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DUST EVENT DETECTION FROM LIDAR MEASUREMENTS

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Sistemele de detecție la distanță cum este LIDAR-ul pot detecta nori şi aerosoli. Utilizarea aerosolilor ca trasori pentru Stratul Limită Planetar a permis să se detecteze profilul vertical şi evoluția în timp a acestuia. Informații asupra profilului vertical al parametrilor meteorologici sunt importante pentru investigații ştiințifice, modelarea climatului şi pentru monitorizarea de lungă durată a poluării. Un alt eveniment atmosferic care poate fi pus în evidență prin detecție LIDAR este apariția aerosolilor în troposfera liberă. În această lucrare se studiază un caz special de invazie de aerosoli de origine sahariană în timpul unei campanii de cercetare LIDAR desfăşurată în atmosfera de deasupra oraşului Bucureşti în primăvara anului 2006. Sistemul experimental utilizat (aflat în dotarea INOE-Bucureşti) are la bază un laser cu Nd:YAG care emite pulsuri cu durata de ordinul ns la lungimile de undă $\lambda = 1064 nm$ *(oscilația fundamentală) şi* $\lambda = 532 nm$ *(armonica a doua) şi poate detecta aerosoli cu dimensiunea de ordinul micronilor pe distanțe de până la 10km cu rezoluție de 3m.*

Active remote sensing systems such as Lidars (LIght Detection And Ranging) can detect clouds and aerosols. Use of aerosols as tracers for the Planetary Boundary Layer (PBL) allows the observation of its vertical profile and time evolution. Information on the vertical profile of meteorological parameters is essential for scientific investigations, climate modeling and for long time pollution monitoring. Another atmospheric event that can be identified by lidar measurements is the aerosol intrusion in the free troposphere. This paper studies a special case of aerosol intrusion determined during a campaign for PBL height characteristic of Bucharest atmosphere. Because we can not specify the aerosol type from elastic backscatter Lidar signal, a model data prognosis and air masses backward trajectories have been used to further investigate our experimental results. The lidar system at INOE, (LISA) is based on a Nd:YAG laser working at the 1064 nm fundamental wavelength and at 532 nm second harmonic and delivering pulses with high repetition rate. The system can detect micron size aerosols from long distances (up to 10 km), with a very good spatial resolution (3 m).

Keywords Lidar, dust event, aerosols, retrieval algorithm

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1.Introduction

The Lidar system uses a laser to excite backscattering by particles of the atmosphere. Detected backscattered signal is generated by air density fluctuations (Rayleigh scattering) and by small aerosol particles always present in the atmosphere. The presence of aerosol particles causes an increasing of the backscattered light and thus it can be detected knowing the clean atmosphere background. The optical signals received by the telescope are selected by wavelength using an optical analyzer and then directed to the photosensitive detectors. These will convert the optical signal into electrical signal, recorded as a function of time by analog-to-digital converters and/or photon counting devices and the results are stored onto a computer. The main advantage of a lidar system is that it provides real-time profiles of atmospheric components, which makes it useful for troposphere and even stratosphere study.

However, in order to obtain physical parameters from lidar measurements, the recorded signal must be processed. The algorithm for data processing is different for each particular phenomenon: elastic or Raman. In case of elastic backscatter lidar, for the inversion lidar equation, generally the Fernald-Klett algorithm [2, 3] is used. The Lidar equation is a nonlinear ordinary differential equation, of Ricatti homogeneous type. The solution of the equation is simplified by introducing the reciprocal of the attenuation coefficient, but stability and accuracy of the solution depend on the limits of the integration range.

The use of the Fernald-Klett algorithm introduces several processing errors and requires some approximations, as shown in the following paragraphs. This is why more sophisticated algorithms were developed, based on an iterative approach based on the Mie theory to derive the best fit between theoretical and experimental data [4]. We use an algorithm based on Fernald-Klett method combined with an atmospheric model and Mie algorithm for direct problem (theoretical calculation of optical parameters). In addition, the lidar ratio profile is computed based on the Ackermann model using relative humidity profiles (which can be determined from radio-sonde data or from atmospheric model) [5].

2. Parameters derived from lidar measurements

To analyze the return signal in laser remote sensing means to find solutions for the equation which relates the characteristics of the received signal to the emitted signal and the propagation medium. This equation is the so-called “lidar equation”, which, in the simplest case of the elastic backscattering lidar can be written [1]:

$$RCS(\lambda, Z) = C_S(Z) \cdot \left[\beta_m(\lambda, Z) + \beta_a(\lambda, Z)\right] \cdot \exp\left[-2\int_{Z_0}^{Z} \left[\alpha_m(\lambda, Z) + \alpha_a(\lambda, Z)\right] dz\right] \tag{1}$$

where: λ is the wavelength of sounding radiation, $RCS(\lambda, Z) = S(\lambda, Z) \cdot Z^2$ is the range corrected signal, S is the lidar signal, Z is the distance in the laser path from the transmitter, C_S is the system constant, β_m is the molecular backscatter coefficient, β_a is the aerosol backscatter coefficient, α_m is the molecular extinction coefficient, α_a is the aerosol extinction coefficient and Z_0 is the minimum relevant distance from the transmitter.

Aerosol Lidar measurements at one wavelength can deliver aerosol backscatter profiles using inversion. The molecular components (β_m and α_m) of the backscatter and respectively the extinction coefficients can be computed from pressure and temperature profiles using the standard atmosphere model, but the aerosols components must be both derived by inverting eq. 1. To obtain the solution by using Fernald-Klett method, an a priori relation between β_a and α_a, or equivalently, the Lidar Ratio:

$$LR_a(Z) = \alpha(Z) / \beta(Z) \tag{2}$$

must be assumed (for simplicity of notation, λ is not marked in the following equations). If the profile of the Lidar Ratio is supposed to be known, the solution of Lidar equation can be written:

$$\begin{aligned} \beta(Z) = -\beta_m(Z) + RCS(Z) \cdot \exp\left[-2(LR_a(Z) - LR_m) \cdot \int_{Z_C}^{Z} \beta_m(z)dz\right] \\ \left[\frac{RCS(Z_C)}{(\beta_a(Z_C) + \beta_m(Z_C))} - -2LR_a(Z) \cdot \right. \\ \left. \int_{Z_C}^{Z} RCS(z) \cdot \exp\left[-2(LR_a(z) - LR_m) \cdot \int_{Z_C}^{Z} \beta_m(z')dz'\right] dz\right]^{-1} \end{aligned} \tag{3}$$

where $RCS(\lambda, Z) = S(\lambda, Z) \cdot Z^2$ is the range corrected signal, Z_c the calibration point, m denotes the molecular component and the index a stands for the aerosol component.

By consequence, in order to obtain the backscattering coefficient profile and the extinction coefficient profile, the lidar ratio must be guessed over the entire interval. This assumption introduces errors which can be neglected for the backscattering coefficient, but become important when one must extract the values of microphysical parameters. This is why, generally no information about the aerosol composition or microphysics can be obtained from elastic channels with good precision, even if an iterative algorithm is used.

3. Methodology

A lidar measurements campaign was organized in the spring of 2006 at ROMEXPO site (44°24'49'' N, 26°05'48"E), in the northern part of Bucharest. The goal of this campaign was to put in evidence the diurnal cycle of PBL in a typical urban atmosphere, where traffic is the main source of pollution. Almost continuous measurements were recorded for several days. For this study we selected a special event of dust intrusion that occurred during this campaign, in order to prove how lidar data and theoretical models can work together to provide information about aerosol layers in the free troposphere.

The data presented in this paper were recorded on April 5th at 532 nm sounding wavelength. The laser beam was sent on the vertical up to 9 Km altitude and the acquisition was set at 2 minutes temporal resolution and 3 m spatial resolution, on a total recording time of 3 hours. The procedure was repeated in the morning, midday and after sunset monitoring the PBL evolution. During measurements low clouds and strong wind were present.

Basically, apart from clouds, no other layer can be visualized directly in the lidar signal. Regardless of the data processing method used, only the aerosol optical parameters (the backscattering and the extinction coefficients) can be obtained. Knowledge of these two parameters is enough to show the absence or the presence of a dust intrusion. This was the case on April 5th, when plotting the RCS versus time, a non-typical behavior was observed at 14 UTC (fig. 1) and also at 17 UTC (fig. 2).

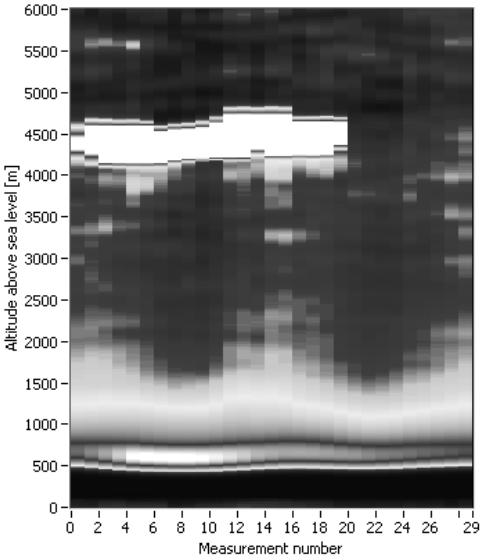

Fig. 1. Range Corrected Signal (a.u.) – temporal evolution - on April 5th 14:00 UTC, 532 nm sounding wavelength

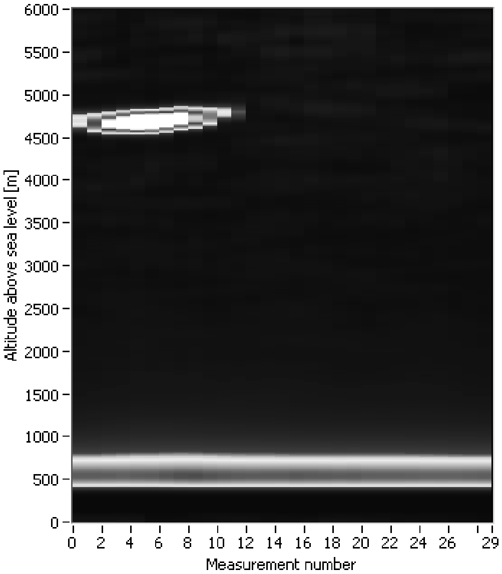

Fig. 2. Range Corrected Signal (a.u.) – temporal evolution - on April 5th 17:00 UTC, 532 nm sounding wavelength

In fig. 1, the lidar range corrected signal shows the temporal evolution of the PBL affected by strong turbulence in the morning. The top of the PBL is often marked with a temperature inversion, a change in air mass and a change in the wind speed and/or in the wind direction. The PBL is most accurately definable in situations where differential advection occurs or when a shallow front is present at the surface. The transition between the PBL and free troposphere is not well defined but an important gradient in the RCS is visible at the top of the PBL (around 1500-1700 m altitude). This representation shows clearly the presence of a dense cloud at 4500 m altitude at the beginning of the record. The clouds scatter the light so strongly that usually, no other layer can be detected above them. However, as in the present case, even if the cloud is dense enough, another layer - marked by unusual high values of RCS - can be identified at higher altitudes. This layer is more visible in the last part of the record, when the cloud disappeared. We can note that this layer reached 3000 – 5000 m at 14:00 UTC. At first sight, this is an aerosol layer of an unknown source. The high altitude of this layer is an indirect indicator of its provenience, which can be far away from the measurement site.

The phenomenon was recorded also after sunset (fig. 2), at 17:00 UTC but the behavior in this case was different due to PBL cycle. After sunset, one can observe the collapse of the PBL down to several hundreds meters. This permitted the aerosol layer from high altitude to descend to the lower levels, increasing the particles density into the remains of the PBL. In the same time, the strong wind had an important contribution to the horizontal dispersion of the aerosols. These two effects (vertical and horizontal dispersion) determined the decrease of the aerosol concentration at high altitude, which is visible in fig. 2.

4. Results of the computation

To further analyze the recorded event, we concentrated on the following two objectives. First, the derivation of optical parameters was necessary in order to quantify the intrusion. For this purpose, a 10 measurements average was used for the computation of the backscattering coefficient profile by the LiSA data processing method. The backscattering profile was calculated for two times: 14:00 UTC and 17:00 UTC. In the resulted graphs we can observe increased values of the backscattering coefficient between 3000 m and 5000 m at both times (14:00 and 17:00 UTC). This is caused by the presence in the free troposphere of previous mentioned aerosols layer. The results of data processing are shown in figure 3, where the continuous line represents the backscattering coefficient profile at 14:00 UTC and the broken line represents the backscattering coefficient profile at 17:00 UTC.

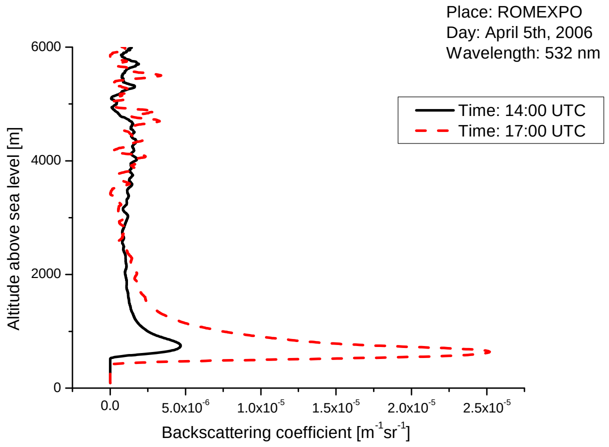

Fig. 3: Backscattering coefficient on April 5th, 532 nm sounding wavelength – dust intrusion layer at 3000 – 5000 m penetrating from the free troposphere (14:00 UTC) in the PBL (17:00 UTC)

The second objective was to identify – if possible – the source of this aerosol layer. As mentioned before, only optical characteristics of aerosols can be derived from elastic backscatter lidar data. In order to obtain more information about microphysical properties of aerosols or the aerosols origin, additional models are required. First level information was obtained from the DREAM (The Dust REgional Atmospheric Model) prognosis model developed by Dr. Slobodan Nickovic [6] and running at the Supercomputing Center in Barcelona [7].

The aerosol intrusion phenomenon recorded at ROMEXPO site proved to be consistent with the DREAM prognosis for April 5th (fig. 3). According to DREAM, a dust intrusion originating from Sahara was forecast to reach Romanian territory on April 5th around 12 UTC and to travel toward Est. The forecast of the same model showed that after a few hours the concentration of dust will decrease, due to strong wind and horizontal dispersion.

Apart from the prognosis of DREAM model, another analysis is necessary to confirm the origin of the dust. This is the air mass back-trajectories analysis for which we used the version 4 of the Hybrid Single –Particle Lagrangian Integrated Trajectory model (HYSPLIT) [8]. As inputs of the model we used the coordinates of lidar location and specific levels at 3000m, 4000m and 5000m altitude. These values were chosen based on the backscattering coefficient profiles derived previously. The model was run backward for 6 days and backward trajectories are shown in fig. 5. One can observe the change of the trajectories with altitude (5000m and 4000m starting point: circles and squares, respectively on the graph). These maps clearly identify the Saharan origin of the upper air-masses.

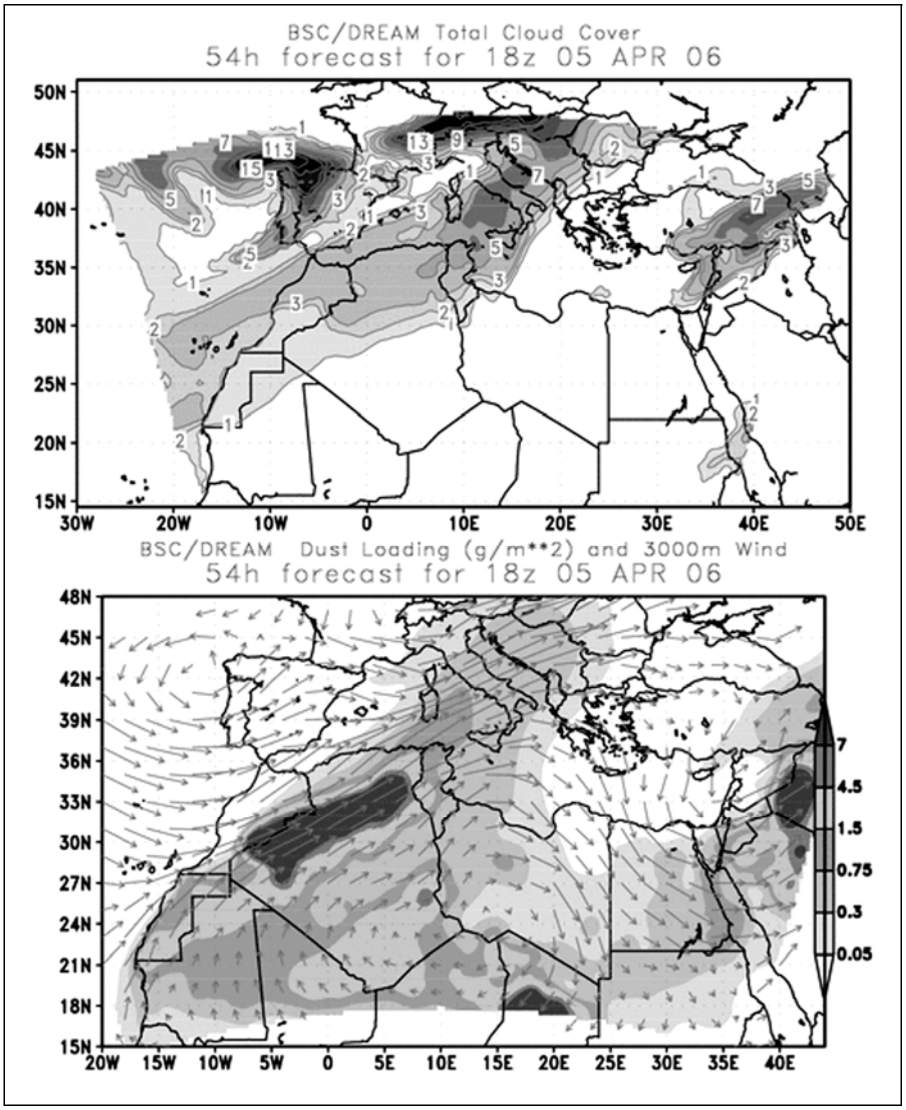

Fig. 4. DREAM forecast for April 5th 2006: 18 hours UTC 0

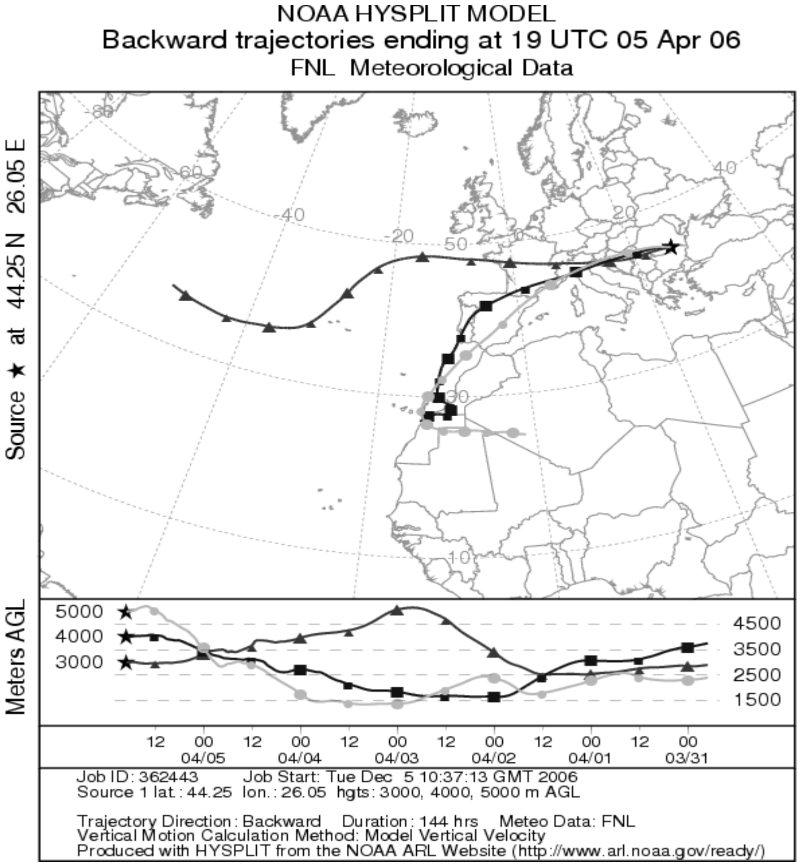

Fig. 5 Backward trajectories of Saharan Dust Event on 5 Apr. 2006

Saharan dust layers reach the southern part of Romania predominantly by cyclonic circulation due to the strong trough observed at all the levels from a cyclonic system located in northwestern part of Africa (see fig .6). Fig. 6 represents the 850hPa (~1500m) geopotential height, 12:00 UTC on 5.04.2006 [www.wether.de].

In this case the height of the detected layer is the result of the advection of air masses and not to vertical mixing. The dust layer was formed when aerosol was injected by air mass from northern part of Africa (Saharan dust). Again, the lidar measurements proved to be consistent with model outputs. By combining lidar with DREAM and HYSPLIT models we could put in evidence a significant dust intrusion episode in the free troposphere above Bucharest site, but also to identify the source of this dust as being the Sahara desert, which may seem incredible for Romania but is indeed true.

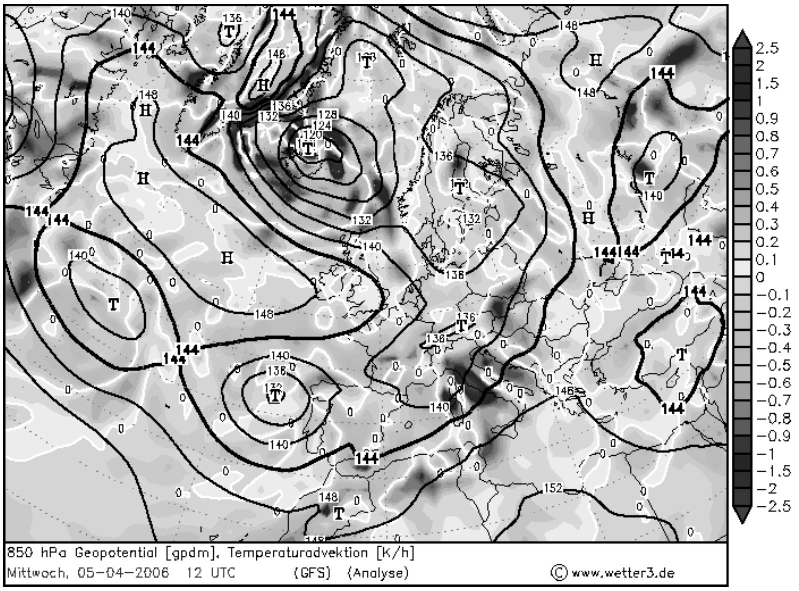

Fig. 6 850hPa (~1500m) geopotential height, and 1200 UTC on 5.04.2006.

One can observe the warm air advection.

5. Conclusions

Lidar measurements provide useful information about the vertical distribution of aerosols and the vertical structure of aerosol layers. Their temporal evolution is important for the characterization of the PBL.

To interpret lidar data it is necessary to take into account the meteorological parameters but also to accept that the origin of air mass influences the state of the atmosphere and the height of the local PBL. The type of aerosols and their origin cannot be determined using only Lidar data; additional models are needed. If the source of the aerosols is known, some microphysical parameters can consequently be derived, including the lidar ratio.

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