LIDAR STUDIES OF URBAN AEROSOL IN THE LOW ATMOSPHERIC LAYERS

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Lidar investigations of aerosol behavior in the low atmosphere over Sofia have been carried out in parallel with meteorological observations performed using a tethered balloon and an aerological system "Meteor". New applications of an aerosol lidar to tracking the evolution of atmospheric volumes of a steady stratification determining the altitude of upper boundary of temperature inversion, and detecting the altitude intervals of wind shear are demonstrated.

In spite of numerous lidar investigations of aerosol in the lower atmosphere, the information about this important component of urban air available from the literature is insufficient and some times contradictory. The models developed so far describe, as a rule, only general tendencies and do not allow for comprehensive identification of the role of meteorological factors.[1–3] Therefore usefulness of lidar data on the urban atmosphere obtained in parallel with meteorological observations essentially increases. From this viewpoint, the complex atmospheric experiments that are being conducted at the polygon of the Institute of Electronics, Bulgarian Academy of Sciences in the outskirts of Sofia with the help of lidars and standard means of meteorological observations are quite informative.

During the last "Zond–88" expedition the main attention was paid to intercomparison of the lidar data obtained by an aerosol lidar[4] with data on meteorological processes obtained with the help of a tethered balloon[5] and an aerological system "Meteor".[5] The experimental results have demonstrated high potentiality of lidars for monitoring the atmosphere and, in particular, for tracking the processes of generation, development, and destruction of the steady stratification of the atmosphere and atmospheric layers trapping the aerosol.

Some results of the lidar investigations of an urban aerosol and meteorological observations carried out during the "Zond–88" expedition in the period of October 5–24, 1988 are discussed below.

The lidar investigations were performed using a three–beam aerosol lidar[4] capable of sounding the atmosphere along three paths (three optical receiving systems and a laser beam splitted into three beams of approximately equal power) at a wavelength of 0.53 μm, the angular distance between the paths being about 5–10°. Use of the three sounding paths enabled us to obtain, along with usual information about the atmospheric aerosol the data on profiles of the wind velocity and on, the aerosol transfer using a correlative or spectral technique of processing of temporal fluctuations of return signals acquired for thusly arranged sounding paths at different altitudes.[7] The lidar transmitter uses an IZ–25 Nd:YAG laser delivering 0.025 J per pulse at second harmonic wavelength at the repetition rate 12.5 Hz. The diameter of the receiving objectives is 150 mm. The lidar operation range varied from 0.8 to 1.5 km depending on weather conditions. The spatial resolution was about 7.5 m, capacity of an ADC used to record lidar returns was equal to 10. A "Pravets–16" micro–computer with the operational memory of 640 kbyte was used for post–detection storage and processing of lidar returns. Time resolution of the lidar wind velocity measurements was 12.5 min and 32 s when measuring scattering coefficients.

The profile meteorological observations were performed with the help of the tethered balloon, which could effectively work at the wind velocity less than 6 m/s, and the aerological system "Meteor". The "Meteor" system operated in a routine mode.[6] The tethered balloon could be fixed for a necessary period of time at any altitude with an altitude step 5–10 m. The highest altitude reached with the balloon was 1–1.5 km. High precision is a specific feature of the balloon measurements: the rms error of temperature measurements is 0.1°C, and that of the wind velocity measurements is 0.1 m/s.

The meteorological situations we had during experiments were formed by anticyclones with a fine and calm weather and by atmospheric fronts accompanied by a rather strong wind and cloudiness. Special attention was paid to the atmospheric processes resulting in formation and destruction of elevated temperature inversions preventing the aerosol removal from the ground atmospheric layer.

Figure 1 presents the lidar data on the altitude of the low and upper boundaries of the aerosol layers observed in the region of temperature inversions. These data were obtained under the anticyclone conditions being typical for synoptic objects without distinct fronts. The criterion used for identifying the lower boundary of an aerosol layer is the 20–30% increase of the lidar return amplitude. The upper boundary of the layer was identified at the altitude where the fall off of an averaged quadratic–amplified lidar return experiences an attenuation of 0.5 dB per 50 m. Figure 2 shows the temperature profiles corresponding to time interval presented in Fig. 1.

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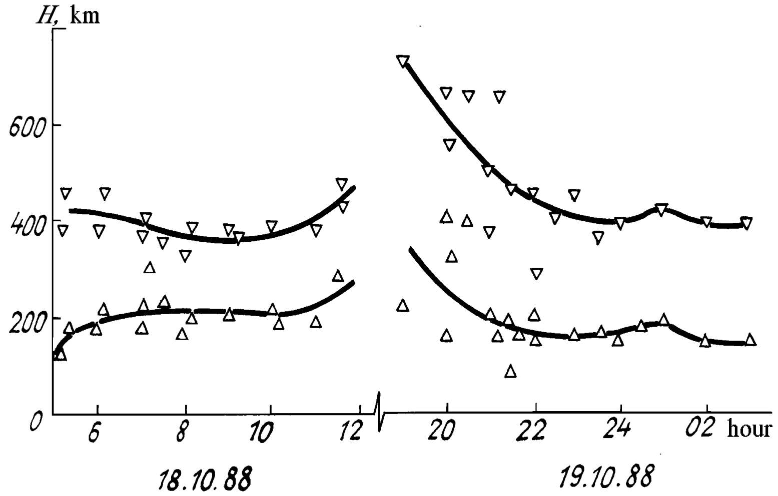

FIG. 1. The diurnal behavior of the altitudes of the lower (Δ) and upper (Y) boundaries of the aerosol layer.

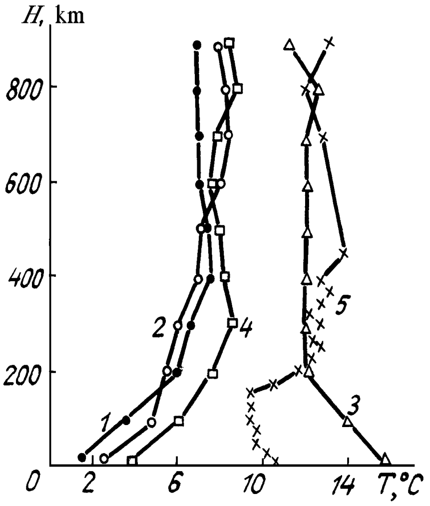

FIG. 2. Temperature profiles obtained by the radiosonde on October 18, 1988 at 01:30 AM (1), 07:30 AM (2), 01:30 PM (3), and on October 19, 1988 at 01:30 AM (4), as well as by the tethered balloon on October 19, 1988 at 09:30 AM (5).

As can be seen from Fig. 1, the altitudes of lower and upper boundaries of the aerosol layer have a distinct diurnal variations. Their lowest altitudes are observed during nighttime while sharp increase of the altitudes occurs at noon and afternoon. For the period from 08.00 PM to 10.00 AM the layer base is at 150–200 m altitude, while that of the upper boundary varies from 350 to 450 m. Analysis of temperature profiles corresponding to this period of time shows that the temperature inversion starts immediately near the ground surface and only at 9–10:00 AM it breaks off from the surface and its lower boundary rises to the altitude of about 150 m. In the latter case the aerosol layer base coincides with the altitude of the temperature inversion lower boundary. Before this time the lower boundary of the aerosol layer is within the temperature inversion layer. The upper boundary of the layer coincides with the upper boundary of the temperature inversion.

The total thickness of the aerosol layer for the period from 8:00 PM to 10:00 AM is about 150–300 m, while its minimum values are observed in the morning hours between 8:00 and 10:00 AM and the maximum ones are observed during nighttime between 3:00 and 6:00 AM.

Near the noon the altitude of the aerosol layer (its lower and upper boundaries) sharply increases exceeding the level of 400–700 m and even higher, (see Fig. 1) and aerosol of the lower atmosphere looses the properties of an aerosol layer, i.e., the aerosol layer is destroyed. Aerological data corresponding to this time interval show an (Fig. 2) essential temperature increase at all altitudes and a total destruction of the steady stratification of the atmosphere that prevents the aerosol removal and formation of aerosol layers. Such a state of the atmosphere (without distinct atmospheric layers) exists till 7:00 PM, i.e., until the sunset. After sunset a restoration of the steady temperature stratification occurs and a stratified structure of the aerosol vertical distribution is also regenerated due to the cooling processes. The altitude of the aerosol layer gradually decreases and reaches the nighttime values as early as at 10:00 PM.

It should be noted that the lidar data on the aerosol relation to the temperature stratification well agree with the average data on thickness of the temperature inversion layer which for Sofia in autumn and winter is normally at 370 to 510 m altitude.

It can be stated that the results of this optical–meteorological experiment essentially improve our understanding of interaction between the processes of aerosol accumulation in the lower atmosphere and its thermal structure[1,9,10] providing for identification of time intervals during a day when air pollution can reach dangerous levels in the atmosphere over certain areas. The use of a lidar as a mean for air quality monitoring capable of estimating mass concentration of pollutants and making mapping of pollutions over an extended areas is strongly recommended during such periods.

Wind velocity plays an important role in the processes of the atmospheric pollution accumulation transfer and diffusion. Wind behavior in the urban atmosphere has also been studied during the expedition using a lidar method. Figure 3 presents the wind velocity vertical profiles measured by the lidar and radiosonde in close moments of time. The weather conditions corresponded to periphery of an extensive anticyclone centered over the Baltic sea with the low pressure region, system of fronts, and essential wind gradients over the Apennines area.

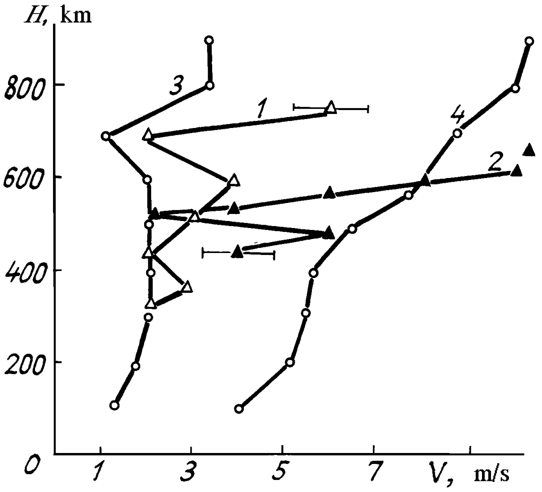

FIG. 3. Wind velocity vertical profiles measured by the lidar on October 20, 1988 at 8:00 PM (1) and 9:40 PM (2) and by the radiosonde on October 20, 1988 at 8:00 PM (3), and on October 21, 1988 at 9:40 PM (4). The horizontal bars indicate the rms error of lidar measurements.

As can be seen from Fig. 3 the profiles measured by the radiosonde in the lower atmospheric layers (below 400–600 m) belong to the class of the low–gradient ones, the total variation of the wind velocity magnitude does not exceed 1 m/sec. The mean wind velocity changed by 3 m/sec during 4 hours (an interval between sonde launches). At higher altitudes the radiosonde and lidar data acquired just after the sonde launch revealed an essential dependence of wind velocity on altitude (at altitudes of 500–800 m) characterized by the wind shear up to 10 m/sec over 100 m (curve 2). The wind shear structures in the wind field make the process of pollutants removal from their sources more intense.

By comparing the altitudes where great wind gradients occur with the altitudes of aerosol layers and temperature inversions (Figs. 1 and 2) one can notice that the altitudes of the greatest wind velocities coincide with the upper boundary of aerosol and inversion layers. The dynamics of the atmospheric layer with great wind shears is similar to the behavior of the upper boundary of the aerosol layer. Thus, from 8:00 to 9:40 PM (the moments of lidar measurements of wind velocity profile) the altitudes of the greatest wind velocity and of the upper boundary of the aerosol layer lowered down by 200 m. The phenomenon that the existence of the temperature inversion layers is accompanied by the layers of maximum wind velocity at its upper boundary is well known in micrometeorology and is theoretically explained.[11]

Since the correlation lidar technique of wind velocity measurements is based on the statistical analysis of optical signals reflected by different atmospheric volumes, the investigation of correlations between variations of signals reflected from the atmosphere at successive altitudes is of certain interest. The presence or absence of the correlation between the lidar return fluctuations at various altitudes is indicative of the scale of aerosol vertical inhomogeneities. In particular, the occurrence of wind shears in the atmosphere at some altitudes may lead to the loss of correlation between the fluctuating signals at these altitudes and to the decrease of the inhomogeneities vertical scale.

We use the spatial correlation matrices as of a measure of correlation between lidar returns coming from different altitudes. The table presents two correlation matrices obtained using the results of soundings performed in time close to the lidar measurements of wind velocity profiles presented in Fig. 3. The first matrix corresponds to the altitude interval 418–642 m and curve *1* in Fig. 3 and the second one to the altitude interval 448–672 m and curve *2* in Fig. 3. The table shows that the correlation coefficients have the greatest values near the main diagonal and become less while moving from it. Moreover, if in the first matrix one can see a noticeable correlation (0.1–0.2) between two, three, and even four neighbour altitudes, in the second the mentioned values are kept only between two adjacent altitudes. This difference may be explained if one takes into account time behavior of the meteorological parameters presented, in particular, in Fig. 3. The wind velocity variation at an altitude interval presented in the first matrix did not exceed 2 m/sec, while for the second it was about 10 m/sec. Other meteorological parameters (temperature, pressure) remained practically unchanged. As a consequence it can be stated that the wind shear resulted in the loss of correlation between the lidar signal fluctuations occuring at altitudes differing greater than 32 m. Therefore, one can detect the atmospheric regions of wind shear with the help of an aerosol lidar using them from the interlevel correlation matrix for lidar returns without measuring the wind velocity itself.

TABLE I. Spatial correlation matrices of the lidar signals obtained on October 20, 1988.

H, m	Time							
	8:27 PM							
418	1.000	0.163	0.142	0.107	0.097	0.086	0.037	0.072
450		1.000	0.257	0.137	0.025	–0.012	0.031	0.014
482			1.000	0.249	0.111	0.011	–0.023	0.064
514				1.000	0.318	0.112	0.119	0.114
546					1.000	0.395	0.304	0.233
578						1.000	0.473	0.346
610							1.000	0.432
642								1.000
	9:47 PM							
448	1.000	0.157	0.140	0.069	0.114	0.033	0.093	0.077
480		1.000	0.254	0.042	0.148	0.095	0.078	0.062
512			1.000	0.104	0.132	0.094	0.042	0.074
544				1.000	0.118	0.080	0.083	–0.006
576					1.000	0.128	0.085	0.072
608						1.000	0.125	0.101
640							1.000	0.157
672								1.000

Thus, the investigations of the urban aerosol enabled us to conclude that an aerosol lidar is capable of tracking the evolutions of atmospheric regions with the steady stratification determining the altitude of the upper boundary of the temperature inversions and detecting the altitudes of the wind shift. Moreover, the above–mentioned capabilities are demonstrated by an ordinary single–path aerosol lidar in the atmosphere free of stack plumes far from the atmospheric pollution sources. The application of a lidar to investigation of stack plumes themselves have been demonstrated earlier many times (see, for example, Ref. 12).

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