DYNAMIC OF THE LOWER TROPOSPHERE FROM MULTIWAVELENGTH LIDAR MEASUREMENTS

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Abstract. The dynamical behavior of the PBL (Planetary Boundary Layer) has a direct effect on the air quality and on the boundary layer parameterization schemes used in local, regional and global models. Active remote sensing systems such as LIDARs (Light Detection and Ranging) use aerosols of the atmosphere as tracers for identification of atmospheric state determined by convective activity, turbulence or dust intrusions. In this paper we have used multiwavelength lidar measurements from a scientific research center in Magurele, Bucharest area (44.35 N latitude, 26.03 E longitude) to provide information about the PBL height evolution, correlated to Saharan dust intrusions over Romania and to meteorological conditions. The Richardson number method is used to estimate the boundary layer height from the radio-soundings. We have used pressure, temperature and dew point profiles as well as the wind direction profiles from NOAA (National Oceanic and Atmospheric Administration) data base. The height of layers in the lower troposphere from lidar signal was calculated using the gradient method- minima of the first derivative. The results were consistent with the ones obtained from radio soundings.

Key words: LIDAR, aerosol, planetary boundary layer, dust layer, remote sensing.

1. INTRODUCTION

The Planetary Boundary Layer (PBL) has an important role for the whole atmosphere-Earth system because it acts as an interface where the coupling between the atmosphere and the Earth's surface occurs. Knowledge of the PBL height is an important meteorological parameter because it describes the dynamical behavior of this layer. Substances emitted into the PBL are dispersed through turbulence and eventually become well-mixed over this layer. Therefore, the PBL height is a fundamental parameter to characterize the structure of this lower layer of the atmosphere, required in dispersion models. Environmental applications also include long-term air-quality and climate modeling, air chemistry, and meteorological forecast modeling.

The top of the PBL has been given many names, the most popular being inversion height, mixing height and Mixed-Layer Depth (MLD). The commonality exists in that they all refer to the greatest depth to which atmospheric constituents
are well mixed. The PBL is usually within 1000 meters off the surface but it is variable in space and time, ranging from hundreds of meters to a few kilometers [1].

Strawbridge, K. B. and B. J. Snyden [2] demonstrated that LIDAR technique has been shown for many years to provide accurate measurements of the MLD. Remote monitoring has two main advantages compared to other measurements methods to detect the atmospheric layered structure: (i) it is a non interfering probe less technique and (ii) this method is capable of three-dimensional measurements over distances of several kilometers in altitude [3]. The assessment of layer altitude from remote sensing data is not a closed issue, having in view the fact that instrumental performance and data handling procedure influences greatly the result. Various methods have been tested to retrieve PBL height from LIDAR corrected signals. The decision to use one or the other is depending on the signal to noise ratio in certain atmospheric conditions. The best way to evaluate the accuracy of the retrieval is to compare results obtained by at least two different methods. In order to test the possibility to use in a continuous and automatic manner LIDAR profiles to measure PBL height and detect aerosol layers, we have implemented a set of numerical algorithms which computes PBL from LIDAR and radio-sounding data. These algorithms were used on various datasets, describing various atmospheric conditions and aerosol loads.

This paper presents recent studies of aerosol vertical profiles measured using a multiwavelength lidar RALI, which is part of EARLINET (European Aerosol Lidar NETwork) [4] both at a fixed location (Magurele-Bucharest) and during field campaigns. The gradient method was applied to the individual LIDAR profiles (Section 2 – Data and Methods). The results, presented in Section 3, were compared to layers height calculated from radio-soundings data. In addition, the results were discussed in synoptic context, using prognosis dust load maps and air mass back-trajectories. The conclusions are presented in the final of the paper.

2. DATA AND METHODS

Generally, several methods have been considered for extraction of the MLD and layer heights from LIDAR data. These include critical threshold techniques, gradient techniques, and wavelet analyses [5, 6]. The LIDAR signal shows a strong backscattering within the PBL, decreasing through a transition zone and becomes weak in the free troposphere, because the PBL contains more aerosols than free atmosphere. This behavior is the base for the LIDAR estimation of the layering in the atmosphere. However, interpretation of the Lidar data must take into account possible advections of air masses that can change the vertical mixing.

For this study we have used results from measurements performed since May 2008 by the multiwavelength lidar, RALI, following the EARLINET protocol [7]:
regular measurements in the lower and upper troposphere (up to 10km maximum range at 3.75m range resolution) three times a week, one around local noon, when the PBL is well developed and two within a time window of 1 hour before and up to three hours after the sunset. This study is the first evaluation of the data from a multi wavelength lidar related to the aerosol in the troposphere from measurements in Romania. Previous measurements with an elastic backscatter lidar have shown good results [12].

The laser radiation of RALI is emitted at 1064, 532 and 355nm and collected at 1064, 532p, 532s, 355, 607, 387 and 408nm. The 607 and 387nm radiation corresponds to the Raman lines of Nitrogen, excited with 532 and 355 nm respectively. The 408nm radiation corresponds to the Raman line of water vapor excited with 355nm. Almost all channels have both analog and photon counting detection, in order to increase the range (analog for the lower troposphere and photon counting for the upper troposphere).

In many cases the PBL height is easily visible in LIDAR false-grey plots and can be determined with a simple algorithm as the absolute minimum of the first derivative of the range corrected signal (RCS), defined as:

$$RCS = \left( S - S_0 \right) \cdot r^2. \quad (1)$$

In equation (1) \( r \) is the distance between the laser source and the target (it is also called range), \( S \) is the lidar signal and \( S_0 \) is the background signal. Whenever the signal to noise ratio is sufficiently high (e.g. greater then 3), the optimum results in the retrieval of layer altitude are obtained by applying the gradient method to the RCS. This is due to the fact that this method is not very sensitive to layer substructure and returns only the major peaks of the RCS derivative. For example, complex profiles are measured in a continental polluted site as is Magurele, therefore several minima exist whenever a distinct layer is present in the atmosphere. Therefore, a too sensitive method – such as statistical or wavelet analysis – could be inappropriate. Moreover, the signal to noise ratio of the profiles measured using such a powerful system as RALI is generally over the threshold up to 10 km, therefore more sophisticated retrieval methods are not necessary for the identification of the PBL.

From the meteorological point of view – on the other hand - the top of the PBL is marked by a temperature or an equivalent potential temperature inversion, a change in air mass, a hydro-lapse, and change in wind speed and/or direction [8]. The humidity also affects the mixed layer. All these information are provided by radio-soundings. Therefore, a complementary method which can be used for the assessment of LIDAR detection capability have to take into consideration meteorological parameters. We are using the ones measured by radio soundings,
and provided every three hours by NOAA data base. One of the parameters that correlate temperature, humidity and wind behavior and determine the stable or unstable layers is the Richardson number \([9]\). The Richardson number, \(R_i\) is a function of altitude, as follows:

\[
R_i = \frac{g \frac{\partial \theta}{\partial z}}{\left(\frac{\partial V}{\partial z}\right)^2}.
\]  

(2)

In equation (2) \(g\) is the acceleration due to gravity, \(\theta\) is the potential temperature, \(z\) is the height and \(V\) the wind speed. Whenever the \(R_i\) is < a critical value of 0.21, \(R_{ic}\) the atmosphere can be considered fully decoupled from the PBL. If \(R_i\) is < 0, the layer can be considered buoyantly unstable and turbulent \([1]\).

To emphasize the change in air mass kinematics backward trajectories have been invoked. The version 4 of the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT4), developed by the National Oceanic and Atmospheric Administration (NOAA)’s Air Resources Laboratory (ARL) \([10]\) was used. Saharan dust intrusion over Romania was forecasted by the Dust REgional Atmospheric Model (DREAM) \([11]\).

3. RESULTS AND DISCUSSION

The tracer role of aerosols has been used in the vertical RCS profiles to determine the height of PBL and any distinct aerosol layers in the troposphere. The graphs underline not only the vertical distribution, but also their temporal evolution (Figs. 1, 3, 5). We present in here only few examples, but all measurements during May 2008 to February 2009 have been analyzed. During the day, the turbulence determines the mixed layer height (Figs. 1, 5). The MLD is about 1300–1500 m. In the evening (19UTC), the PBL height is usually lower due to the decrease of energetic fluxes, and the atmosphere became more stable (Fig. 3).

The radio-sounding data were used to calculate the Richardson number profile and a subroutine was integrated into the Labview data processing algorithm. The software identifies the altitudes at which the critical value 0.21 is achieved and returns all height intervals showing both stable and unstable atmospheric conditions. Values obtained were compared with those derived from lidar profiles when gradient method is applied on RCS. In principle, both methods should deliver same altitudes for the top of the PBL and aerosol layers. However, differences could arise from the fact that the two datasets are not really describing the same
atmosphere column. First of all, radio-sounding data are 3 hours average profiles, thus are not simultaneously with lidar profiles which are obtained every 1 min and which clearly show changes in the atmosphere during the 2 hours measurements (Figs. 1, 3, 5). Second, the distance from lidar location and the coordinates of the radio-sounding must be considered. Finally, the vertical resolution of the two datasets is different and interpolation procedures applied to radio-sounding data are not always infallible. Therefore, the comparison between the PBL heights obtained from the two methods has to take into account only ranges of values.

The lower left panels in Figs. 2, 4, 6 show the sign change of Richardson number at the same height as of the change in humidity mixing ratio and virtual temperature profiles. We choose to show the graphs of the virtual potential temperature in order to include the buoyant effects of water vapor and liquid water vapor in the air for non-cloudy and cloudy atmosphere. This is the best method in the case of a convective mixed layer, as is indicated by [5]. The results, indicating the aerosol layers heights are in good agreement with the ones determined by the lidar.

In some cases lidar can not detect the MLD simply because the PBL top is below the overlap altitude [13]. An example is given in Fig. 3 showing RCS-80 minutes time evolution on July 12th 2008, at a coastal site near the Black Sea, Constanta. Black vertical lines indicate the layers heights at ~1400m and ~2400m detected by applying the gradient method. The lidar is missing the lower layer (MLD) due to the 700 m overlap height (the height where is reached the full overlap between the transmitted laser beam and the telescope field of view). Using Richardson number method for the radio sounding data the layers were identified at 683 m, ~1500 m and ~2300 m (Fig. 4), proving that the lidar is correct in detecting the aerosol layers, but is just missing the PBL.

Finding with a good precision the layers altitude is important not only for air pollution studies but also for the assessment of various – sometime quite remote – aerosol sources. The lidar technique proved to be a suitable tool for the study of aerosol long-range transport, which influences local atmospheric behavior. For example, Saharan dust intrusions and biomass burning have been proven to influence air masses over Romania [14, 15]. Therefore to demonstrate the change in air mass and consequently any intrusion of Saharan dust, kinematics backward trajectories have been invoked through HYSPLIT4 model. This software uses as input the altitudes in order to trace the trajectory of air masses – both backward (to origin) and forward (to destination). Apart from the model uncertainty, small variations in layer altitude introduce large variations in the computed trajectory itself. Consequently, accurate information about the height of the layer is mandatory to increase the level of confidence.
An example is given in Fig. 7 where the altitude change in trajectory can be observed on July 21, 2008. The map identifies the Saharan origin of the air-masses at 3500 m altitude. Lidar measurements over Magurele show distinct aerosol layer around 3000 m for July 21th (not shown) and July 22 (Fig. 6). For accurate description of the dust load over Romania the DREAM model was used (Fig. 8) and is confirming the Saharan dust intrusion.

Following the previous analysis, we can therefore appreciate that the layer’s height determined from LIDAR RCS profiles is reasonably good. They prove to accurately identify the Saharan dust intrusion over Romania.

Fig. 1 – Minute resolution RCS (a.u.), vertical range 700 m – 5000 m, in Magurele, on August 4th 2008 starting at 10:45 UTC, 532nm sounding wavelength; the black points indicates the layers detected using gradient method at ~1200 m and 2200 m.
Fig. 2 – The profiles of the humidity mixing ratio (left upper corner), potential temperature logarithm and virtual potential temperature (right side panels) and Richardson number profile (left lower panel) for August 4th, 12 UTC. These profiles emphasize the layers at ~1200 m, and 2400 to 3600 m similar to the ones from Fig 1.

Fig. 3 – Similar as in Fig. 1 but on July 12th, 2008 starting at 19:10 UTC, at Constanta, near Black Sea coast; layers detected at ~1400 to 2300 m and 4000 m.
Fig. 4 – Similar as in Fig. 2 but on July 12th, 2008 18 UTC; layers detected at ~680 m and 1500 to 2300 m.

Fig. 5 – Similar as in Fig. 1 but on July 22nd, 2008 starting at 14:42 UTC; layers detected at ~1500 to 1900 m and 3700 down to 3400 m.
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Fig. 6 – Similar as in Fig. 2 but on July 22th, 2008 15UTC; layers detected at ~2000 m and 3700 m.

Fig. 7 – Back trajectories at 2500 m, 3500 m and 5500 m arriving at 15 UTC on July 22, 2008 at Magurele site; lower panel MLD detected at 1712 m over Magurele consistent with the one detected from lidar (Fig. 7).

Fig. 8 – BSC/DREAM dust loading and 3 km wind field prediction for July 22nd 2008, (18:00 UTC) showing Saharan dust Romania.
4. CONCLUSIONS

Using the gradient method (minima of the first derivative) we determined the PBL height and aerosol layers in the lower troposphere from the multiwavelength lidar, RALI measurements. The results were consistent with the ones obtained from radio soundings. The vertical profile of the Richardson number showed the unstable and/or stable atmospheric layers. The small differences between the values of the MLD and other aerosol layers determined from radio-soundings and LIDAR data can be explained by the fact that the LIDAR-derived transition zone does not respond directly to the thermodynamic properties of the atmosphere.

LIDAR images (RCS signal) have shown the time evolution of the mixed layer depth and distinguished different atmospheric layers. From May 2008 up to now RALI system was suitable to detect and monitor aerosol layers' intrusion in Romania, from long range transport.

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REFERENCES


