-Mediterranean zone. Such maps are prepared by the Forecast system of Barcelona Supercomputing Center, Spain, and are accessible via Internet (http://www.bsc.es/projects/earthscience/DREAM/. DREAM-maps give an image of the wind direction and magnitude of dust load in the atmosphere above North Africa and

Europe. An additional source of information about the origin of the aerosol layers is offered be the HYSPLIT model (Draxler R. R., 2010; Rolph G. D., 2011). It can be run interactively on the web through the READY system on the site of the Air Resource Laboratory of NOAA (National Oceanic and Atmospheric Administration), USA. The calculations of backward air mass trajectories yield a plot of the path that the air mass travelled for a chosen time period before arriving at the lidar station.

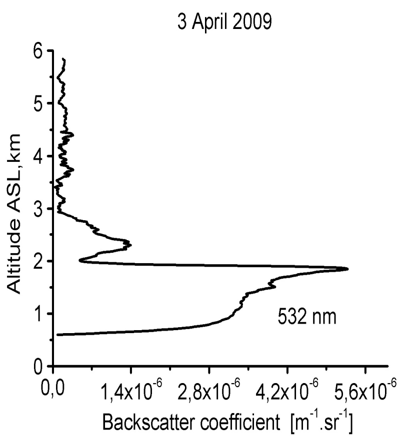
Experimental data and comments

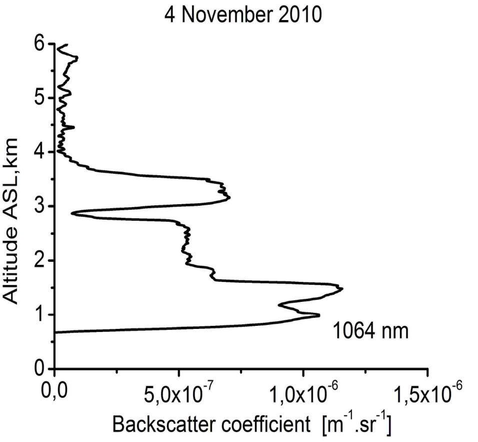
Using the lidar described above, studies of the atmosphere over Sofia during Saharan dust incursions have been conducted for more than ten years. A large data base was acquired, systematized and analyzed. The results demonstrated that Saharan dust can be present within the entire troposphere, with the separate incursion events differing in the height of dust transport, the vertical mass distribution, as well as in the frequency of observation of events with similar spatial stratification. The following basic conclusions were drawn: 1). Saharan dust was most often detected over Sofia to a height of 5-6 km, with the dust aerosol being found either within a distinct layer above the atmospheric boundary layer (ABL), or having penetrated the ABL from the ground up to the height quoted. 2). Very seldom, Saharan dust was transported simultaneously in two separate layers above the ABL, or within the entire trposphere to the extreme heights of 12-14 km. These conclusions will be illustrated by the lidar experiments described below.

We present the results mainly in terms of vertical atmospheric backscatter coefficient profiles (the *x*-axis representing the value of the calculated atmospheric backscatter coefficient; the *y*-axis, the altitude. The measurement date and the sounding laser wavelength are cited over the respective lidar profile plot. Also, 2D-colormaps of the aerosol stratification time evolution are constructed for some separate measurements (the *x*-axis representing the time interval of the measurement; the *y*-axis, the altitude). For each of the experiments, a DREAM-map is enclosed demonstrating that the Barcelona Supercomputing Center has forecast a Saharan dust transport over Bulgaria, whose location is indicated by a black circle. It should be noted that the HYSPLIT model allows one to depict up to three trajectories on a single map. This is why, of all trajectories calculated for the time interval of a particular measurement, on the respective HYSPLIT map we include those three of them that end over Sofia at heights falling within characteristic sections of the recovered atmospheric backscatter coefficient profile. Such a choice assists one in explaining the results. As was mentioned above, the information provided by the DREAM and HYSPLIT is used to draw conclusions concerning the origin of the particles in the aerosol layers registered. However, when drawing such a conclusion, one should always bear in mind that, since aerosols are transported over long distances in the atmosphere, mixing between aerosol populations from different source regions and with different composition can take place (for example, mixing between desert dust, continental aerosols and maritime particles). Thus, the particles detected by the lidar are the final result of the mixture of Saharan dust with different types of aerosols, partially coated by water.

As examples of observing Saharan dust in a distinct layer above the ABL, we describe in more detail the experiments performed on April 3, 2009, and November 4, 2010

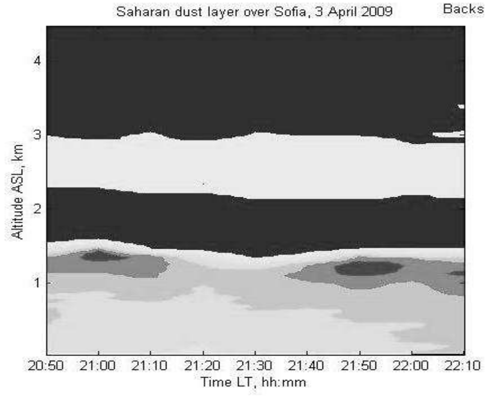
(Fig. 1). For these dates, the DREAM model has forecast dust transport over Bulgaria (Sofia) (Fig.1 e, f).

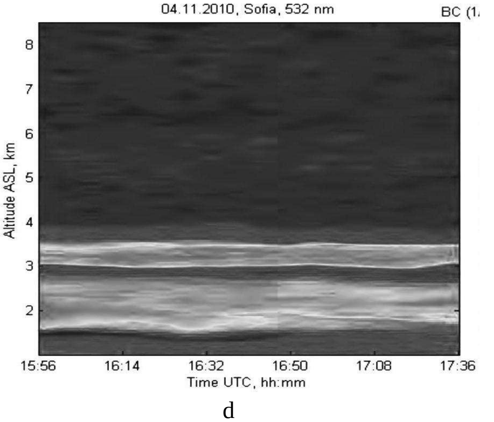




a

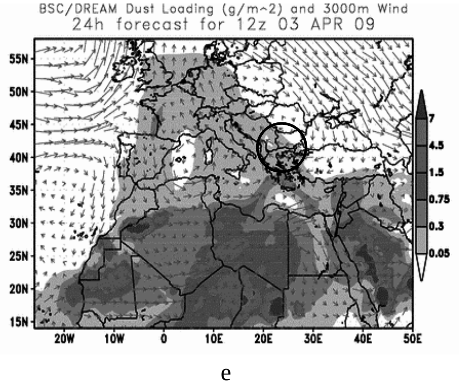
b

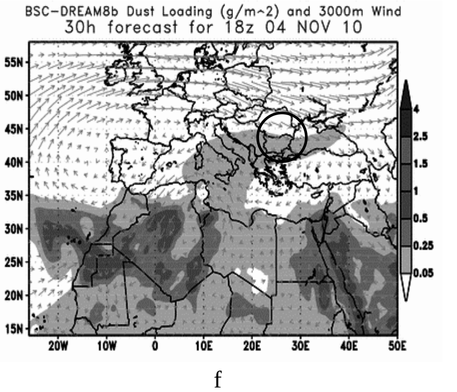




c

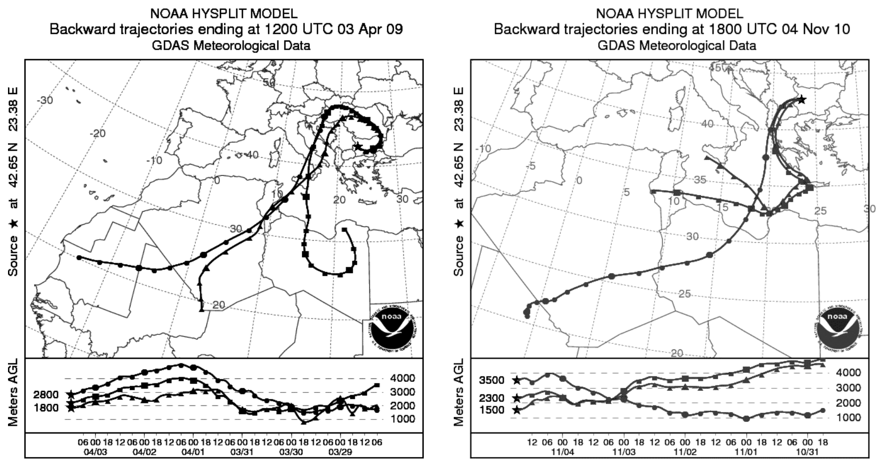
d





e

f



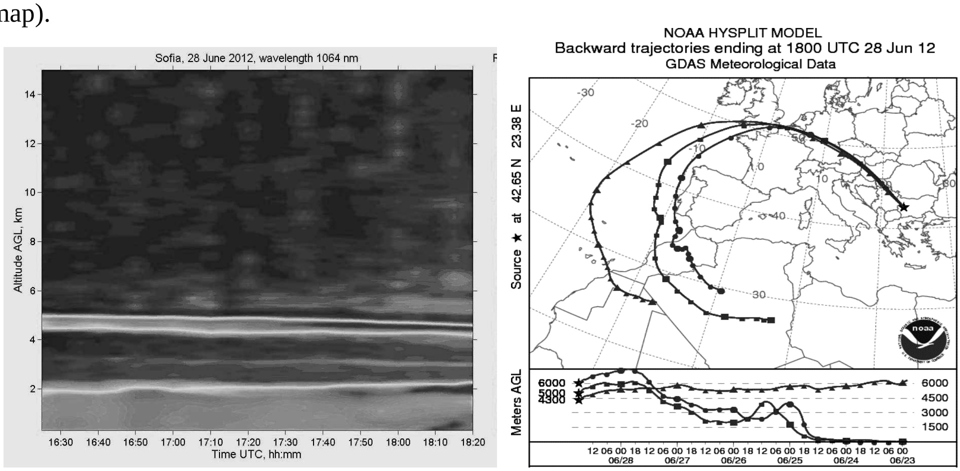
j h

Fig.1. Lidar observations of Saharan dust above Sofia on April 3, 2009 and November 4, 2010: a, b). retrieved vertical atmospheric backscatter coefficient profiles; c, d). time evolution maps of the mass spatial distribution; e, f). DREAM forecast maps showing Saharan dust transport over Bulgaria; j, h). HYSPLIT model backward trajectories.

The lidar profile (Fig.1 a) and the 2D-map (Fig.1 c) show that the layer above the ABL, registered on April 3, 2009, was located within the height interval of 2-3 km with a mass center at about 2.5 km. Further, the profile curve reveals an atypical increase with the height of the aerosol concentration in the ABL, with a maximal value at a height of about 1.8 km. The HYSPLIT backward trajectories calculated for the height range of 1.5-3 km, three of which are presented in Fig.1.j, reveal that, before reaching Sofia, the air masses in this range have moved low above the surface of Sahara (North Africa) and passed through the heavily dusted space over the Mediterranean Sea, as seen in the DREAM map. Fig.1.j presents the trajectories terminating above Sofia at the heights of 1.8, 2.2 and 2.8 km. These were selected purposefully, since their ends coincide with characteristic regions in the curve of the retrieved lidar profile of the atmospheric backscatter coefficient. In this particular case, at the height of 1.8 km we determined the highest atmospheric backscatter coefficient value, while the heights of 2.2 and 2.8 km are the lower and the higher boundaries of the layer above the ABL. We thus concluded that the aerosol layer within the range 2-3 km contained mainly Saharan dust. We further assumed the presence of large amount of Saharan dust in the ABL is the cause of the anomalous increase with the height of the aerosol mass concentration, its largest value being at 1.8 km.

The lidar data acquired on November 4, 2010, are presented in Fig.1.b,d. One can see that a temporally stable layer was detected above the ABL, with the center of mass near a height 3.5 km and well delineated boundaries at 3 km and 4 km. One can also see that in the ABL the aerosol concentration was maximal at 1.5 km, while further up to about 3 km it varies negligibly. The calculated HYSPLIT trajectories, which during the measurements terminated in the 2.8-4.3 km range, have started much farther south over Sahara and passed through vast dusted spaces before reaching Sofia. Fig.1 h presents the one ending at 3.5 km, where the center of mass of the layer above the ABL was. The black-and-white image in the HYSPLIT map necessitates the explanation that this is the trajectory beginning over Sahara and passing for a considerable distance at a height of about 1 km above the desert surface. The calculated HYSPLIT trajectories below 2.8 km originate and traverse a dusted space over the Mediterranean Sea. Of these, the map shows the ones that end above Sofia at the heights of 1.5 km and 2.3 km, thus falling in the above-mentioned specific sections of the lidar profile below 3 km. The main conclusion pointed to by the experimental data is that the aerosols detected in the 3-4 km range were trans-boundary transport of Saharan dust. The lower calculated trajectories give is reason to assume that desert dust was also present in the ABL, where it was mixed with anthropogenic aerosols generated in the city. Judging from the curve of the lidar profile shown, the aerosol pollution of the air above Sofia was the largest at heights of 1-1.5 km.

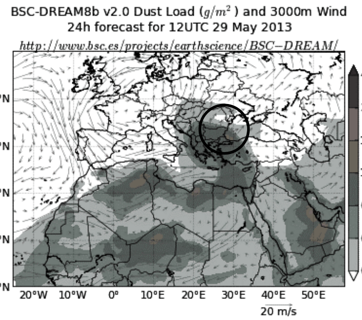
We will now briefly present another example of detection of a distinct Saharan dust layer above the ABL (Fig.2). The monitoring was carried out on June 28, 2012. On the time-height map (Fig.2 a), constructed from a series of 26 lidar profiles, one can see a dense thin aerosol layer with boundaries at about 4.5 and 5 km. These heights remained unchanged during the monitoring, so that the lack can be assumed of dynamic processes in the atmosphere during the experiment. The analysis of the calculated HYSPLIT trajectories strongly suggest that the aerosol layer registered is the result of a direct transfer of dust from Sahara. The trajectories in Fig.2 b show that the air masses above Sofia in the 4.3-6 km during the experiment originate from Sahara. Special attention should be paid to the trajectories that terminate over Sofia at 5 и 6 km, since five days before these have started immediately above the desert surface (the two trajectories on the right-hand side of the map).



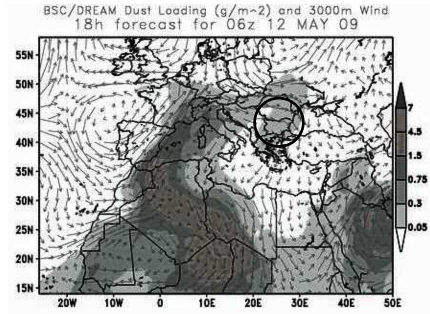
a b

Fig.2. Lidar observations of Saharan dust above Sofia on June 28, 2012: a). time evolution maps of the mass spatial distribution; b). HYSPLIT model backward trajectories.

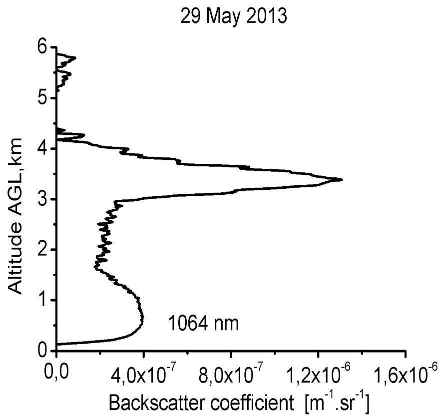
In contrast with the observations described above, the lidar data in Fig.3 and Fig.4 illustrate Saharan dust transport within a wider layer. The data further demonstrate that the separate transport events are characterized by individual specific vertical mass stratification. This is exemplified by the results obtained on May 29, 2013, and May 12, 2009, and presented below (Fig.3 a, b).


BSC-DREAM8b v2.0 Dust Load (g/m^2) and 3000m Wind
24h forecast for 12UTC 29 May 2013
http://www.bsc.es/projects/earthscience/BSC-DREAM/
20 m/s

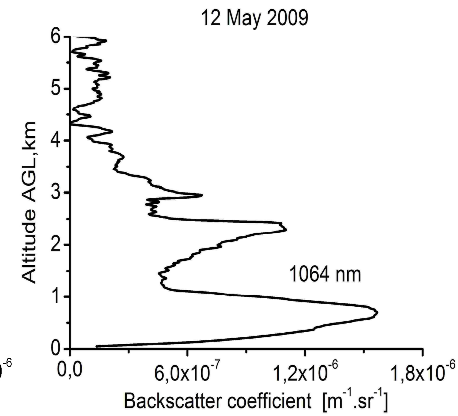
a


BSC/DREAM Dust Loading (g/m^-2) and 3000m Wind
18h forecast for 06z 12 MAY 09

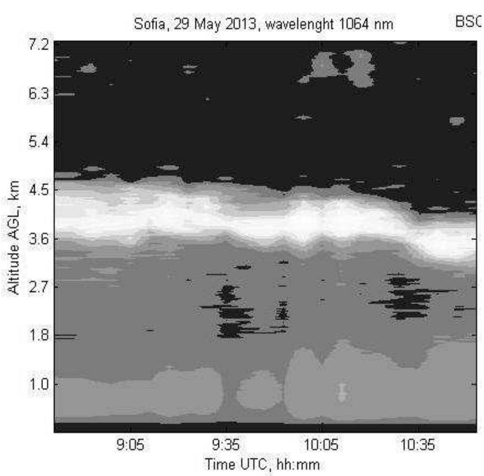
b


29 May 2013
Altitude AGL,km
1064 nm
Backscatter coefficient [m^{-1}.sr^{-1}]

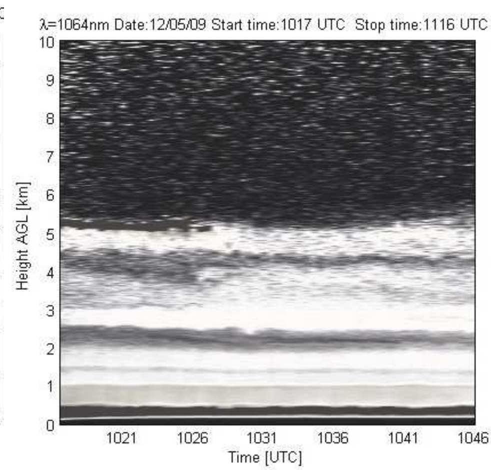
c


12 May 2009
Altitude AGL,km
1064 nm
Backscatter coefficient [m^{-1}.sr^{-1}]

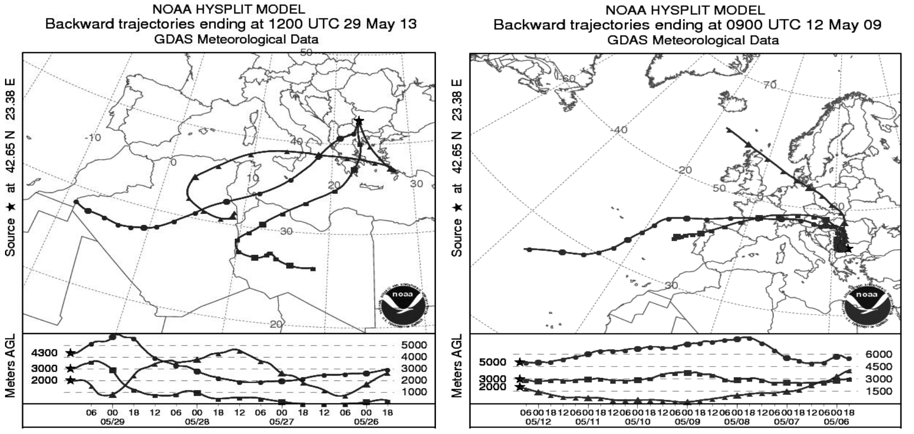
d


Sofia, 29 May 2013, wavelenght 1064 nm
Altitude AGL, km
Time UTC, hh:mm

e


λ=1064nm Date:12/05/09 Start time:1017 UTC Stop time:1116 UTC
Height AGL [km]
Time [UTC]

f



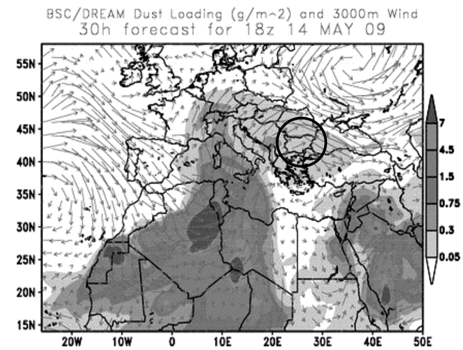
j h

Fig.3. Lidar observations of Saharan dust above Sofia on May 12, 2009 and May 29, 2013: a, b). DREAM forecasts showing Saharan dust transport over Bulgaria; c, d). retrieved vertical atmospheric backscatter coefficient profiles; e, f). time evolution maps of the mass spatial distribution; j, h). HYSPLIT model backward trajectories.

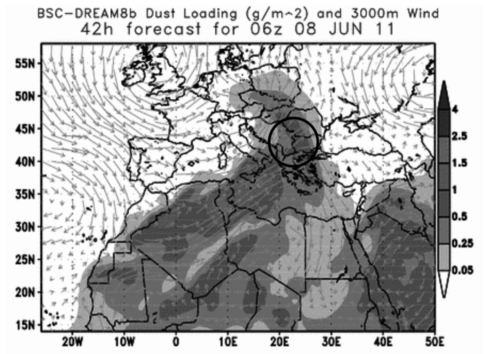
The profile curves (Fig.3.c, d) and the time-height maps (Fig.3.e, f) show that in both cases aerosols were registered above the ABL, up to heights of 4.5 and 5.5 km, respectively. On May, 2013, a dense aerosol layer was present with boundaries at about 3 and 4.5 km and a well-expressed center of mass at 3.5 km. Below this layer, the aerosol concentration was smoothly decreasing down to 1.6 km, after which the lidar profile followed the typical aerosol distribution in the ABL. This mass stratification from the ground up to 4.5 km is revealed better by the profile, since the black-and-white image in the map (Fig.3.e) hinders strongly the presentation of the finer graphical details. The calculated HYSPLIT trajectories, which during the measurements ended in the 2-5 km range of heights, originated above Sahara surface. Fig.3.j presents those that terminated at heights of 2, 3 and 4.3 km above Sofia. The trajectory starting in western Sahara, whose path has passed a long distance immediately above the surface, presents the route of the air masses above the lidar station at about 3 km, where the layer’s center of mass was determined. These facts led us to the conclusion that the aerosol detected in the 2-4.5 km range of heights was dust transferred directly from the space above Sahara desert, with the predominant part of its mass being concentrated in a layer with boundaries at 3 и 4.5 km.

An example for Saharan dust indirectly transported to Bulgaria is presented by the results obtained on May 12, 2009. The lidar profile (Fig.3.d) and the 2D map (Fig.3.f) show the existence of aerosols up to 5.5 km above Sofia. One can also see a well-expressed inhomogeneous vertical stratification of the particles concentration, namely, it was larger at heights of about 2, 3 and 5 km. In contrast with the case described above, none of the HYSPLIT trajectories calculated for May 12, 2009 started and passed over North Africa prior to this measurement (Fig.3.h). However, their paths cross a dense cloud of Saharan dust located above vast regions of Europe (Fig.3.b). Due to this complex aerosol condition of the atmosphere over Europe, one can assume that the lidar data included here (Fig.3.d and Fig.3.f) represent aerosols of different origin, but among them there certainly was a considerable amount of Saharan dust particles.

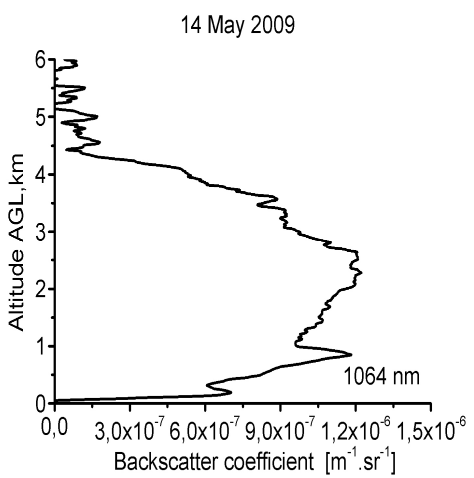
Fig. 4 includes lidar results (Fig.4.c, d) acquired on May 14, 2009, and June 8, 2011, in order to visualize the events of Saharan dust transport most often detected, namely, when the transport takes place within the entire space from the ground up to a height of 5-6 km, while the aerosol concentration varies insignificantly with the height. The monitoring of May 14, 2009, was chosen because it was conducted just two days following the one of May 12, 2009, and described above. Undoubtedly, the difference between the lidar data (Fig.3.d and Fig.4.c) and the HYSPLIT trajectories included (Fig. 3.h and Fig.4.e) for the two days is due to the continuous dynamic changes of the atmosphere, this being its basic property.



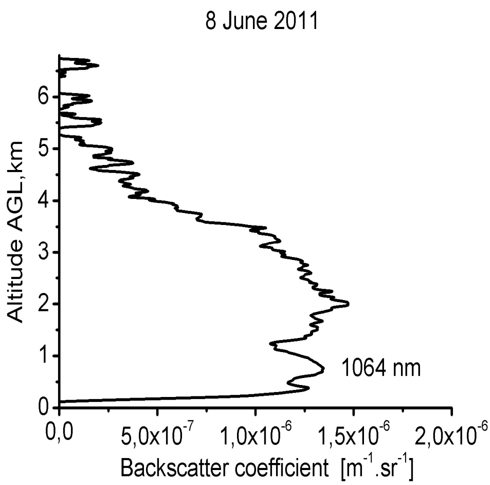
a



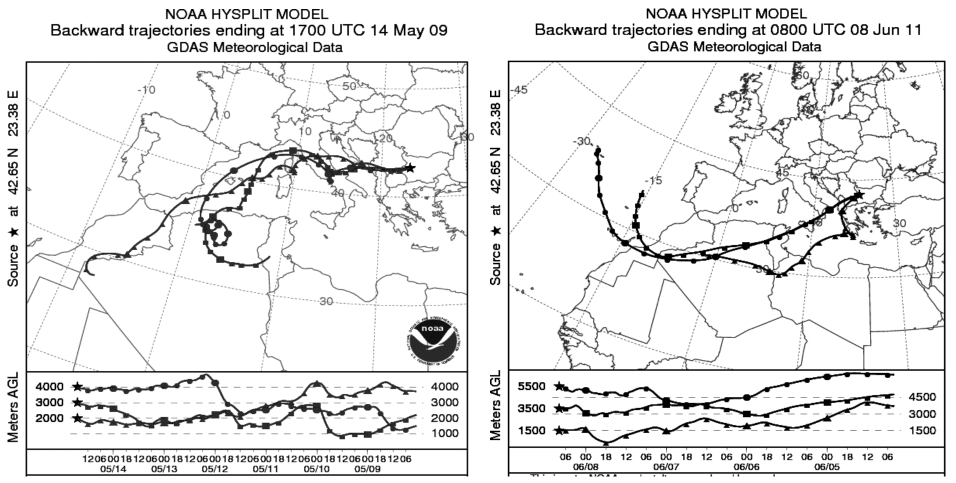
b



c



d



e f

Fig.4. Lidar registrations of Saharan dust above Sofia on May 14, 2009 and June 8, 2011: a, b). DREAM forecasts showing Saharan dust transport over Bulgaria; c, d). retrieved vertical atmospheric backscatter coefficient profiles; e, f). HYSPLIT model backward trajectories.

The results of the lidar measurements performed on May 14, 2009, and on June 8, 2011, do not differ significantly. During these two days, the aerosol load had a higher boundary at about 5 km, the center of mass was roughly at 2-2.5 km, the concentration of particles above it gradually decreased with the height, and the border with the ABL was expressed weakly. The corresponding DREAM maps (Fig.4.a, b) show that dense Saharan dust covered Bulgaria’s territory. For the days of measurement, the HYSPLIT backward trajectories were calculated in the height range of 1.5-5.5 km. It is not necessary to describe them in detail, because it is obvious that they pass over Northern Africa/Sahara desert and across the highly dusted space over Mediterranean Sea before the end point above Sofia (Fig.4.e, f). This is the reason why we assume to suppose that the air masses in the range 1.5-5.5 km during the measurements were desert aerosols transported to a long distance from North Africa.

The next results demonstrate that Saharan dust can be transported simultaneously in two separate layers located above the ABL (Fig.5), or through the entire troposphere up to the tropopause (Fig.6). As we already noted, such transport events are detected very rarely.

The data acquired on June 29, 2006 are presented in Fig.5. On this day, a dense dust cloud was located in the atmosphere over North Africa and Europe (Fig.5.c). The lidar data (Fig.5.a and Fig.5.b) indicate the existence of aerosols over Sofia up to a height of 4.5-5 km. The lidar profile shows that they were distributed mainly in the ABL up to 1 km, and in two layers above the ABL in the 1-2 km and 3-5 km ranges. In the first two ranges, the particles concentration was the highest at about 0.5 km and 1.5 km, while in the top layer the concentration was lower and did not vary significantly with the height.

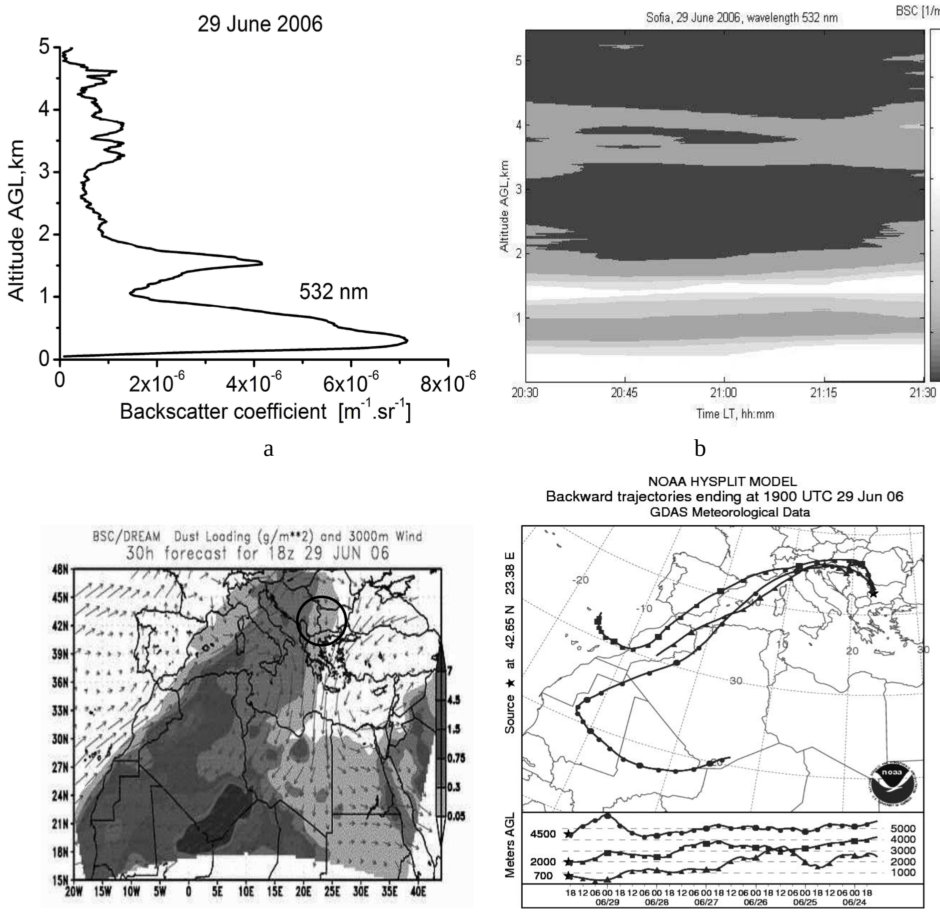


Fig.5. Lidar monitoring of Saharan dust above Sofia on June 29, 2006: a). retrieved vertical atmospheric backscatter coefficient profile; b). the time evolution map of the mass spatial distribution; c). DREAM map showings Saharan dust transport over Bulgaria; d). HYSPLIT backward trajectories.

The HYSPLIT trajectories calculated for the 0.5-5 range reveal that the air masses above Sofia up to 5 km have crossed dusted atmosphere over North Africa, the Mediterranean Sea and Europe. Fig.5.d. shows three of those, with end points above the city at 0.7, 2 and 4.5 km. The one originating the farthest in the southern part of Sahara ended during the measurements at 4.5 km above Sofia; the one starting further to the west, at 0.7 km; and the third one, at 2 km. Our analysis led us to believe that the aerosol loading of the air above Sofia from the ground to a height of 5 km was in this case the result of a direct transfer of desert dust from North Africa; in the free troposphere it was transported simultaneously in two separate layers.

We will finally describe the results obtained during the monitoring conducted on April 15, 2009, (Fig.6), when we observed a unique event of aerosol loading of the free troposphere up to 12-14 km.

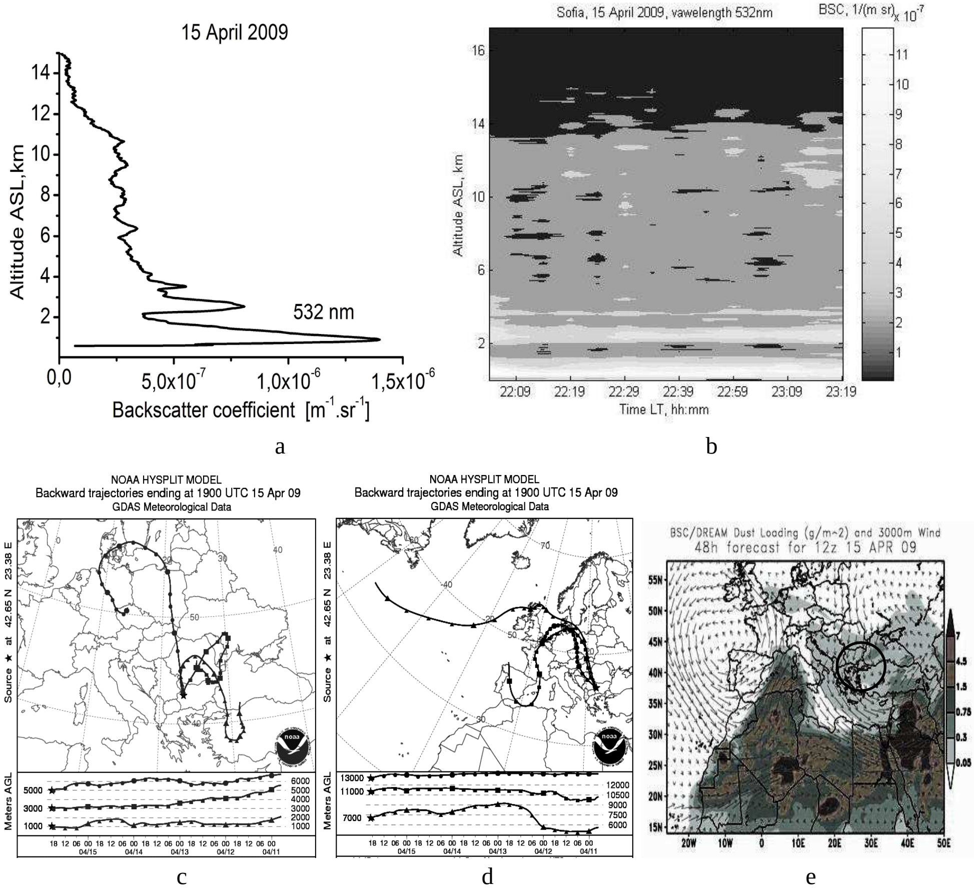


Fig.6. Lidar monitoring of Saharan dust above Sofia on April 15, 2009: a). retrieved vertical atmospheric backscatter coefficient profile; b). the time evolution map of the mass spatial distribution; c,d). HYSPLIT-backward trajectories; e). DREAM forecast map of Saharan dust transport.

Specific features of the mass stratification of the aerosol layer in the free troposphere (Fig.6.a, b) are its well-expressed lower boundary with the ABL at a height of 2 km, a higher particles concentration at heights 2.5-3 km (a well-expressed center of mass), after which the concentration falls smoothly up to about 6 km; it varies weakly further up to 11 km, after which it decreases again up to a height of 14 km. This extraordinary aerosol loading as a function of the height necessitated that we calculate and analyze HYSPLIT backward trajectories within the entire troposphere. Some of these, up to 5 km, are presented in Fig.6.c, while some in the range of 7-13 km, in Fig.6.d. The trajectories included demonstrate that no air masses have reached Sofia directly from the space above North Africa. However, all air masses have moved over regions where the atmosphere has been loaded with Saharan dust (Fig.6.e).

Among the trajectories presented in Fig.6.c, we should single out the one originating from the most heavily dusted south-western territories and having an almost horizontal path over the ground until reaching its end point above Sofia. It describes the motion of the air masses that during the measurements were present in the ABL at a height of 1 km, and where, according to the lidar profile curve, the aerosol concentration was the highest. Such a trajectory path gave us reason to assume that a considerable amount of Saharan dust, mixed with the usual aerosols generated in the city, was present in the ABL above Sofia. A brief clarification is needed here concerning the trajectories in Fig.6.d. The one starting low above the Atlantic Ocean ended over Sofia at a height of 7 km. The other ones originated from and passed through strongly dusted atmosphere above Europe, especially the one which at one point reaches South-West Africa. Thus, assisted by the information provided by the HYSPLIT and DREAM models, we believe that on April 15, 2009, we registered a unique in terms of its height (up to 12-14 km) aerosol loading of the atmosphere over Sofia, which was mainly due to Saharan dust transported to the Balkans from dusted regions over Europe.

Conclusions

We reported on several lidar investigations of atmospheric aerosol loading during Saharan dust intrusions over Sofia. These sounding examples were selected among data systematically acquired within the EARLINET projects. Aerosol layers related to desert dust were observed in the whole troposphere up to a height of 14 km. The lidar observations revealed a multilayering of the dust transport. The internal structure of the dust plumes registered varied from homogenous to well-stratified.

We should further emphasize that the results reported here not only illustrate the exceptional possibilities offered by lidars concerning remote sounding of the atmosphere, but also the good technical performance of our lidar system, which permits us to observe the whole troposphere with high spatial and temporal resolutions.

Acknowledgments. This work is supported by the project of EARLINET ACTRIS-2 (Aerosols, Clouds, and Trace Gases Research Infrastructure Network). The authors gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT model for air mass transport and dispersion and/or READY website used in this publication. The authors would like also to express their gratitude to the Earth Sciences Division, Barcelona Supercomputing Center, Spain, for the provision of the DREAM model aerosol dust data.

References

A. Papayanis, D. Balis, V. Amiridis, G. Chourdakis, et al., 2005.Measurements of Saharan dust aerosols over the Eastern Mediterranean using elastic backscatter-Raman lidar, spectrophotometric and satellite observations in the frame of the EARLINET project, *Atmospheric Chemistry and Physics*, **5**, 2065-2079.

A. Papayanis, V. Amiridis, L. Mona, R. E. Mamouri et all., 2009.Coordinated lidar observations of Saharan dust over Europe in the frame of EARLINET_ASOS project during CALIPSO overpasses: a strong dust case study analysis with modelling support, *Proceedings of SPIE*, **7479**, doi: 10.1117/12.830842, 74790C-1 ÷ 74790C-10

Albert Ansmann, Jens Bösenberg, Anatoli Chaykovsky, Adolfo Comerósabine Eckhardt, Ronaldo Eixmann, Volker Freudenthaler, and Paul Ginoux, 2003.Long-range transport of Saharan dust to northern Europe: The 11-16 October 2001 outbreak observed with EARLINET, *Journal of Geophysical Research*, **108**, AAC1-AAC12.

Albert Ansmann, Holger Baars, Matthias Tesche, Detlef Muller, Dietrich Althausen et all., 2009.Dust and smoke transport from Africa to South America: Lidar profiling over Cape Verde and the Amazon rainforest, *Geophysical Research Letters*, **36**, L11802, doi: 1029/2009GL037923

A.S. Goudie and N.J. Middleton, 2001.Saharan dust storms: nature and consequences, *Earth-Science Reviews*, **56**, 179-204

Alpert P. and Ganor E., 1993.A jet stream associated heavy dust storm in the eastern Mediterranean, *Journal of Geophysical Research*, **98**, 7339-7349

A. Deleva, A. Slesar, and S. Denisov, 2010.Investigations of the aerosol fields and clouds in the troposphere with Raman-aerosol lidar, *Bulgarian Geophysical Journal*, **36**, 26-39

Atanaska D. Deleva, Ivan V. Grigorov, Lachesar A. Avramov, Vladimir A. Mitev, Alexander S. Slesar, and Sergey Denisov, 2008. Raman-elastic-backscatter lidar for observations of tropospheric aerosol, Proc. **SPIE 7027**, 70270Y-1÷70270Y-8

Chiapello J., Bergametti G., Chatetnet B., Bosquet P., Dulac F., Santos Guares E., 1997.Origins of the African dust transpotred over the northeastern tropical Atlantic, *Journal of Geophysical Research*, **102**, 13701-13709

Duce, R. 1995. Sources, distributions, and fluxes of mineral aerosols and their relationship to climate, In: Aerosol Forcing of Climate (R. J. Charlson and J. Heintzenberg, Eds.), John Wiley, Chichester, U. K, 43–72.

De Tomasi F., Blanco A., Perrone MR., 2003.Raman monitoring of extinction and backscattering of African dust layers and dust characterization, *Applied Optics*, **42**, 1669-1709

DREAM: http://www.bsc.es/projects/earthscience/DREAM/

Draxler R. R., and Rolph G. D., 2011. HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website (http://ready.arl.noaa.gov/HYSPLIT.php). NOAA Air Resources Laboratory, Silver Spring, MD.

E. Hamonou, P. Chazette, D. Balis, F. Dulac, X. Schneider, E. Galani, G. Ancellet, and A. Papayannis, 1999.Characterization of the vertical structure of Saharan dust export to the Mediterranean basin, *Journal of Geophysical Research*, **104**, D18, 22257-22270

EARLINET; http://www.earlinet.org

F. Immler and O. Schrems, 2003.Vertical profiles, optical and microphysical properties of Saharan dust layers determined by a ship-borne lidar, *Atmospheric Chemistry and Physics*, **3**, 1353-1364

F. G. Fernald, 1984.Analysis of atmospheric lidar observations: some comments, *Applied Optics*, **23**, 652-653

Gian Paolo Gobbi, Francesca Barnaba, Riccardo Giorgi, and Alessandra Santacasa, 2000.Altitude-resolved properties of a Saharan dust event over the Mediterranean, *Atmospheric Environment*, **34**, 5119-5127.

Ina Tegen, 2003.Modeling the mineral dust aerosol cycle in the climate system, *Quaternary Science Reviews*, **22**, 1821–1834.

I. Mattis, D. Muller, A. Ansmann, U. Wandinger, J. Preibler, P. Seifert, and M. Tesche, 2008.Ten years of multiwavelenght Raman lidar observations og free-tropospheric aerosol layers over central Europe: Geometrical properties and annual cycle, *Journal of Geophysical Research*, **113**, D20202, doi: 10.1029/2007/JD009636

Joseph M. Prospero, 1999.Long-range transport of mineral dust in the global atmosphere: Impact of African dust on the environment of the southeastern United States, *Proceedings of the National Academy of Sciences of United States of America*, **96**, 3396-3403

J. Barkan, P. Alpert, 2008.Synaptic patterns associated with dusty and non-dusty seasons in the Sahara, *Theoretical and Applied Climatology*, DOI 10.1007/s00704-007-0354-9

J. D. Klett, 1981.Stable analytical inversion solution for processing lidar returns, *Applied Optics*, **20**, 211-220

L. Mona, Z. Liu, D. Muller, A. Omar, A. Papayanis, G. Papalardo, N. Sugimoto, and M. Vaughan, 2012.Ladar measurements for desert dust characterization: An overview, *Advances in Meteorology*, ID 356265, 36 pages, doi: 10.1155/2012/356265

Maria Raffaella Vuolo, Hélene Chepfer, Laurent Menut, and Gregory Cesana, 2009.Comparison of mineral dust layers vertical structures modeled with CHIMERE-DUST and observed with the CALIOP lidar, *Journal of Geophysical Research*, **114**, D09214, doi:10.1029/2008JD011219

Mitsakou C., Kallos G., Papantoniou N., Spyrou C., Solomos S., Astitha M., and Housidas C., 2008.Saharan dust levels in Greece and received inhalation doses, *Atmospheric Chemistry and Physics*, **8**, 7181-7192.

Natalie M. Mahowald, and Lisa M. Kiehl, 2003.Mineral aerosols and cloud interactions, *Geophysical Research Letters*, **30**, 1475, doi:10.1029/2002GL016762

Perez L., Tobias A., Querol X., Pey J., Künzli N., Pey J., Alastuey A., Viana M., Valero N., Gonzáles-Cabré M., and Sunyer J., 2008.Coares particles from Saharan dust and daily mortality, *Epidemiology*, **96**, 800-807

Papayannis A., Amiridis V., Mona L., Tsaknakis G., Balis D., Bösenberg J., Chaikovsky A., et all., 2008.Systematic lidar observations of Saharan dust over Europe in the frame of EARLINET (2000-2002), *Journal of Geophysical Research*, **113**, D10204, 2007JD009028

P. Kishcha, F. Barnaba, G. P. Gobbi, P. Alpert, A. Shtivelman, s. O. Krichak, and J. H. Joseph, 2005.Vertical distribution of Saharan dust over Rome (Italy): Comparison between 3-year predictions and lidar soundings, *Journal of Geophysical Research*, **110**, D06208, doi:10.1029/2004JD005480

R. L. Miller and I. Tegen, 1998,Climate response to soil dust aerosols. *Journal of Climate*, **11**, 3247-3267

Rolph G. D., 2011. Real-time Environmental Applications and Display sYstem (READY) Website (http://ready.arl.noaa.gov). NOAA Air Resources Laboratory, Silver Spring, MD

U. Pöschl, 2005.Atmospheric Aerosols: Composition, Transformation, Climate and Health Effects, *Atmospheric chemistry*, **44**, 7522-7540

Yoram J. Kaufman, Didier Tanré and Olivier Boucher, 2002,.A satellite view of aerosols in the climate system, *Nature*, **419**, 215-223, www.nature.com/nature

Yoram J. Kaufman, Ilan Koren, Lorraine A. Remer, Daniel Rosenfeld, and Yinon Rudich, 2005.The Effect of Smoke, Dust and Pollution Aerosol on Shallow Cloud Development Over the Atlantic Ocean, *Proceedings of the National Academy of Sciences of United States of America*, **102,** 11207–11212

Лидарна регистрация на вертикалната стратификация на Сахарски прах по време на транспорт над София

А. Делева

Резюме: Атмосферните частици (аерозолите) и главно минералният прах въздействат на живота на Земята чрез различни начини. Най-важните параметри за определяне на влиянието на аерозолите върху климата и екологичното състояние на околната среда са техните оптични параметри (коефициент на обратно разсейване и на екстинкция) както и тяхното разпределение в пространството. В тази работа са анализирани резултати, получени от вертикално дистанционно сондиране на атмосферата по време на няколко нахлувания на Сахарски прах над София. Изследванията са направени с аерозолен ЛИДАР (*LI*ght *D*etection *A*nd *R*anging), базиран на Nd:YAG лазер. Описаните експерименти илюстрират, че регистрираните с лидара аерозолни/прахови слоеве се различават по височина, плътност, дебелина и стратификация по височина. Някои от резултатите показват, че аерозолите могат да достигат и да присъстват в тропосферата до изключителната височина 14 km. В тази работа лидарните данни са представени като изчислени вертикални профили на атмосферния коефициент на обратно разсейване и цветни карти на височинно-времевата еволюция на регистрираните аерозолни полета в атмосферата. При анализа на експерименталните данни са използвани прогнозите на HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) и DREAM (Dust REgional Atmospheric Model) моделите за дните на измерванията, за да се направят изводи за произхора на регистрираните аерозоли във въздуха.