LIDAR MONITORING OF SAHARAN DUST TRANSPORT OVER THE CITY OF SOFIA IN THE PERIOD 2006-2008

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Abstract. Desert dust aerosols are the most abundant and massive type aerosol particles that are present in the atmosphere. One environmental consequence of atmospheric dust loadings is their significance for climate through a range of possible influences and mechanisms. In this work results from three years long lidar monitoring of Saharan dust transportation over the city of Sofia are presented. Remote atmospheric investigations are carried out at the second Nd:YAG laser wavelength in the period 2006-2008. Vertical profiles of the aerosol backscatter coefficient are processed and analyzed. The mass temporal evolution and the spatial distribution of the registered desert dust layers are illustrated by 2D-colormaps in height-time coordinates. The observations described here are in good agreement with the forecasts of Barcelona Supercomputing Centre, concerning Saharan dust transport to Europe.

Key words: Saharan dust transport, troposphere, lidar, aerosol.

Introduction

Atmospheric aerosols are a significant source of direct and indirect global climate forcing. Furthermore, in the past decades several studies indicated a clear connection between suspended particulate matter and health effects (Tasić et al., 2006; Prospero et al.,1999; Perez et al., 2008; Mitsarou et al., 2008).

There is a natural aerosol component consisting mostly of soil dust, sea salt and organic matter that is geographically and seasonally variable. Global mineral dust emissions are estimated 100-500 millions of tons per year, of which the largest part is attributed to deserts (Frontozo M. et al., 2007). Sahara is the major source of mineral dust on Earth. It produces more aeolian soil dust than any other world desert (around 60-200 millions of tons per year). Under certain weather conditions, dust particles from Saharan desert get transported over the Mediterranean Sea to most of Europe. The Balkan Peninsula is under the influence of Saharan dust transport and deposition, too (Vukmirović et al., 2004). The presence of desert particles in the air modifies atmospheric radiation properties and thus affects regional climate.

The residence time of aerosols in the atmosphere (in particular of mineral dust) is of only a few days; therefore their distribution is highly variable both in space and time. This is the reason why remote sensing of aerosols and the lidar technique have increasingly developed as the best method and apparatus, respectively, to catch individual events and to integrate them into regional or global pictures of the aerosol transport.

In recent years many studies have been recognized in other more precisely to understand and study the properties and the different influences of desert mineral dust. Lidar Networks such as the **E**uropean **A**erosol **R**esearch **Li**dar **N**etwork (EARLINET) seem to be the most appropriate for an adequate monitoring of long-range dust transport (EARLINET web-site; Papayannis et al., 2008). For the first time within this framework the Saharan dust loadings over Europe are frequently observed and documented. The results deduced from the collected lidar data in the frame EARLINET show that multiple dust layers of variable thickness (300-7500 m) have been observed. The center of mass of these layers was located in altitudes between 850-8000 m. However, the mean thickness of the dust layer typically stayed around 1500-3400 m and the corresponding mean center of mass ranged from 2500 to 6000 m. Several models have been developed for simulation and prediction of the atmospheric dust cycles. During the EARLINET project, **D**ust **RE**gional **A**tmospheric **M**odel (DREAM) is used as one of the forecasting models to issue early warning of Saharan dust transport over Europe (DREAM web-site). Our Raman-aerosol lidar is involved in coordinate lidar measurements (in particular observations of Saharan dust events) within the EARLINET-ASOS project from 2006. The carried out lidar measurements over the city of Sofia under Saharan dust outbreaks conditions concerned the retrieval of the vertical profiles of the aerosol backscatter coefficient at 532 nm using the Fernald inversion technique (Fernald, 1984).

Methodology and lidar description

Laser remote sensing is an active investigative method because it uses laser light for the retrieval of atmospheric parameters. This is different from passive methods, which use light from natural sources (sun, moon) or thermal emission. Short laser pulses are emitted into the atmosphere and the portion scattered back is subsequently detected. The magnitude of the received lidar signal is determined mainly by the energy of the laser pulse and both the backscatter and attenuation atmospheric properties. These optical characteristics of the air depend upon the number, size distribution, shape and refractive index of the atmospheric constituencies (molecules and particles) with which the laser beam interacts. Since the light travels at known velocity, measuring the delay time between the emitted and the received pulses one is able to calculate the distance of the probed atmospheric volume under study (Measures, 1984).

Lidar (**Li**ght **D**etection **A**nd **R**anging) is a well-established optical system for measuring trace molecular constituents, aerosols, atmospheric structure and dynamics, clouds, and also meteorological parameters, such as temperature, humidity and wind velocity.

The capability of the lidar technique to derive range-resolved vertical profiles of the aerosol optical parameters with very high spatial and temporal resolution was used to identify the altitude of dust layers and temporal evolution of intrusions. The Raman-aerosol lidar developed at the Institute of Electronics was used in this study. The light source of the lidar is a Q-switched frequency-doubled Nd:YAG laser (pulse energy: up to 1 J at 1064 nm, 100 mJ at 532 nm; pulse duration: 15 ns FWHM; repetition rate: 2 Hz) provided with a single-pass optical amplifier. Laser light backscattered by atmospheric molecules and aerosols is received by a Cassegrain telescope (aperture: 35 cm; focal distance: 200 cm). The parallel output beam formed by the telescope output optics is passed to the spectrum analyzer for spectral separation of the incoming optical signals. The wavelength separator consists of three selective spectral channels for 1064nm, 532nm and 607nm (the Raman shift wavelength of nitrogen molecules with respect to the one of the sounding laser radiation at 532nm). Data acquisition system includes both hardware and software components. These are newly developed products, specialized in accomplishing the lidar measurement and data processing. The hardware components have been designed as an integrated photo-receiver modules consisting of photo-receiving sensor, controlled photo-receiver power supply, amplifier, 14-bit ADC, and USB-interface for computer connection. Distinguishing features of the photo-receiver modules are high sensitivity, high amplification factor, low noise level, low power consumption, small dimensions and weight. The data acquisition software contains two main programs and several auxiliary ones. The first main program is designed for real-time control of the lidar system during measurements, reading information from the photo-receiving modules, displaying lidar profiles at each laser pulse or after averaging, and saving data. The second main processing program provides input of lidar measurement data, pre-processing of raw data, writing processed results into a database.

Experimental results

In this work we present several lidar results of a Saharan dust event observed over the city of Sofia (42^{o}39’14”N, 23^{o}23’14”E). The remote laser monitoring is carried out at the second Nd:YAG laser wavelength (532 nm) in the period 2006-2008. The investigations are performed after sunset, under low background conditions. In figures DREAM dust model maps are supplemented. They show that Saharan dust intrusions in Balkans are forecasted by the Barcelona Supercomputing Center for the days of our investigations.

Two black and white color maps in Fig.1 and Fig.2 illustrate spatial and temporal evolution of the Saharan dust layers observed on 29 June and 26 September 2006, respectively. The tick-labels on x-axis mark the start time of consecutive measurements with integral time 10 minutes (accumulation of data by 1200 different profiles, received by every laser impulse). The color scale (on the right) shows the magnitude of calculated backscatter coefficient. The presence of dense aerosol layers in the free troposphere is also visible on the selected backscatter profile presented in the figures. The lidar investigations of the atmosphere during the two days are carried out under cloud free conditions. However the obtained results show, that the observed events differ by means of density, thickness, height stratification and altitude of mass center location of the dust layers.

The calculated values of the aerosol backscatter coefficient give us reason to make the conclusion that on 29 June 2006 over the city there was desert dust at an altitude up to 7,5 km (Fig. 1). The atmosphere was relatively tranquil during the experiments thus the borders of the two parts of the layer are clearly visible, as seen on the color graph. The lower part is situated in the mean altitude range 1,8-3,5 km. It is more dense with peak of the order 4,5x10^{-6} [$m^{-1}sr^{-1}$] and centre of mass located around 2,8-3 km. The upper part has lower density and more even mass distribution (the mean value 1,3 x10^{-6} [$m^{-1}sr^{-1}$]) in the altitude range 4-7 km. The larger values of backscatter coefficient obtained at altitudes lower than 1,5 km are ascribed to the gravity deposition of the large dust particles and the presence of anthropogenic aerosols emitted in the planetary boundary layer over the city. The black circle marks the location of Bulgaria on the DREAM forecast map.

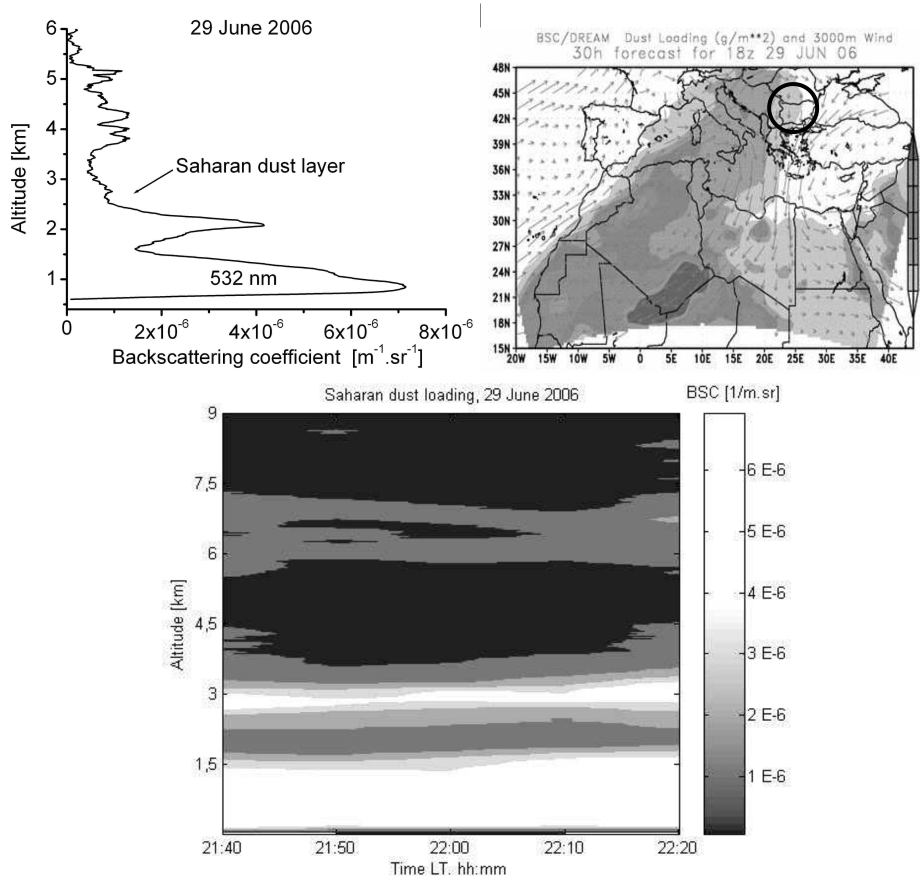

Fig. 1. Saharan dust time-spatial distribution over the city of Sofia on 29 June 2006.

Figure 2 presents results from the monitoring of dust loading on 26 September 2006**.** Saharan layer is situated in the altitude range 2-3,2 km**.** In contrast to the previously described investigation it has lower density (calculated backscatter coefficient is in the interval (1,2-2,4)x10^{-6} [m^{-1}sr^{-1}]) and has no clearly distinguished center of mass. Dynamic space density distribution has been detected. Most probably the observed temporal evolution of the layer is caused by intense vertical and horizontal air currents.

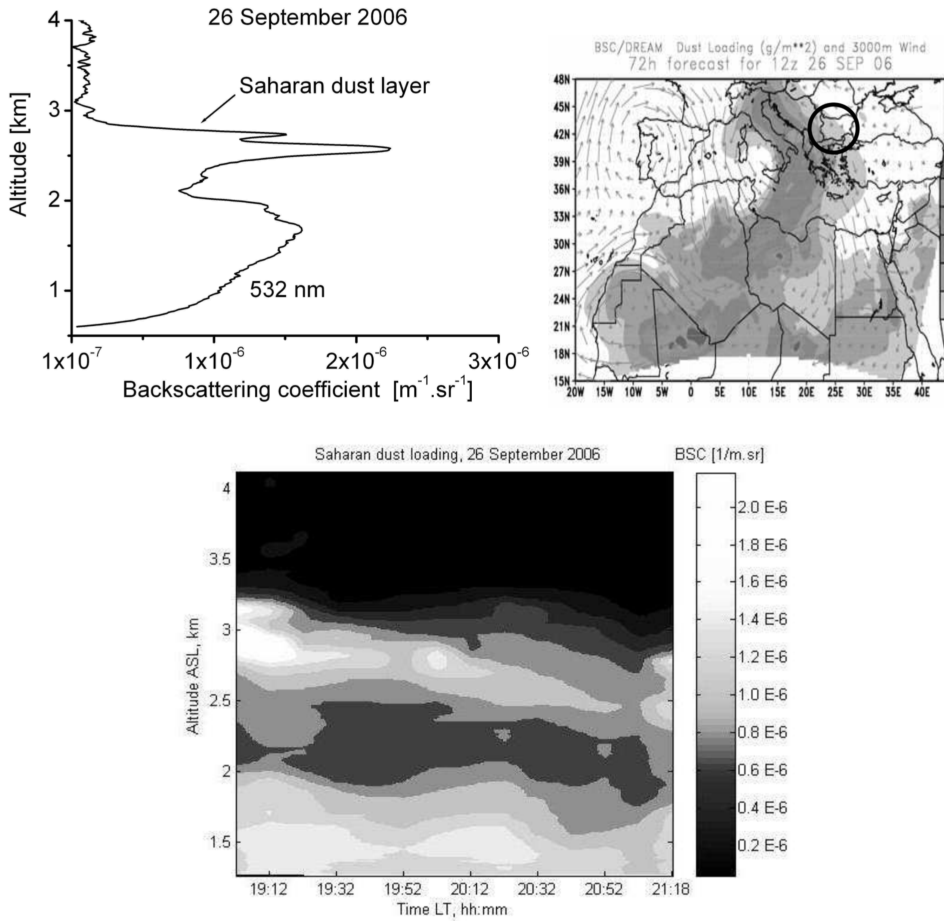

Fig. 2. Saharan dust time-spatial mass distribution over the city of Sofia on 26 September 2006.

The high output power of the laser in combination with the high spectral selectivity and sensitivity of the lidar receiving system give us opportunity to observe the atmosphere up to 16 km. Thus during the monitoring of Saharan dust intrusion highly situated aerosol layers and clouds are simultaneously registered. In the following graphs such cases are illustrated by means of lidar profiles. On 28 June 2007 and 19 April 2008 the acquired experimental data are highly similar. From the calculated values of the aerosol backscatter coefficient it is seen that most of the time of the experiment the atmosphere above the Saharan dust was clear (left profiles in Fig 3) but in a short time a dense thin aerosol layer is formed at an altitude about 12 km (right profiles). Probably it is cirrus cloud. Cirrus clouds have been identified to be one of the most uncertain objects in atmospheric research. They are situated in the altitude range from 6 km to the tropopause top. This type of cloud is composed primarily of ice crystals and very often exist only in short time interval.

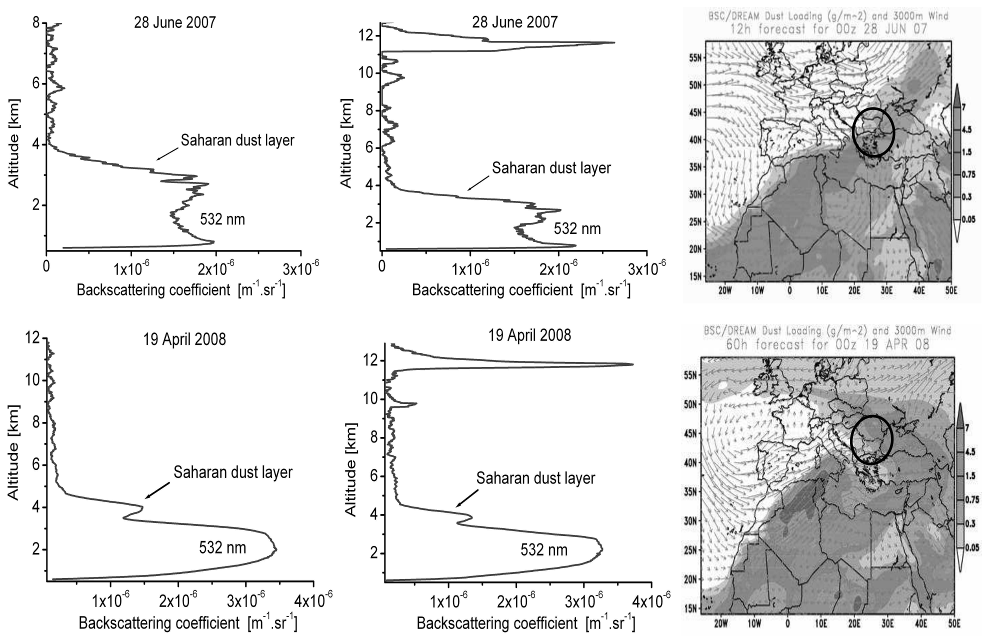

Fig.3. Saharan dust layers and thin cirrus clouds situated at the altitude 12 km.

Rarely observed state of the atmosphere has been registered on 14 September 2006 (Fig. 4). For a time period of one hour 18 profiles with 3 minutes accumulation time have been recorded. During the monitoring of the Saharan event there was uninterrupted registration of dense aerosol layer at 9-16 km height. Distinguishing feature of the highly situated layer is its dynamic altitude density distribution which is clearly seen on the included lidar profiles.

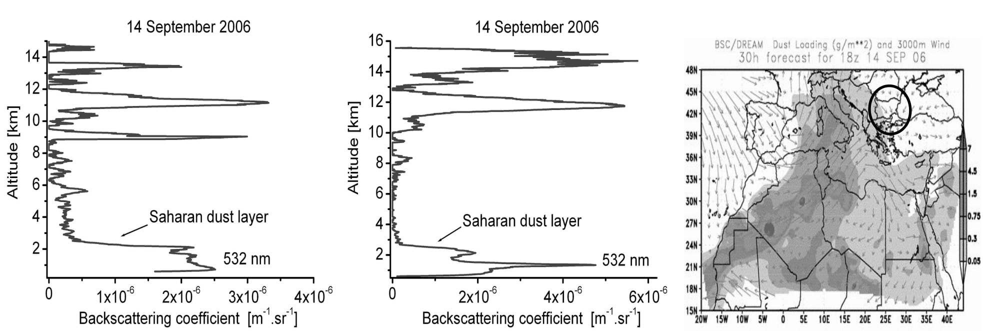

Fig.4. Saharan dust layer and thick aerosol layer situated in the altitude range 8-16 km.

Conclusions

As a partner of EARLINET-ASSOS project from 2006 we have participated in the network activities. A large database is created accumulating the aerosol backscatter profiles. The calculated data are uploaded on the EARLINET server in Hamburg. The results presented in the current paper are derived from the regular lidar measurements performed by our team in the framework of the project. One can deduce from the included lidar profiles that the sounding Saharan layers differ substantially by means of density, thickness, temporal mass stratification and location altitude. In some of the described cases the boundary between the dust desert layer and planetary boundary layer is clearly distinguished (Fig.1, Fig.2, a lower example in Fig.3), but in some other ones the layers are penetrating one another (Fig.4, an upper example in Fig.3). This difference is associated with a variety of the weather conditions and air currents in the days of the experiments.

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Лидарен мониторинг на пренос на прах от Сахара над София през периода 2006-2008

А. Делева

Резюме. Пустинният прах е аерозолът в атмосферата в най-голямо количество и с най-големи частици. Важността на атмосферния прах за околната среда е неговото влияние върху климата, което се осъществява чрез различни въздействия и механизми. В тази работа са представени резултати от тригодишен лидарен мониторинг на пренос на прах от Сахара над София. Дистанционните изследвания на атмосферата са направени с втората хармонична на Nd:YAG лазер през периода 2006-2008г. Вертикални профили на аерозолния коефициент на обратно разсейване са изчислени и анализирани. Времевата еволюция и пространственото разпределение на масата на регистрираните слоеве пустинен прах са илюстрирани чрез 2D-цветни карти. Описаните тук наблюдения са в добро съответствие с прогнозите на Суперкомпютърния център в Барселона за пренос на Сахарски прах към Европа.