LIDAR INVESTIGATIONS OF ATMOSPHERIC AEROSOL IN THE WIND SHEAR LAYERS

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Some results are presented of the experimental investigations of atmospheric aerosol in the wind shear layers. It is shown that optical properties of atmospheric aerosol in the wind shear layers significantly differ from those in the layers located above and below. The differences in power spectra of optical inhomogeneities inside and outside the wind shear layers are investigated. Some features of diurnal behavior of upper and lower boundaries of the turbulent mixing layer are studied.

Known connections between atmospheric aerosol properties and dynamic processes in the atmosphere result in the dependence of its parameters, including the optical scattering coefficients, on the turbulent regime and wind flow characteristics. This dependence is the most strong in the wind field fluctuations.

General principles and mechanisms of generation and transformation of aerosol inhomogeneities in the troposphere have been described in Refs. 1 and 2. Authors of these papers have theoretically calculated vertical profiles of aerosol structures for some simple models of the Earth's atmosphere. The interaction of an individual particle with air flow has been described based on the Navier–Stokes equation and theoretical estimates of the aerosol inhomogeneity size are obtained in these papers.

A cycle of experimental investigations carried out using an airborne instrumentation complex was described in Refs. 3–5. The bulk of statistical data obtained in this study made it possible to create optical models of atmospheric aerosol fluctuations for some meteorological situations in different regions of Russia.

A single–parameter model of the mean values of optical parameters of atmospheric aerosol has been developed at the Institute of Atmospheric Physics on the basis of generalization of a great amount of statistical data of ground based measurements. This model uses the expansion over eigenvectors of the correlation matrices obtained experimentally.[6,7]

At the same time it should be noted that the aforementioned data were obtained under the atmospheric conditions without anomalies and peculiarities in the vertical stratification of its properties that determine dynamics of the atmosphere, in particular, the wind velocity. Incidentally, some data[8,9] show that the aerosol optical properties in the atmospheric layers where sharp variability of dynamic characteristic of air is observed, for example, in the wind shear layers, essentially differ from the characteristics of the dynamically homogeneous atmosphere.

This circumstance allows us to look forward to development of a basis for monitoring dynamical peculiarities of the atmosphere by means of optical tools. Detection of such peculiarities is important from the stand point of the flight safety, studies of the pollution spread and other applications. Taking into account that the regions where such peculiarities occur have small size, lidars are much promising for this investigations, because they have high spatial resolution and are actually operative.

The purpose of this work is to investigate atmospheric aerosol in the wind shear and inversion layers by means of aerosol lidar that uses correlation technique for measuring wind velocity profiles. The results obtained illustrate the capabilities of the correlation lidar to control the peculiarities of dynamic stratification of the lower atmosphere. This paper generalizes the cycle of investigations carried out near the city of Tomsk from May till September, 1992. The experiment was carried out under the conditions of clear weather with variable cumulus cloudiness at 3–5 km heights, meteorological visual range was 15–25 km. Some experiments were accompanied by measurements with "Meteor–RKZ" complex of balloonborne measurements.

A three–path lidar was used in the investigations. Its functional block–diagram is shown in Fig. 1. A commercially available pulsed laser *1* emitting at the wavelength 532 nm at a pulse power 0.1 J was used as radiation source. Optical signals were received by the refractor *2* that used the aspherical lens with the diameter 0.3 m and the abberation circle of 0.1 mm diameter.

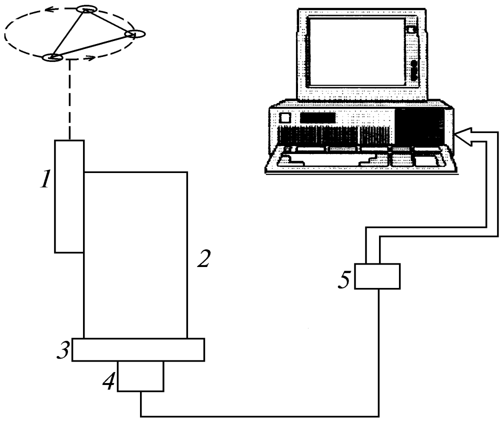

FIG. 1. Functional block–diagram of the wind lidar.

The transmitting–receiving system was mounted on a specially constructed mechanical platform *3* that provides the scanning around the cone envelope without rotation around its own axis as well as the sounding of the atmosphere along three fixed directions during one revolution. The photodetector *4* converts the optical signal into the electric one, which then is directed to the input of an 8–bit ADC *5* with the discretization frequency of 15 MHz. Digital data were recorded with an IBM PC AT in the form of three–dimensional arrays that were processed using a standard routines[10,11] of the correlation technique. As a result, the information was extracted on the scattering coefficient profiles as well as on the profiles of wind speed and direction with 10–20 m altitude resolution. The energy potential of the lidar system made it possible to perform the sounding of the atmosphere both day and night up to 2–2.5 km height.

Profiles of the wind speed and direction obtained by the wind lidar on May 18 and 20, 1992, are shown in Fig. 2. It is seen that the wind speed monotonically increased from 1–1.5 m/s in the near ground layer to 2–4 m/s at the height of 2 km in both cases. The exception is the height range from 700 to 820 m where both the speed and direction of wind experience sudden changes. To estimate the statistical connections between different height levels, the correlation matrices were calculated for the height ranges of the wind shear (700–820 m), as well as above (820–940 m) and below (550–670 m) this level (see Table I).

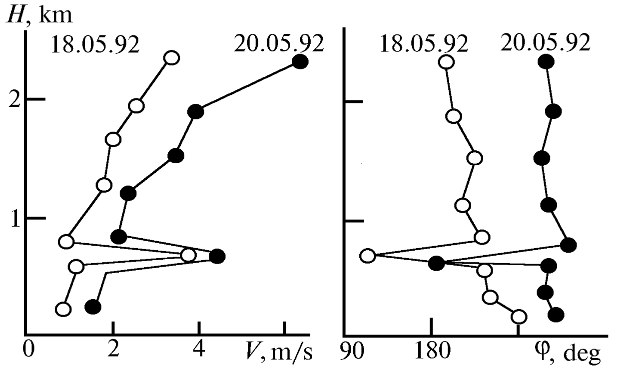

FIG. 2.

It is seen from comparison of the matrices that the behavior of correlation coefficients at the height levels above and below the wind shear level is approximately the same and represents the monotonic function weakly depending on the height difference. At the same time, the height level where the wind shear is observed, is characterized by a more quick change of the correlation coefficient and by the presence of oscillating component. It should be noted that practically always there are the oscillations in the altitude behavior of the correlation coefficient in the presence of the wind shear, hence, one can use them for detecting possible wind shear regions. Rapid variability of the correlation between the optical properties of neighbor height levels are indicative of the fact that the aerosol light scattering characteristics are transformed in the wind shear region. This can be caused by the fact that aerosol in the wind shear region and out of it has different origin. In addition, the fast transformations of the aerosol size spectrum due to an increase in the turbulent diffusion coefficient can be a cause of the correlation break. Unfortunately, the data of the above experiment do not allow us to isolate the mechanism having priority in the break of correlation.

TABLE I. Correlation matrices of aerosol scattering coefficients obtained on May 18, 1992 at different heights.

H, m	700	720	740	760	780	800	820
	1.00	0.39	0.55	0.47	0.53	0.33	0.26
		1.00	0.73	0.67	0.36	0.39	0.33
			1.00	0.85	0.59	0.54	0.50
				1.00	0.63	0.56	0.57
					1.00	0.79	0.60
						1.00	0.76
							1.00

H, m	820	840	860	880	900	920	940
	1.00	0.96	0.97	0.97	0.97	0.95	0.96
		1.00	0.97	0.97	0.97	0.95	0.95
			1.00	0.98	0.98	0.97	0.97
				1.00	0.98	0.97	0.97
					1.00	0.98	0.97
						1.00	0.98
							1.00

H, m	550	570	590	610	630	650	670
	1.00	0.96	0.94	0.93	0.92	0.92	0.92
		1.00	0.98	0.97	0.96	0.96	0.95
			1.00	0.98	0.97	0.96	0.95
				1.00	0.98	0.96	0.94
					1.00	0.98	0.96
						1.00	0.98
							1.00

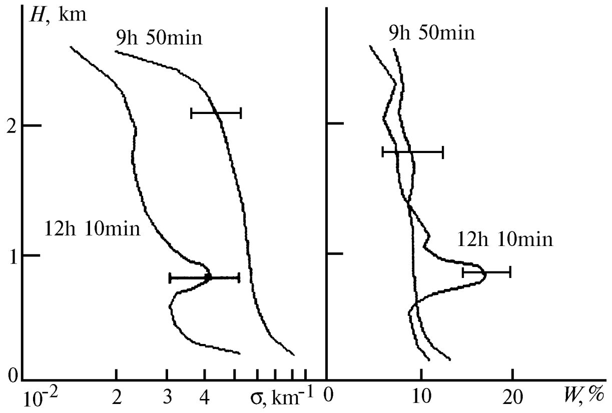

FIG. 3. Vertical profiles of scattering coefficient and variation coefficient obtained on May 20, 1992.

It is interesting to follow the temporal variations in the vertical profiles of optical characteristics for different values of the wind shear. Vertical profiles of the extinction coefficient σ and variation coefficient W are shown in Fig. 3 in the situations when the wind shear was observed and when it was absent. Figures at the profiles mean the time of observations, horizontal bars show the confidence range at the probability level 0.9. It is seen from the figure that a sudden increase in σ and W is observed in the wind shear level in the first case. Vertical profiles at other heights and measurement time are rather monotonic. Their behavior qualitatively coincides with those in the cases described in literature.[12,13] It is quite simple to explain the increase in the scattering coefficient by a transformation of the spectral composition or by variation of the number density of aerosol particles, but to describe the altitude behavior of the variation coefficient in the wind shear region this explanation is not comprehensive. Since the increase in the variation coefficient uniquely determines the greater increase of the variance of the process in comparison with the growth of its mean value, it is necessary to perform spectral analysis of the experimental data for a qualitative explanation.

Visually the series of the optical signals obtained from the wind shear region and out of it are essentially different. At the height of a wind shear aerosol inhomogeneities are of a smaller size and, as a result, signals from this region have larger high–frequency components. It is confirmed by the spectral composition of aerosol inhomogeneities at different heights and different time of observations.

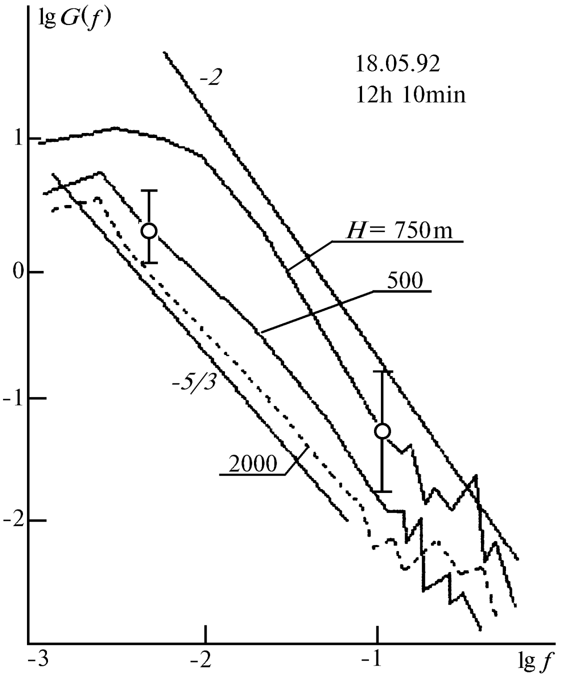

FIG. 4. Power spectra of aerosol inhomogeneities at different heights.

The optical signal power spectra normalized to the variance are shown in Fig. 4. The signals were obtained from the wind shear region as well as from neighbor layers above and below it. As is seen from the comparison of the curves the spectra corresponding to regions out of the wind shear zone have a slope described by the power law with the exponent from –4/3 to –2, that corresponds to the signal fluctuations under conditions of indifferent thermal stratification.[14,15] At the same time, the spectral curves for the level of the wind shear have the shape described by a curve with a power close to –8/3, thus having a more steep slope. Therefore, in the wind shear region there occur processes of a more intense dissipation of turbulent energy that lead to the transformation of the spectral composition of aerosol inhomogeneities, and, hence, to sudden changes of the vertical profiles of W as was observed in the experiment (Fig. 3).

When observing the wind shear, the main attention was paid to the formation and destruction of temperature inversions, because the shear appears at their boundary most frequently. To do it, the upper and lower boundaries of aerosol layers appearing in the temperature inversion region were determined. The level where an increase of 30% in the return signal was observed, was taken as a criterion of the lower boundary. The upper boundary was determined as the level where the rate of decrease in σ value in the scattering coefficient profiles, exceeds 2 dB over 50 m. The results of the lidar control of spatial position of aerosol layers are shown in Fig. 5. The corresponding temperature profiles obtained by means of the "Meteor" aerological complex at different time of observations are also presented here (dashed lines).

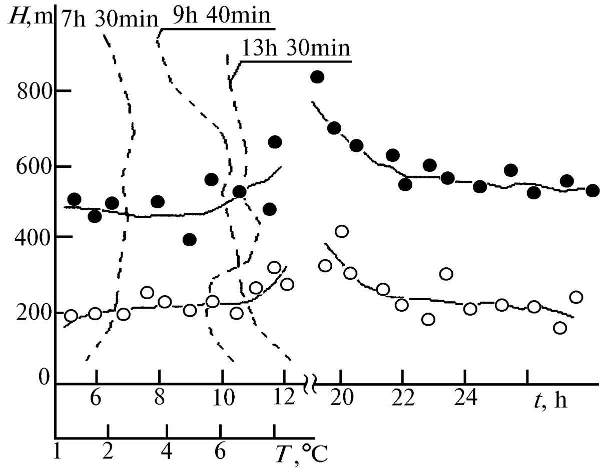

FIG. 5. Results of lidar control of aerosol layers. Solid lines show the heights of the upper (solid circles) and lower (open circles) boundaries of aerosol layer for different time of day on September 12–13, 1994. Dashed lines show the vertical profiles of temperature on September 12.

At is seen from the figure, the heights of lower and upper boundaries of aerosol layer have characteristic diurnal behavior. Small values of heights are observed during dark time, and their increase is observed in the afternoon. The lower boundary of aerosol layer is at the height of 150–200 m from 8 p.m. till 10 a.m., then the upper boundary varies in the range between 350 to 400 m. Analysis of temperature profiles shows that in the evening and night the lower boundary of temperature inversion is exactly at the ground surface. The lower boundary of aerosol layer ascends up to 150 m what is characteristic of morning measurements, and in this case it coincides with the lower boundary of the temperature inversion. The upper boundary of aerosol layer also coincides with the corresponding boundary of the temperature inversion.

The thickness of aerosol layer in the evening and at night is 150–300 m, the minimum thickness is observed in the morning from 8 a.m. till 10 a.m., and the maximum one is observed at night from 3 a.m. till 6 a.m.

The elevation of aerosol layer up to 500–800 m and higher is observed after sunrise and closer to the noon. Then the contrast of aerosol layer optical properties decreases with height and the aerosol layers disappear. Temperature profile at this time is characterized by its increase at all heights and by a complete destruction of the stable stratification that entraps the aerosol emission and forms the aerosol layers. As a rule, this state exists untill the sunset, after which the stable temperature stratification restores and the layered aerosol structure is formed due to the radiative cooling. The height of aerosol layer gradually decreases, and practically reaches the night values by 10–11 p.m.

The fact of existence of the relation between the maximum height of the aerosol layer upper boundary and the height where the wind shear is observed, is of a certain interest. Obviously, it is connected with the fact that the height where the wind shear is observed depends on the level of the temperature inversion upper boundary. The fact that the inversion upper boundary coincides with the level where the wind shear is observed is well–known in meteorology and has its theoretical justification.[8]

Thus, observations of the wind shear layers showed that the dynamic characteristics of these layers essentially affect both the microstructural characteristics and the behavior of aerosol formations in space and time. The results obtained make a good basis for developing the methods of revealing the layers with the wind shear and inversion by means of correlation lidars.

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