LIDAR MONITORING OF CLOUDS AND AEROSOL LAYERS

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Abstract. Aerosols and clouds are of central importance for global climate, atmospheric chemistry and physics, ecosystems and public health. In order to better understand effects on the environment, knowledge of their vertical structure, including parameters such as the thickness, location, top and bottom height, is necessary. In this work we present several examples of lidar monitoring of clouds and aerosols layers which are chosen from the measurements performed in the period 2006-2012. The investigations are carried out with an aerosol lidar, equipped with Nd:YAG laser at wavelengths 532 nm and 1064 nm. Lidar is located in the Institute of Electronics of Bulgarian Academy of Sciences. Experimental data are presented in terms of vertical backscatter coefficient profiles and color maps of the atmospheric field stratification evolution. The results of our atmospheric studies have demonstrated that clouds could be formed with widely differing thicknesses (in the interval 0.5–5 km) and could exist at various heights (2-16 km) in the troposphere up to the tropopause. Some experiments illustrate simultaneously detection of clouds and Saharan dust layers. Also, here we include results of lidar detection of anthropogenic aerosol load over Sofia city. We employed HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) backward trajectories and DREAM (Dust REgional Atmospheric Model) forecasts to make conclusions about atmospheric aerosol's origin. Depicted measurements are extracted from regular lidar investigations of the atmosphere within the framework of the European Aerosol Research Lidar Network (EARLINET).

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

Introduction

The atmosphere is a complex system with many components interacting through a large number of processes on a wide range of scales. Aerosols and clouds participate in determining the Earth's radiative budget, climate and weather (J.E. Penner et al., 2001; Guibert, S. et al., 2005; Solomon, S. et al., 2007). The changes in the energy fluxes of solar radiation (maximum intensity in the visible spectral region) and terrestrial radiation (maximum intensity in the infrared spectral region) in the atmosphere induced by changes of atmospheric compositions and/or surface properties are referred to as “radiative/climate forcing”.

Aerosols are liquid or solid particles suspended in the air. They come from a variety of natural and human processes. On a global basis, the bulk of aerosols originate from natural sources, mainly sea salt, dust, volcanoes and wildfires. Desert dust particles represent a large fraction (of the order of 30-50%) (Gian Paolo Gobbi et al., 2000) of the naturally occurring tropospheric aerosols and the scientific community has made great efforts to document and understand the interactions of mineral aerosols (dust) with environment. The Saharan desert is the largest source of dust and produces more aeolian mineral particles than any other world desert (Prospero M. Joseph, 1999; Vukmirović Z.M. et al., 2004; Perez L. et al., 2008). At present the quantity of anthropogenic emissions in the atmosphere increases because of rapid growth of the industry, transport, processes of urbanization, etc. Human-produced particles can be dominant form of aerosol in highly populated and industrialized regions, and in areas of intense agricultural burning. Urban aerosols have been identified as important species of concern due to their potential health and environmental impacts (U. Pöschl, 2005; Tasić M. et al., 2006; Atanaska Deleva et al., 2010). Key parameters for determining the impacts of aerosols to climate forcing and ecological state of the environment are their optical parameters (extinction and backscatter coefficients), as well as their spatial distribution. Aerosol effects on climate are generally classified as direct or indirect with respect to radiative forcing of the climate system. The direct aerosol impact is caused by scattering or absorbing sunlight, and absorbing and emitting some terrestrial infrared radiation. The indirect effect is provoked by the aerosol capability to act as cloud condensation nuclei. Also, aerosols alter warm, ice and mixed-phase cloud formation processes by increasing droplet number concentrations and ice particle concentrations. In this manner, aerosols influence cloud cover, cloud optical properties and lifetime (Natalie M. Mahowald, 2003). The effect of aerosols on the radiative properties of Earth's cloud cover is defined as indirect effect of aerosols, or indirect climate forcing.

Clouds are groups of tiny water droplets or ice crystals in the air and are formed by different processes. They can come in all sizes and shapes, and can form near the ground or high in the troposphere. Clouds contribute differently to short-wave and long-wave radiation depending on their type, altitude, thickness, structure, particle size, etc. On the one hand, they act like greenhouse gases, absorbing infra-red thermal radiation from the Earth and trapping the heat in the lower atmosphere. On the other hand, they reflect incoming solar radiation back into space (albedo effect), effectively cooling the planet. The information with respect to cloud vertical distribution is required because light scattering and absorption are altitude dependent, as are cloud properties (Ulrike Lohmann et al., 1995; S. Veerabuthiran, 2004; L. L. Pan et al., 2011). For example, the greenhouse effect is weak for low altitude clouds, so their albedo effect dominates. In contrast, cold high altitude clouds (Cirrus clouds) may either cool or warm the climate depending of their geometrical characteristics and location. These two opposing effects are an important difference between Cirrus clouds and other hydrometeor layers in the atmosphere. Most frequently Cirrus clouds are thin and wispy. They are presented at all latitudes and are formed in the upper levels of the troposphere at heights greater than 6 km. Cirrus clouds are composed predominately or wholly of ice non-spherical crystals, reflecting the extreme cold, and they can take a variety of shapes and thickness. As a general rule, Cirrus clouds are thin enough to be transparent or very close to it because humidity is low at such high altitudes.

Low-altitude clouds play an important role in global climate forcing, weather, and precipitation. In particular, low clouds often have large liquid water part and are involved in interactions with anthropogenic aerosols in the planetary boundary layer. Therefore, it is a significant challenge to accurately measure their optical and geometrical properties in order to assimilate them into global climate model. Unfortunately, for satellite sensors with visible and near-infrared channels, measurement of low and optically thin clouds from space is very difficult due to their partial transparency, land surface emission, and fact that they are relatively warm. On the other hand, lidars (LIDAR-LIght Detection And Ranging) are an excellent way to obtain high-resolution aerosol or cloud data to complement satellite data. They are increasingly used because the investigated atmospheric parameters could be retrieved with high spatial and temporal resolution. Lidar measurements can elucidate the aerosol concentration, optical depth, cloud position and thickness which are important for a better understanding of the Earth-radiation budget and climate. The largest active aerosol research project in Europe EARLINET (European Aerosol Research Lidar Network) can provide an important contribution in the aerosol study. It is founded as a coordinated network of lidar stations that uses advanced methods for vertical profiling of the atmosphere. EARLINET was the first very important step in our continent to unite the lidar groups with the main goal of establishing a quantitative comprehensive statistical data base of both horizontal and vertical aerosol distribution on a continental scale. Additional more specific measurements (on Saharan dust, volcanic ash, forest fire) are also included in the project work program (Papayannis A. et al., 2008). Bulgarian lidar station at Sofia was involved in systematic investigations on a regular base of three measurements per week according to the schedule of the EARLINET project (EARLINET:http://www.earlinet.org).

In this work, we present results of laser remote detection of aerosol layers and clouds in the troposphere over Sofia. Some experimental examples illustrate observations of clouds during Saharan dust transport. We should emphasize that the results reported here not only illustrate the exceptional opportunities offered by lidars concerning sounding of the atmosphere, but also the good technical capabilities of our lidar system, which permits us to observe the whole troposphere with high spatial and temporal resolution.

Technical equipment and data processing

The results presented here are based on measurements with an elastic backscatter Nd:YAG lidar. It is described in details elsewhere (Atanaska D. Deleva et al., 2008; A. Deleva et al., 2010), and for that reason only brief description of its set-up is given below. Lidar system is configured in a mono-static biaxial alignment pointing at angle 32º with respect to the horizon, as determined by its disposition in the lab. Therefore despite signals from as far as 30 km distance are recorded the maximum sounding height is limited to 16.4 km above ground level. A solid-state Q-switched frequency-doubled Nd:YAG laser (pulse energy: up to 600 mJ at 1064 nm, 80 mJ at 532 nm; pulse duration 15 ns FWHM, laser-beam divergence 3 mrad, fixed repetition rate 2 Hz) is utilized as a light source. Laser radiation backscattered by the atmosphere is received by a Cassegrain telescope (aperture: 35 cm; focal distance: 200 cm). The output beam from the telescope is passed to the spectrum analyzer for separation of the incoming optical signals. Data acquisition system includes hardware and software components. The hardware have been designed as an integrated photo-receiver modules consisting of photo-receiving sensor, controlled photo-receiver power supply, amplifier, 14-bit analog-to-digital converter (ADC), and USB-interface for computer connection. The data acquisition software contains two main programs. The first one is designed for real-time control of the lidar system during measurements. Received signals are digitized every 100 ns with an ADC, resulting in a 15 m range resolution (about 7.5 m altitude resolution). Thus, the lidar measures the temporal evolution of atmospheric aerosol backscatter with high time and range resolution. The second main program is a package providing the calculation of the atmospheric backscatter coefficient and determination of the error in the estimates. The well known Klett-Fernald-Sasano inversion algorithm is used in these retrievals (J. D. Klet, 1981; F. G. Fernald, 1984; Ya Sasano et al., 1985). The Nd:YAG lidar entered on operation in the beginning of 2006, equipped with only one spectral channel at wavelength 532 nm. At that time the lidar was included in the EARLINET network and we started to perform regular lidar measurements with accord to the project schedule. In 2008 was put into operation the second spectral channel for registration of lidar signals with wavelength 1064 nm and thus we were able to perform atmospheric monitoring with the first and second harmonic of the laser radiation. The decision to use one or two laser wavelengths depends on the working condition of the system and the weather. The daily investigations in sunny weather are performed with the first harmonic (1064 nm) most often because the background of the received signal is lower and there is no risk of saturation of the photo-receiver. Thus, presented here backscatter coefficient profiles from 2006 till now are obtained by single- or double wavelength monitoring of the atmosphere.

Lidar observations and comments

Lidar measurements described below are obtained within the frame of the EARLINET. A large database is created accumulating the aerosol backscatter profiles until now. The calculated data are uploaded on the common EARLINET-server in Germany. During EARLINET project, DREAM (Dust REgional Atmospheric Model) is used to make conclusions about the type and the origin of the aerosol layers, observed by the lidar (DREAM:http://www.bsc.es/projects/earthscience/DREAM). DREAM-weather forecast maps elaborated by Barcelona Supercomputing Center (BSC) give an image of the wind direction and speed, position of clouds and magnitude of dust load in the atmosphere above North Africa and Europe. In this paper, the location of Bulgaria on the DREAM-maps is indicated by a black circle. HYSPLIT (**HY**brid **S**ingle-**P**article **L**agrangian **I**ntegrated **T**rajectory) model provides additional information about the origin of the detected aerosol layers (Draxler R. et al., 2003; Rolph G., 2011). It represents a complete system for computing simple air parcel trajectories to complex dispersion and deposition simulations. The calculations of backward air mass trajectories give a plot of the road that the air mass traversed for a chosen time period before to arrive to the location of lidar observations. Both DREAM and HYSPLIT models are freely available on the Web.

We analyze the results of the lidar atmospheric sounding calculating vertical backscatter coefficient profiles and compiling time evolution maps of these profiles or maps of the range-corrected measurement signals (RCS). Since the magnitude of the atmospheric backscatter coefficient value is proportional to the aerosol density, the changes of the calculated profiles in time and space illustrate the temporal evolution and the stratification of the aerosol fields or clouds over the lidar station. RCS is produced by subtracting the estimated background noise from the raw lidar signal and multiplying by the square of the distance to the backscattering atmospheric sample. We present here the results mainly in terms of vertical atmospheric backscatter profiles (x-axis represents the value of the calculated atmospheric backscatter coefficient; y-axis – the altitude above sea level, ASL). The measurement date and laser sounding wavelength are written over the lidar profile plot. Also, in this work we conventionally call the clouds observed "low" and „high" depending on their location in the troposphere. The first group comprises clouds situated roughly up to 6 km, the second one - clouds above 6 km.

Figure 1 shows the results of simultaneous lidar observations of the Saharan dust load and low clouds. This is expected because aerosol particles can act as cloud condensation nuclei that form clouds (Sassen, K. et all., 2003). The measurements are performed on 31 March 2009 and 3 October 2012. Experimental examples described below illustrate Saharan dust transport over Sofia in early spring and in the beginning of the autumn. Saharan dust outbreaks over the eastern Mediterranean, including the Balkans, occur predominantly during spring and early summer, but autumn can also be considered a period with Saharan incursions**.** As a partner of EARLINET we participate in the Saharan-dust-transport network activities (A. Deleva, 2010).

The measurement on 31 March 2009 was performed in the morning (7:51-9:47 UTC, universal time coordinate). For this day DREAM-model (Fig.1 c) forecasted strong Saharan dust load over Mediterranean Sea and Central Europe, including Bulgaria. The lidar profile (Fig.1 a) outlines the registered cloud with center of mass at 5.8 km (cloud's base and top 5.5 km and 6.5 km, respectively) and the aerosol layer just below it in the range 3.5-5.5 km with center of mass at about 4.5 km. Besides that it is visible that the atmosphere was aerosol loaded also below 3.5 km as below that altitude the concentration of particles gradually increases. For the period of the measurement we found HYSPLIT backward trajectories (for 100 hrs duration) in the altitude range 1.5-6 km, which pass over Northern Africa/Sahara desert and across the highly-dusted space over Mediterranean Sea before the end point above Sofia. This is a reason to suppose that the air masses in the range 1.5-6 km were transported desert aerosols from Africa. As before mentioned, HYSPLIT backward trajectories show how the air masses had moved for chosen period of time (here 100 hours) before they arrive over the lidar station on particular altitude (here the range 1.5-6 km). In Fig.1b we include three of the calculated air mass trajectories, two of which (4.5 km and 5.8 km) coincide with the abovementioned mass centers of the detected layer and cloud. The third trajectory (2 km) is in the range 2-3.5 km, where we most often register Saharan dust layers above PBL (planetary boundary layer). The high-altitude trajectory originated from above the Atlantic Ocean, passed over Sahara and, as seen in Fig.1b, has kept the direction of their motion semi-constant until reaching Sofia. Probably, these quickly moving air streams brought humidity from above the Atlantic, which we observed as a cloud. The lower trajectories display that the air masses at altitudes 4.5 km and 2 km have been moving, accordingly very close above Sahara's surface and Libyan dessert some days before. It is certain that they have been transporting a large amount of African desert dust. Based of the two models' forecast, we draw the conclusion that the aerosols registered by us in the range 3.5-5.5 km were of Saharan origin. Additionally the image of the trajectory on 2 km altitude supports our opinion that the air under that layer contained not only anthropogenic aerosols typical for PBL over city, but also long-distance transported particles from Africa.

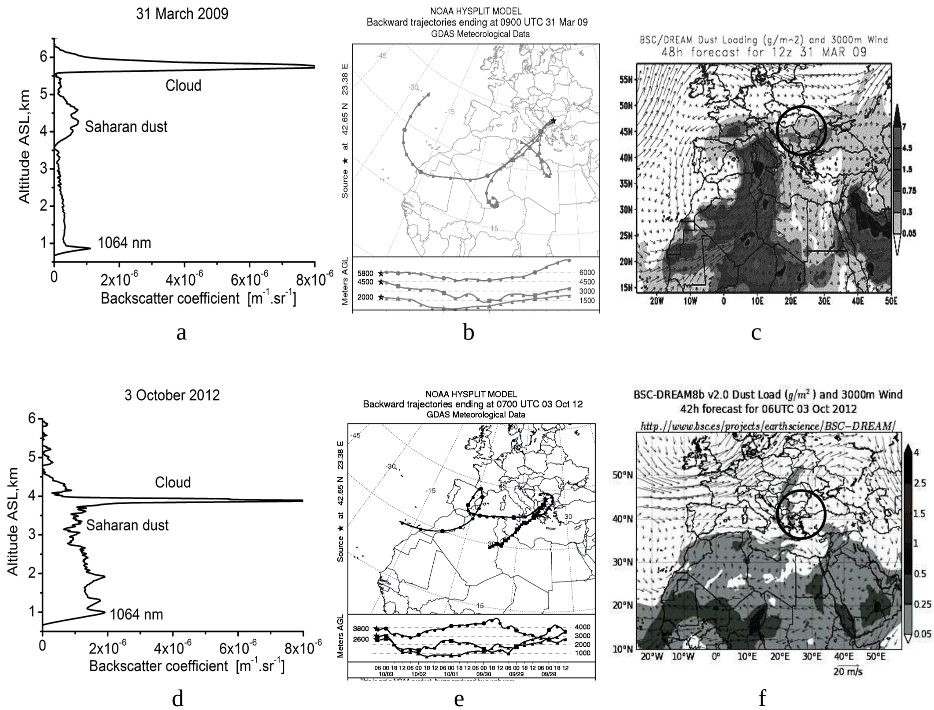
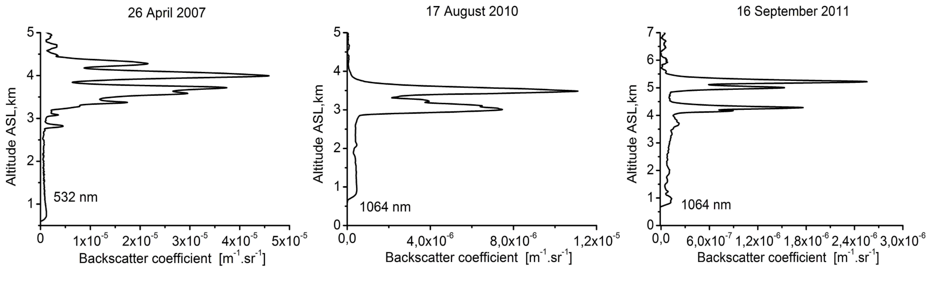


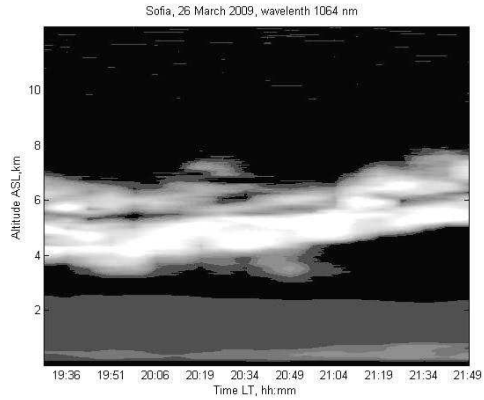
Fig.1. Lidar observations of Saharan dust and clouds: a), d) – retrieved atmospheric backscatter coefficient profiles; b), e) – HYSPLIT model backward trajectories and c), f) – DREAM forecast maps showing Saharan dust transport over Bulgaria (Sofia) on 31 March 2009 and 3 October 2012.

On 3 October 2012 we also registered low cloud during Saharan dust incursion (Fig.1 d, e, and f). The investigation started at 7:37 UTC and ended at 8:52 UTC. We registered a thin cloud with a mass center at about 3.8 km and an aerosol load over Sofia reaching 4.5 km (Fig.1. d). It is interesting to comment on the DREAM-model forecast for the time of the measurement (Fig.1 f). According to this forecast, a narrow plume of Saharan dust would be raised, be directed towards Europe and reach the northern parts of the continent. The dust should spread over Bulgaria's western parts, where Sofia is located. For the period of the measurement we calculate HYSPLIT air mass backward trajectories (for 140 hrs duration) in the altitude range 1.5-5 km. We should note in advance here that the analysis of the corresponding HYSPLIT maps revealed that the movement of the air flows in the range 3-5 km and of those in the lower atmosphere up to 2.7 km differ substantially. The difference is in the fact that the air masses in the shown higher range have moved over Sahara, as the ones in the lower parts of the atmosphere the air flows were kept and moved in closer to Bulgaria regions. Besides that in accordance with the DREAM forecast the atmosphere over the most part of these regions was not loaded with Saharan dust. The described till now is illustrated with the HYSPLIT map in Fig.1e where we include three backward trajectories, which are located at altitude 2.6 km, 3 km and 3.8 km. The black-and-white image makes hard distinguishing the trajectories in altitude, so we will clarify it in more detail. The trajectory which starts over the Atlantic ocean and moves over Sahara shows the movement of the air masses which during the investigation were over the lidar station on height 3.8 km. They transported humidity and desert dust which most probably have participated in the creation of the registered cloud over the lidar station. The movement of the which during the investigation are on 3 km over Sofia is shown with the trajectory which starts from Sahara. On the lower part of HYSPLIT-map is visible that these air flows were moving close over the Sahara and Mediterranean surface. That led us to the conclusion that the upper part (3-4.5 km) of the observed aerosol layer contains substantial amount of Saharan dust. Totally opposite is our conclusion for the origin of the aerosols in the atmosphere up to 2.7 km altitude. As before mentioned the analysis of the HYSPLIT trajectories showed that the lower air flows were moving close to or directly above Earth surface in regions close to Bulgaria (HYSPLIT map shows the trajectory at 2.6 km). That’s why above all the low air streams were carrying anthropogenic aerosols and ones emitted by the Earth surface. The described up to now we can summarize as follows. On 3 October 2006 we have registered an aerosol load of the atmosphere above Sofia which extended up to 4.5 km height. In the region 3-4.5 km the aerosols had Saharan origin while at lower levels prevailed anthropogenic and ground-emitted aerosols. The measurement described here is interesting because we have registered Saharan dust event in the autumn, which is possible, but rare. However that incursion could be expected because the weather in the beginning of October 2012 was unusually warm for the season (at places with temperatures above 30ºC). The reason for those summer temperatures was the penetration of hot air masses from Africa in Europe. On the basis of the lidar results we could conclude that the air currents from South have transported considerable amount of aerosols from the Sahara desert.

On Fig.2.(a-c) we show some more examples of lidar observation of low clouds, situated on different height and with different stratification.



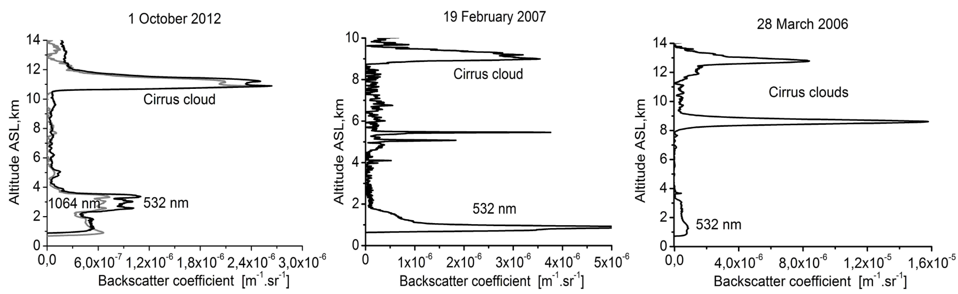
a b c



d

Fig.2. Lidar observations of low clouds: a), b), c) - retrieved atmospheric backscatter coefficient profiles; d) - RCS-color map of the spatial distribution of cloud field over Sofia on 26 March 2009.

Figure 3 presents the results of several measurements of Cirrus clouds, located above 6 km.



a b c

d e f

Fig.3. Lidar observations of high altitude Cirrus clouds.

We conventionally call the Cirrus clouds lidar detected “thin, typical and thick” depending on their geometric thickness (the difference between the cloud’s top and base). The first group comprises high clouds with thickness up to 0.5 km, the second, with thickness 1-2 km, and the third, more than 3 km. Following our proper data set of Cirrus cloud observations from 2006 till now, we could make a rough estimate concerning registration frequency of different types of high altitude clouds, as follows. In most of the lidar observations we have observed typical Cirrus clouds with thickness 1-2 km situated within the range of heights 9-13 km (Fig.3 a, b). We registered thin clouds at various heights (Fig.3 b, c, d) very rarely. Thick clouds (Fig.3 e, f) exist in the atmosphere predominantly in the cold winter months. The base and top of the Cirrus clouds observed cover a large altitude range (5-16 km) in the upper troposphere.

Figure.4 illustrates simultaneous lidar observations of clouds situated in the large altitude range (4-13 km). The measurement was performed over the lidar station on 6 April 2009.

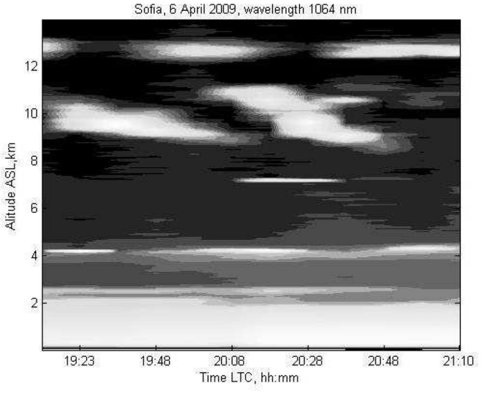


Fig.4. RCS-map of the cloud field stratification measured on 6 April 2009.

In Fig.5 we present the results of several lidar measurements performed on no-Saharan-dust-affected days. The retrieved lidar profiles from the observations carried out on 6 July 2006, 23 June 2011, and 16 September 2011 display we detected aerosol layers extended to 3.5 km and 5.5 km heights.

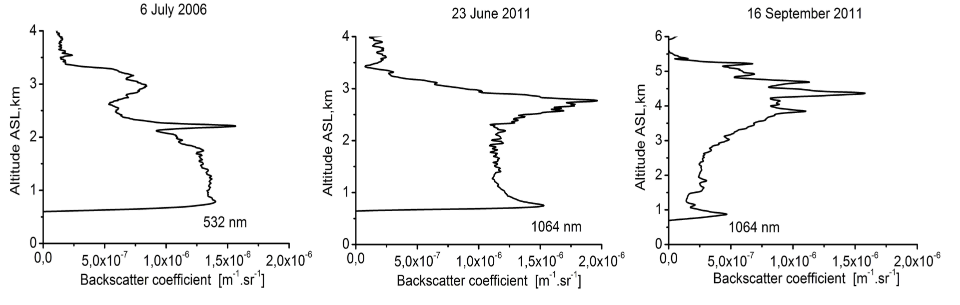
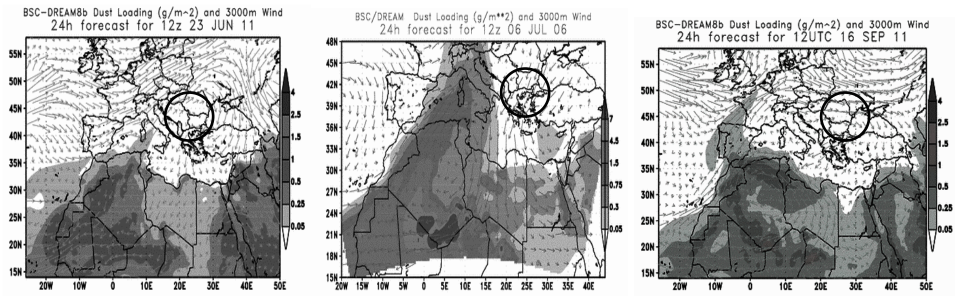


Fig.5. Retrieved atmospheric backscatter coefficient profiles showing considerable aerosol loading over Sofia on no-Saharan dust affected days.

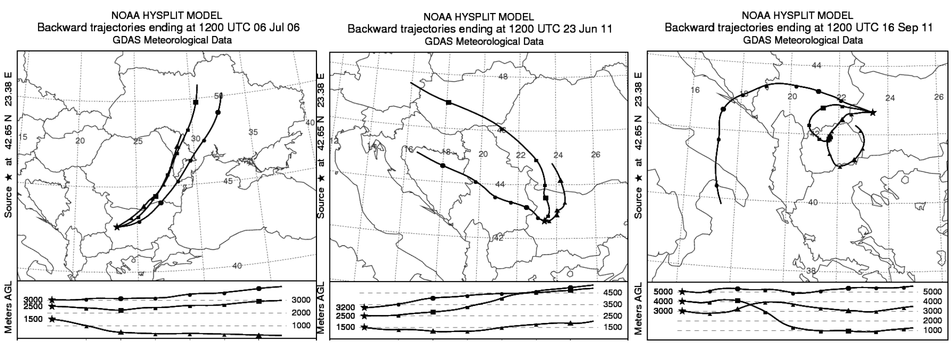
DREAM forecasts (Fig.6) for the days of lidar monitoring show an atmosphere free of desert dust over Balkans.



a b c

Fig.6. Forecast maps of Saharan dust load in the atmosphere, provided by Barcelona Supercomputer Center (BSC) for the days of lidar measurements: a). 6 July 6 2006; b). 23 June 2011; c). 16 September 2011.

The HYSPLIT trajectories (Fig.7) for the particulate measurements are calculated for 40 hrs duration. Their heights are chosen according to the lidar profile delineations.



a b c

Fig.7. Backward air mass trajectories, calculated using HYSPLIT model: a). 6 July 6 2006; b). 23 June 2011; c). 16 September 2011. They show the origin and the way of air mass three days before arrival over the lidar site.

HYSPLIT trajectories reveal that shortly before its arrival above Sofia, the air masses on altitude 1.5 km (Fig.7 a, b) and 4 km (Fig.7 c) were moving just above the ground of the continental regions close to Bulgaria. Thus they were transporting considerable amounts of continental and anthropogenic aerosols, which are characteristic for the low troposphere above more densely populated regions. It’s worth notice the trajectory on 5 km, calculated on 16 September 2011 (Fig.7 c). Its beginning is somewhere above the Mediterranean and moves almost horizontally to its end above Sofia. That gives a reason to conclude that the air in the higher part of the registered layer (3-5 km) where we registered strong backscattered signals was with higher humidity and contained small watered aerosol particles. All other trajectories calculated for the three measurement days have beginning over the continent and HYSPLIT backward trajectories show that the air masses at their heights pass over continental regions where atmosphere was not loaded with Saharan dust. Therefore we conclude that in the days of the described measurements the air above Sofia up to height of 3.5 km and 5 km contained substantial amount of anthropogenic aerosol.

Conclusions

The results presented in this paper are derived from a long term remote sensing monitoring of the atmosphere above Sofia performed with Nd:YAG lidar. The experimental examples described here emphasize on the detection of clouds and aerosol layers because aerosols, clouds and aerosol-cloud interactions are recognized as the key factors influencing the Earth's radiative budget and the ecological state of the environmental. The analysis of our results from 2006 till now shows that clouds could be formed with widely differing thicknesses (in the interval 0.5–5 km) and could exist at various heights (2-16 km) in the troposphere up to the tropopause. Some experiments illustrate detection of clouds during Saharan dust transport over the lidar station. Also, here we include results of lidar observation of aerosol loading over our city up to 4-5 km heights on no-Saharan dust affected days. As neither other source of aerosols, nor dust transport from Sahara over the Balkans was forecasted for the days of lidar investigations, our conclusion was that the anthropogenic aerosols of human activities and traffic in town caused the observed aerosol stratification.

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Лидарен мониторинг на облаци и аерозолни слоеве

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Резюме. Аерозолите и облаците силно влияят върху глобалния климат и екологичното състояние на околната среда. Това зависи преди всичко от локализацията им, от техните геометрични (дебелина) и оптични (разсейване, поглъщане) параметри. В тази работа описваме резултати от лазерен дистанционен мониторинг на облаци и аерозолни слоеве над София, които са част от базата-данни от систематични изследвания на атмосферата, извършени от 2006 до 2012г.. Изследванията са направени с Nd:YAG-аерозолен лидар с дължини на вълната 532 nm и 1064 nm. Лидарът е разположен в лаборатория „Лазерна локация" на Института по електроника, Балгарската Академия на Науките. Тук експерименталните данни са представени като изчислени вертикални профили на коефициента на обратно разсейване и цветни карти на височинно-времевата еволюция на регистрираните аерозолни полета в атмосферата. Резултатите от нашите лидарни наблюдения показват, че облаците могат да имат силно различаващи се дебелини (в интервала 0.5–5 km) и могат да съществуват на различни височини (2-16 km) в тропосферата чак до тропопаузата. Някои от примерите илюстрират едновременна регистрация на облаци и аерозолни слоеве, съдържащи прах от пустинята Сахара. Също така в тази работа сме включили резултати от лидарен мониторинг на антропогенни аерозоли във въздуха над София. При анализа на експерименталните данни ние сме използвали прогнозите на HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) и DREAM (Dust REgional Atmospheric Model) моделите за дните на измерванията, за да направим изводи за произхора на регистрираните аерозоли във въздуха. Описаните измервания са част от регулярните изследвания на атмосферата, които се извършват с Nd:YAG-лидара в изпълнение на работната програма на европейския аерозолен изследователски проет EARLINET.