Optica Applicata, Vol. XXIX, No. 4, 1999

Aerosol layers in the atmosphere observed by vertical-sounding lidar as an indication of mixing layer height – comparison with acoustic sounding data

Jacek Walczewski, Andrzej Bielak, Wiesław Kaszowski

Institute of Meteorology and Water Management, Section Cracow, ul. P. Borowego 14, 30–215 Kraków, Poland.

The main objective of the study was to compare the height to which aerosols are mixed with the vertical range of turbulent processes that may be responsible for mixing. The aerosol mixing height was determined by lidar sounding of the atmosphere, the vertical range of turbulent processes was estimated on the basis of the analysis of acoustic echoes obtained by means of acoustic (sodar) soundings of the Atmospheric Boundary Layer (ABL). Data from 344 observation hours (parallel lidar and sodar soundings) are analysed. In addition, some data on the SO_2 – mixing height (compared with lidar and sodar data) were taken into account. The analysis is made separately for two kinds of ABL structures, differing in their physical characteristics: convective structure and stable (inversion) structures. For both cases, the relative indices representing the relation of lidar to sodar estimations of mixing height are characterized by some distribution of values. This distribution suggests the existence of a combination of physical factors creating the aerosol mixing layer. In this combination of factors, the contribution of such processes like vertical motions generated by convection turbulence generated by gravitational waves, turbulence produced by wind shear, may create different vertical structures of aerosol layer. The complexity of the problem makes it necessary to organize further experiments with parallel application of different measuring techniques.

1. Introduction

Mixing layer height is one of the main parameters describing the Atmospheric Boundary Layer (ABL); it is often used in air pollution dispersion models. Mixing layer height is defined as the height to which pollutants released from the earth's surface are mixed. For aerosols, this height may be estimated by means of vertical sounding of the atmosphere by laser beam emitted by lidar. Mixing height is also determined as the height to which the processes responsible for mixing (vertical motions and turbulence) are observed. One of the approaches is analysis of the vertical profile of temperature.

A series of experiments concerning the determination of vertical distribution of aerosol layers by means of lidar observations was performed in the Division for Remote Sensing of the Atmosphere, Institute of Meteorology and Water Management, Cracow, Poland. Lidar sounding data were compared with the results of continuous acoustic sounding of the ABL with the use of sodar, at the same site. The acoustic sounding gives some information on atmospheric turbulence, because turbulence plays an important role in the scattering of sound in the atmosphere.

The measurements were made with use of lidars LIVERS [1] and KEMA [2] and sodars SAMOS-4 and SAMOS-4C [3].

Lidar LIVERS (Lidar for VERtical Sounding, developed in Divison for Remote Sensing of the Atmosphere) is implemented with a ruby laser (wavelength 694 nm) Q-switched by rotating prism. After Q-switching the pulse has energy 0.1 J and duration in the limits of 100 ns. Pulse repetition frequency is 1 per minute. LIVERS is a stationary device emitting vertical beam.

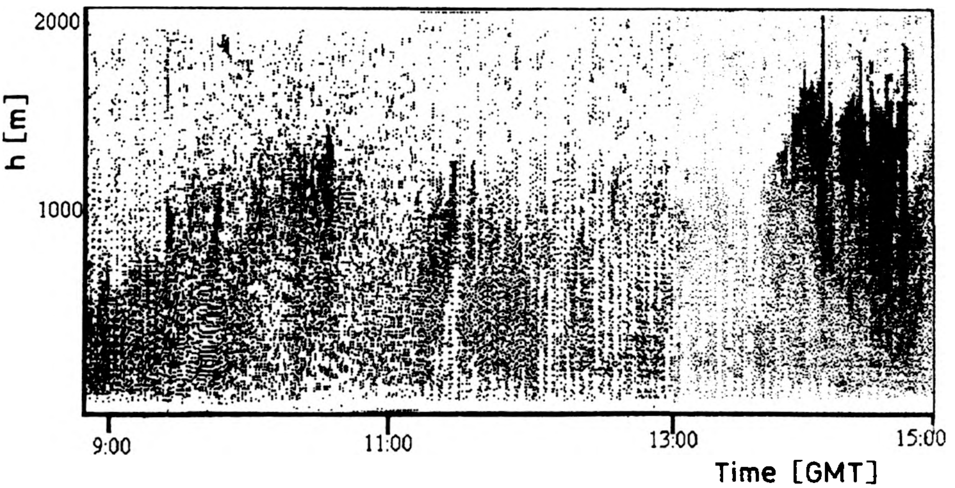

Fig. 1. Example of lidar record KEMA. Vertical axis – height, horizontal axis – time, backscatter intensity marked by grey-tone (June 16, 1995).

Lidar KEMA is a mobile instrument installed in a van. For measurements, the optical system is moved up above the van's roof. Lidar is owned by Dutch Energy Agency KEMA and has been loaned to the Division for Remote Sensing of the Atmosphere for a period of 2 years. Lidar is equipped with a Nd:YAG laser with doubled frequency. The characteristics of the pulse are as follows: wavelength 532 nm, pulse half-width 6–7 ns, energy 100 mJ, repetition frequency 10 Hz. The inclination of the sounding beam may be selected in the sector 0–90°. The vertical position of the beam gives the dead zone height up to 200 m. Thus, inclination 60° was used to reduce the vertical range of the dead zone to 100 m (backscattered signal intensity was projected on the vertical axis). The results of sounding were presented in the form of height-time cross-sections of backscatter intensity, giving the information on the presence of atmospheric aerosol (light scattering particles). Examples of records are given in Figs. 1 and 2.

Sodar of the SAMOS type (developed in the Division for Remote Sensing of the Atmosphere) is a monostatic, vertical acoustic sounder, using 1.6 kHz acoustic frequency. Pulse duration is 50 ms, time interval between pulses 6 s, sounding range 1000 m. Sodar SAMOS-4C, operating since August 1993, is implemented with digitalization of signal and complete computerization of data processing. The back-

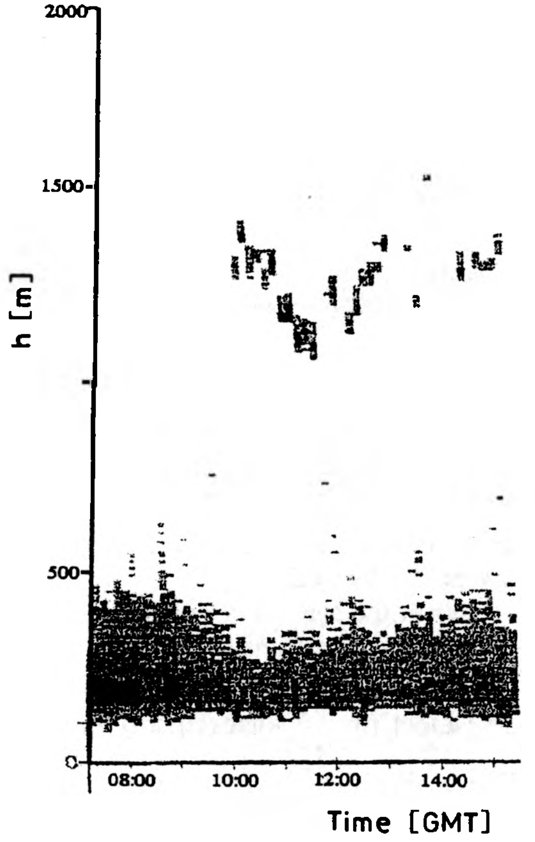

Fig. 2. Example of lidar record LIVERS, for description, see Fig. 1. Note: dead zone of observation (the lowest 100 m), ground-based aerosol layer, elevated aerosol layer (August 19, 1993).

scatter signal ("echo") is recorded versus time and height. An example of analog presentation of the record is given in Fig. 3, where one can distinguish some characteristic forms of sodar "echoes", representing different kinds of ABL structures.

2. Basic interpretation schemes for lidar and sodar records

In the sodar records 4 basic echo types may be distinguished:

– Vertical convective echoes generated by convective structures of ABL, usually connected to the temperature drop versus height.

– Ground-based horizontal echoes connected to the temperature inversion in the air layer near the ground (sometimes up to several hundreds of meters).

– Elevated horizontal echoes connected to the elevated layers of air with temperature inversion (they may be seen, in different numbers, at different heights).

– Echoes of wind noise, connected to the mechanically generated turbulence (sometimes covering completely the record).

The forms of lidar-recorded signals ("echoes") are connected to the backscatter of laser beam by aerosol particles. They make it possible to estimate the depth of

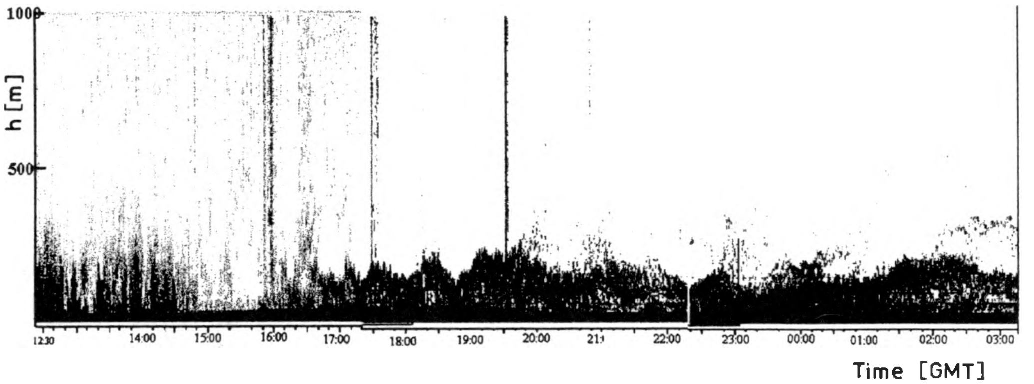

Fig. 3. Example of sodar record from March 10, 1995, 12:30 h to March 11, 1995, 03:20 h. Vertical axis – height, horizontal axis – time GMT. Note: 12:30–14:30 – convective plumes, 16:30–03:20 – ground-based inversion layer.

aerosol layer over the ground or determine the heights at which elevated aerosol layers are located.

When the aerosol layer extends from the ground surface up to some height, the latter may be assumed to be the height of mixing layer [4].

3. Selection of observation material for study

The analysis was made of time series of simultaneous lidar and sodar observations performed in different meteorological conditions (in different atmospheric stability types).

The data analysed are covering, in general, 344 hours of synchronous lidar-sodar observations (equivalent for more than 14 days). This material is composed of data from the following measuring campaigns:

– some short-lasting series of 1993 year (LIVERS+SAMOS-4 and LIVERS +SAMOS-4C),

– series of the years 1994–1995, each one lasting several tens of hours (LIVERS+SAMOS-4C and lidar KEMA+SAMOS-4C),

– short series of measurements from the years 1996–1998 (LIVERS+SAMOS-4C).

4. Comparison of sounding results

4.1. Convective conditions

Following the method applied by WALCZEWSKI [5], mean hourly values of z_L/z_C were calculated, where z_L denotes the depth of aerosol layer observed by lidar, and z_C – maximal heights of convective echoes recorded by sodar at the same time. The file of z_L/z_C values comprises 78 data items, whose distribution was investigated (Fig. 4), with the following results:

– 24% of data fall within the values interval 0.8 – 1.2. This refers to cases where aerosol layer depth is equal, or nearly equal to the heights of the tops of convective echoes recorded by sodar.

– About 55% of cases are comprised in the group of values higher than 1.2 (aerosol layer depth higher than convective echoes).

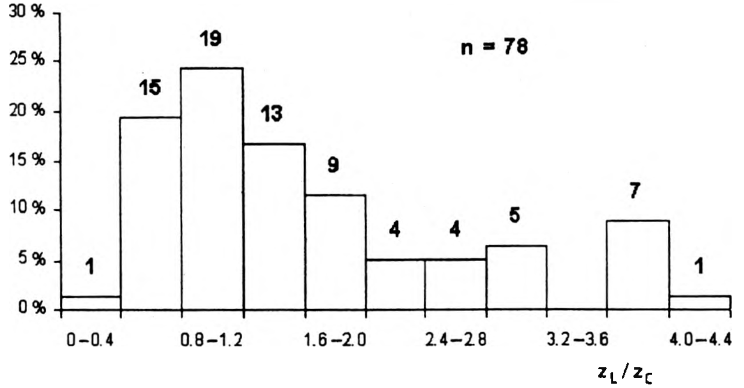

Fig. 4. Distribution of relation z_L/z_C (depth of the lidar-observed dust layer to the maximal height of sodar-observed convective structures). Measurements taken in Cracow, 1994–1996.

For some part of the cases from the second group observational material was available, giving evidence of the fact that the deep aerosol layer was formed on the previous day and remained at this comparatively big height through the night, after disappearance of intensive vertical motions. This might be due to the survival of aerosol layer in so-called residual layer (nocturnal layer of weak turbulence), or due to the advection of aerosol-rich air from other localities.

A separate group is composed of 19 cases in which the depth of aerosol layer is equal to the height of the base of elevated inversion layer, observed by sodar and situated above the convective echoes (so-called *capping inversion*). For these cases one can apply the broadly accepted scheme assuming the height of capping inversion as the mixing layer height in convective ABL. On the other hand, there are some observations of situations, in which this scheme does not work. Interesting contribution to the discussion of this problem is given by a series of measurements of the vertical distribution of SO_2 concentrations.

The measurements were made by Division for Remote Sensing of the Atmosphere with the use of a correlation spectrometer installed in an aircraft [6]. Measurement flights were made in summer seasons of the years 1992 (7 flights) and 1993 (5 flights). The observed ground-based SO_2 layer was created by emissions from industrial sources, like local metallurgical plant, cocking plant, cement factory, industrial boiler installations supporting technological processes, and dispersed small sources of SO_2 like bakeries, kitchens, *etc.* To the higher atmospheric layers (above the level 200 m) SO_2 was supplied by tall stacks of the power plants situated in the vicinity of Cracow, and in more distant regions, like Upper

Silesia; these elevated plumes were observed as layers of gas separated from the ground-based layer. Thus, it was reasonable to assume that the depth of ground-based layer of SO_2 represented the height of mixing layer.

From this point of view, the results of the measurements were in some sense surprising, because the ground-based SO_2 layer, by the rule, was not reaching the level of capping inversion (determined by temperature sensor in the aircraft), and sometimes the top of ground-based layer was situated much lower (several hundred meters) than the base of capping inversion.

In five of these experiments synchronous lidar measurement was possible. Let us look at the results of measurements made on August 18, 1993, when the flight for SO_2 measurement was situated in time interval 9:50 – 11:00 hours. The ground-based SO_2 layer was reaching the height of 600 m (Fig. 5), and separate plumes were observed at height intervals 700 – 900 m (high maximum), and 1000 – 1600 m (low-concentration plume). The aerosol layer observed by lidar was reaching 300 m, and higher above, at the height of about 1500 m, a thin elevated layer of aerosol was detected. As can be seen from Fig. 6, this thin layer developed in the morning, increasing its height gradually. The height of convective echoes recorded by sodar was approximately 300 m, and no elevated layer (elevated inversion) was detected in the limits of sodar range (1000 m). Unfortunately, temperature profile could not be

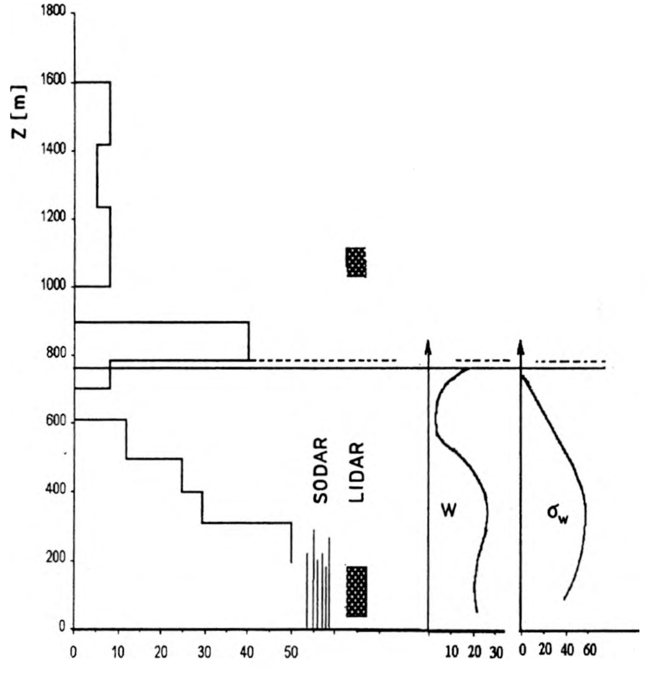

Fig. 5. Graphical representation of measurement results of August 18, 1993. Main graph (left) vertical axis – height, horizontal axis – SO_2 concentration [$\mu g/m^3$], (mean layer concentrations). SODAR – height of sodar-observed convective plumes, LIDAR – lidar-observed aerosol layer, w – vertical velocity [cm/s] and its standard deviation σ_w.

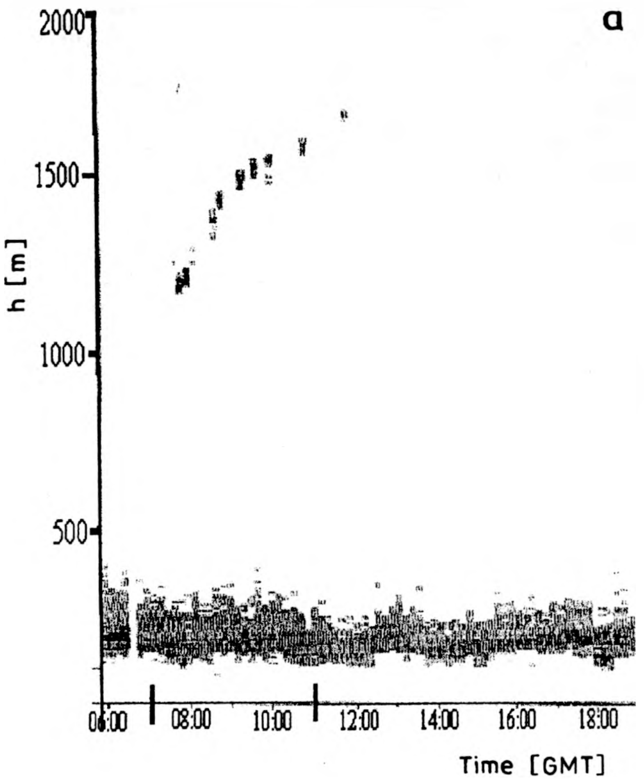

Fig. 6a

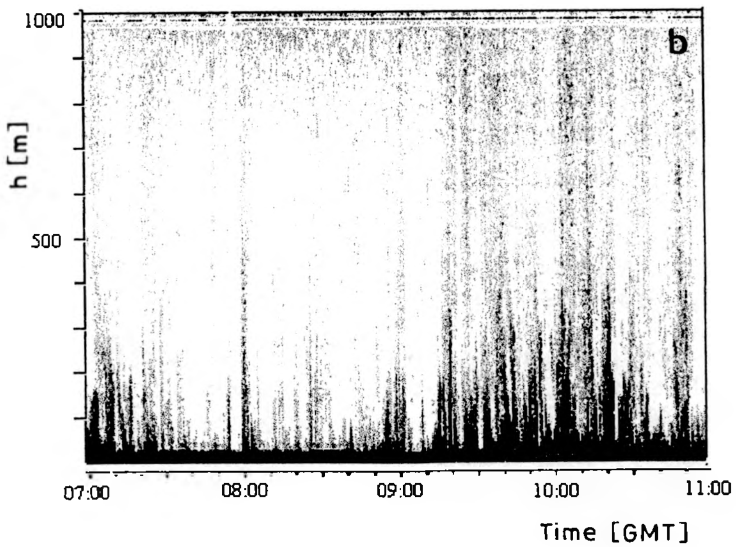

Fig. 6b

Fig. 6. Lidar-record (**a**) and sodar-record (**b**) of August 18, 1993; method of presentation like that in Figs. 2 and 3. At sodar record visible convective plumes.

measured during this flight. The minimum of vertical motion velocity (measured by Doppler sodar) was at the height of approximately 600 m (coincidence with the top of SO_2 layer), whilst the standard deviation of vertical velocities (σ_w) was approaching zero at about 750 meters.

A new series of measurements of this kind started in 1999 and it is hoped to bring new contributions to the discussion on the nature of mixing layer.

4.2. Stable conditions (stable ABL)

The data file in this case comprises results of simultaneous measurements of the heights of lidar-observed aerosol layers and the heights of inversion layers detected by sodar. Figure 7 presents the distribution of the values z_L/z_g, where z_L denotes the depth of ground-based aerosol layer, and z_g – the depth of sodar-observed ground-based layer (interpreted as the height of ground-based inversion), [5]. The number of cases analysed is 142 and in about 45% of the cases values of z_L/z_g are in the range 0.9 – 1.3 which means that the depth of aerosol layer is near to the height of ground-based inversion layer observed by sodar. In about 50% of the cases, however, the aerosol layer is reaching higher than the ground-based layer detected by sodar.

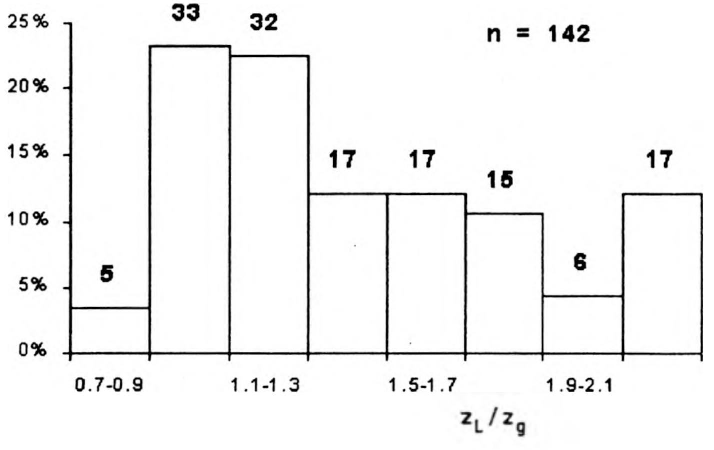

Fig. 7. Distribution of relation z_L/z_g (depth of lidar-observed dust layer divided by the depth of sodar-observed ground based echo layer). Measurements taken in Cracow, 1994 – 1996.

The mechanism generating such situations may be of varying nature. It may be the activity of gravitational waves at the top of stable layer; observed amplitude of such waves reaches 200 m and sometimes more. It may also be the combination of 2 factors: i) intensitve mixing by high-reaching convective processes, in daytime, ii) the following night, "preservation" of aerosol at comparatively high altitude by turbulence generated in the residual layer, above the nocturnal stable layer [7].

In all the cases observed with high reaching aerosol layers, on the previous day, according to sodar observations, very active and high-reaching convective processes were developed, followed by elevated inversion layers after the decay of convection.

Analysing another data file of 241 cases, nearly 60% of them give evidence of coincidence of the heights of the base of elevated inversion layer, observed by sodar (accompanied by different kinds of structures below), and the top of aerosol layer.

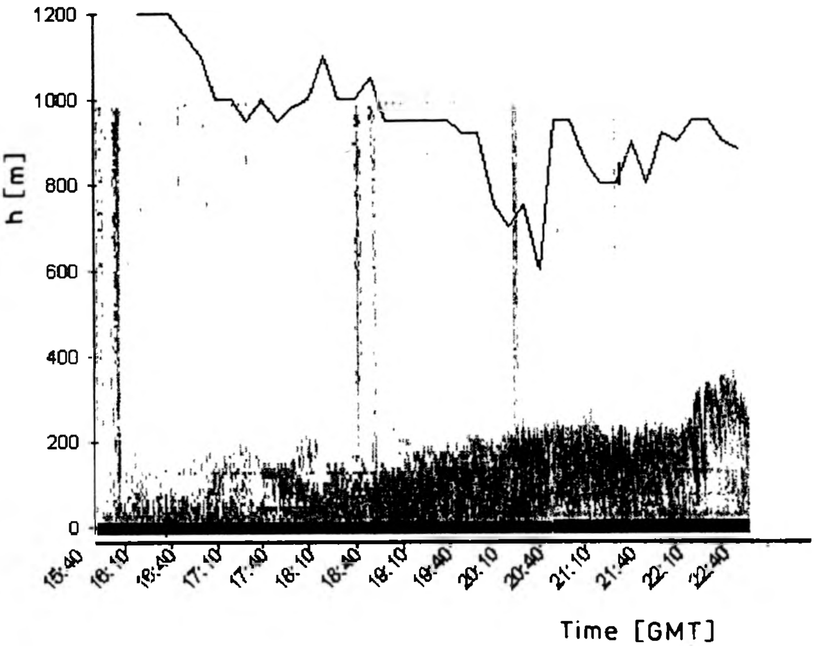

Fig. 8. Sodar record of March 7, 1995 (15:40–23:00) with marked lidar elevated layers (upper heavy line).

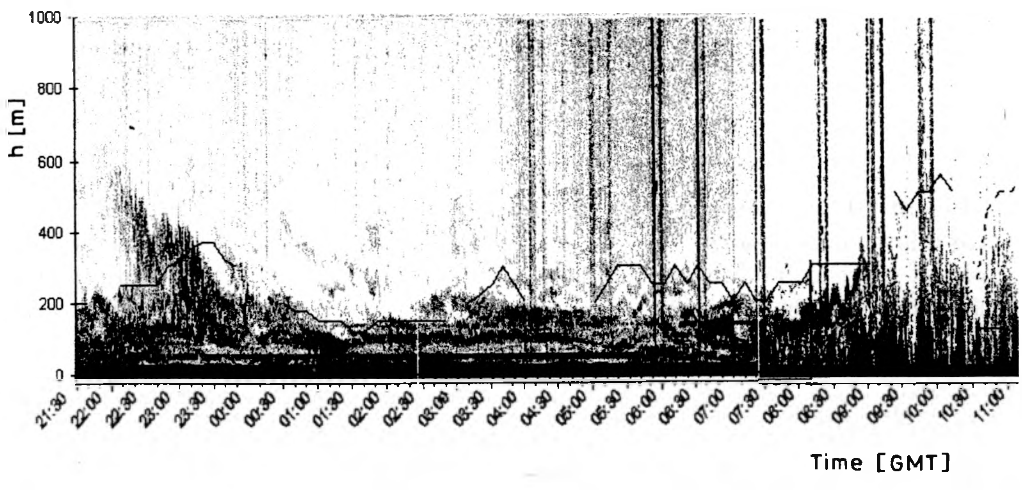

Fig. 9. Sodar record of March 9–10, 1995 (21:30–11:30) with marked depth of the lidar-observed dust layer (solid line).

For illustration of the situations considered above, we present in Figs. 8 and 9 selected parts of time series of data of measurements made with the use of lidar and sodar in the period March 7–10, 1995. In Figure 8, an elevated aerosol layer is visible in time period 16:00–22:40 hours. The base of this layer is situated at heights varying from 600 to 1200 m, well above the ground-based layer observed by sodar. In the limits of sodar-detected layer, no backscatter of lidar signal is recorded, which may suggest very low aerosol concentration. In Figure 9, we see that the depth of aerosol layer reaches the height of an elevated layer detected by sodar above the ground-based layer, in the period from 22:30 hr on March 9 till 9:00 hr next day. Then, when convective layer is developing under the decaying elevated inversion, the aerosol is mixed up to the heights of the highest convective echoes, in the time period 10:00–11:30 hours. To explain the interval of heights achieved during vertical transport of aerosol, it is necessary to take into account the fall velocity of aerosol particles and the values of velocities of vertical motions in the convective air streams. We cannot identify the physical characteristics of the aerosols observed by lidar in the experiments described above, but it is assumed that mean fall velocities of particulates most frequently occurring in the atmosphere vary, depending on diameters of particles, within the limits 0.01–0.06 m/s [8].

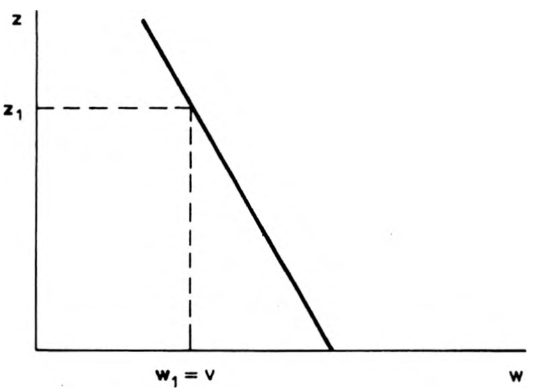

Fig. 10. Schematic presentation of the conditions for creation of an elevated aerosol layer (z – height, w – velocity of atmospheric upward motions, v – fall velocity of aerosol, z_1 – height of aerosol layer).

Figure 10 presents schematically the dependence of the height at which an aerosol layer may be formed on the fall velocity of aerosol and the variability of the speed of upward motions, versus height $w(z)$. The conditions for forming aerosol layer exist at the height z_1 for which the speed of supporting vertical motion equals the fall velocity $v = w(z_1) = w_1$.

5. Conclusions

The research results presented above should be considered as preliminary ones, because the complexity of the problem demands organization of another series of experiments, including application of different measuring techniques.

The results obtained indicate that the mixing of aerosols and gases in ABL is subjected to the influences of different, sometimes complex, mechanisms. As has been noted earlier [5], the mixing processes may be generated by: vertical motions (in convective layer), motions generated by gravity waves, turbulence generated by wind shear in the stable ABL and in the residual layer. Turbulence in residual layer may be due to other processes, too. The existence of turbulent residual layer may cause the survival, through the night, of the deep mixing layer, extended high above the top of ground-based inversion layer, and including substantial part of the residual layer. Different processes, mentioned above, may act jointly or may be correlated as the result of their time sequence.

Lidar observations are valuable empirical documentation of these processes, which are in inadequate extent described by majority of parameterization formulae, used for calculation of mixing layer heights. Continuation of lidar observations of aerosol layers, in combination with other kinds of measurement techniques, may lead to development of reliable methods for determining mixing layer heights, for application in air pollution dispersion models.

References

[1] KASZOWSKI W., BIELAK A., Repts. Inst. Meteorol. Water Mngmt. (in Polish, summary in English), Bull. XVII, No. 3 (1994), 115.

[2] SCHOLTEN R.D.A., ERBRINK J.J., Proc. Intern. Meeting on Application of Sodar and Lidar Techniques in Air Pollution Monitoring, Kraków, September 20–28, 1990, [Ed.] J. Walczewski, pp. XVI 1–XVI 13.

[3] ZARĘBSKI M., Repts. Inst. Meteorol. Water Mngmt. (in Polish, summary in English), Bull. XVII, No. 3 (1994), 101.

[4] KASZOWSKI W., BIELAK A., Repts. Inst. Meteorol. Water Mngmt. (in Polish, summary in English), Bull. XIX, No. 2 (1996), 3.

[5] WALCZEWSKI J., Repts. Inst. Meteorol. Water Mngmt. (in Polish, summary in English), Bull. XX, No. 1 (1997), 45.

[6] WALCZEWSKI J., Repts. Inst. Meteorol. Water Mngmt. (in Polish, summary in English), Bull. XXI, No. 1 (1998), 3.

[7] WALCZEWSKI J., ORKISZ K., Repts. Inst. Meterol. Water Mngmt. (in Polish, summary in English), Bull. XVII, No. 3 (1994), 71.

[8] FREEDMAN F. R., BORNSTEIN R.D., [In] Proc. EURASAP Workshop: *Determination of the Mixing Height – Current Progress and Problems*, Annex, Roskilde, Denmark, 1997,

[9] TWOMEY S., *Atmospheric Aerosols. Developments in Atmospheric Science* 7, Elsevier Publ. Co., Amsterdam, Oxford, New York 1977.

Received September 10, 1999