PRELIMINARY RESULTS OF LASER–ACOUSTIC EXPERIMENT ON THE STUDY OF THE BACKSCATTERING COEFFICIENT FLUCTUATIONS IN THE ATMOSPHERIC SURFACE LAYER

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Experimental data on auto– and cross–spectra of the backscattering coefficient fluctuations are presented for synchronous registration of three components of wind velocity, temperature, and backscattering coefficient in a local air volume at a height of 5 m. *Measurements were carried out with an acoustic meteorological station and an aerosol laser radar. Obtained results have verified the differences between the autospectra of wind velocity fluctuations and backscattering coefficient fluctuations at stable thermal stratification and have shown different behavior of vertical and horizontal turbulent flows of heat and atmospheric aerosol depending on the thermal stratification.*

Problems of propagation, sedimentation, and change of physical–chemical composition of aerosol particles in an outdoor atmosphere are of most interest from the standpoint of fundamental studies. They are also very important for practical applications. At present, there are only few experimental works devoted to the study of fluctuations of the number density of atmospheric aerosol particles. This is primarily due to technical problems associated with registration of particle number in a small air volume.

The aerosol particles are brought into a moving turbulent air flow characterized by the presence of random fluctuations in three components of the flow velocity. In this case, the temperature (heat content), humidity (moisture content), and aerosol particles (number density) represent impurities “sensitive" to the turbulent character of atmospheric air flow, and finally they themselves begin to undergo random changes in time and space.

The importance of experimental investigations of the statistical properties of the aerosol content in atmospheric air is also conditioned by the fact that exact solution of a system of equations describing the turbulent transfer of aerosol particles cannot be found because of its closure which is a consequence of nonlinearity of equations of hydrodynamics.[1] Therefore, investigators have to consider dimensions or to engage in the construction of theories of turbulence, when along with rigorous equations of hydrodynamics, some complementary connections found empirically from experimental data are used. Such theories of turbulence are called semiempirical, and at present they are rather widely used in engineering. Experiment provides the basis for their construction.[2]

For registration of fluctuations in the number density of aerosol particles in the atmospheric air, particle counters,[3] the open nephelometers,[4] and aerosol laser radars (lidars)[5,6] are used by investigators. Studies performed by various authors allowed them to obtain a frequency spectrum of fluctuations in the number density of aerosol particles[5,7] and to estimate dimensions and lifetime of atmospheric aerosol inhomogeneities.[8,9]

Considering the lidar method of study of the fluctuations in the number density of aerosol particles, it should be noted that it harnesses the proportionality of lidar return signal reflected from the atmosphere to the backscattering coefficient. Variations of the latter are primarily due to the fluctuations in the number density of aerosol particles in a sounded volume.[7] Basic advantages of the method are its remoteness, effectiveness, and high spatial resolution.

Among disadvantages of the lidar method of investigations of the statistical properties of atmospheric aerosol are: 1) the presence of factors, in addition to the fluctuations in the particle number density, leading to fluctuations in lidar return signal (variability of the spectrum of particle size and fluctuations of the atmospheric transparency), 2) practical impossibility to calibrate lidar signal against particle number density, and 3) instability of the energy of laser sounding pulses decreasing the signal–to–noise ratio.

Nevertheless, competent experimental design and the use of the normalized statistic characteristics allow one to obtain in practice the qualitative and quantitative information about the statistical properties of aerosol content in the atmospheric air.[10]

This paper describes the results of lidar studies of the statistical properties of atmospheric aerosol. These results are the continuation of works[7] initiated in 1986. We have investigated auto– and cross–spectra of fluctuations of the backscattering coefficient β_π caused by the fluctuations in the aerosol particle content in a local volume and the meteorological parameters (wind velocity and air temperature). Aerosol, like any other

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atmospheric characteristic (humidity, temperature, and so on), in the first approximation may be considered as conservative (persistent), passive (having no effect on dynamics of air flow), and completely entrained impurity.[11] Then autospectrum of fluctuations of the backscattering coefficient must duplicate the spectrum of fluctuations of wind velocity,[7] i.e. it must be the Kolmogorov spectrum with an inertial interval whose slope is equal to −5/3 (the Kolmogorov–Obukhov law of minus five–thirds).

We have already investigated the limits of applicability of the Kolmogorov spectrum model to the description of the power fluctuation spectra[12] of β_π and have found essential differences in the case of the stable stratification corresponding to positive Richardson numbers, when the β_π spectrum slope was close to −11/5 (the Boljiano–Obukhov law); moreover, this tendency was not observed for spectra of wind velocity fluctuations.

Study of the cross–spectra of fluctuations of β_π, wind velocity, and temperature is also useful, because quadrature of the cross–spectra of the impurity fluctuations with the fluctuations of the longitudinal (vertical) component of velocity represent the spectral expansion of horizontal (vertical) turbulent flow of the given impurity. If we consider heat content as an atmospheric impurity and measure the fluctuations of temperature T', denoting the fluctuations of longitudinal component of velocity by u' and vertical by w', then for estimation of horizontal and vertical turbulent heat flows it will suffice to average the corresponding products $u'T'$ and $w'T'$ (see Ref. 1).

$$H_\mathrm{h} = c_\mathrm{p}\,\rho\langle u'\,T'\rangle, \qquad (1)$$
$$H_\mathrm{v} = c_\mathrm{p}\,\rho\langle w'\,T'\rangle, \qquad (2)$$

where c_p is the heat capacity of air at constant pressure, and ρ is the density of air. If we consider as impurity the aerosol content, then horizontal and vertical flows of particles will be defined as:

$$A_\mathrm{h} = C_1\langle u'\,N'\rangle, \qquad (3)$$
$$A_\mathrm{v} = C_1\langle w'\,N'\rangle, \qquad (4)$$

where C_1 is a given constant. Quadrature of cross–spectrum, denoted usually in the literature by $C_{\alpha\beta}$, where the subscripts α and β are taken to mean respectively the impurity (T, N) and one component of the wind velocity (u, w), represents the spectral expansion of flows (1)–(4).

The above–mentioned cross–spectra can be obtained only with simultaneous registration of meteorological parameters and backscattering coefficient in a local air volume. To realize this idea, the experiment was conducted,[13] the geometry of which is shown in Fig. 1.

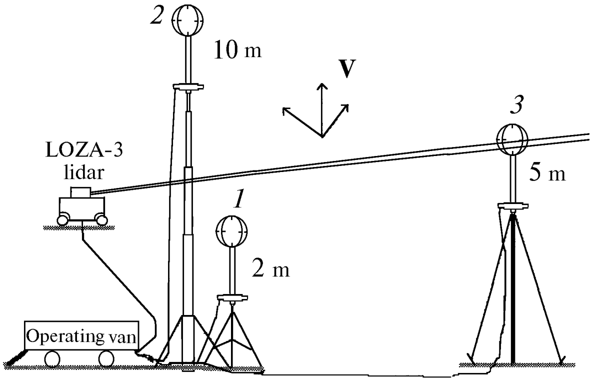

FIG. 1. The geometry of the experiment.

For basic means, three ultrasound acoustic meteorological stations[14] and a LOZA–3 aerosol laser radar were used.[15] The acoustic meteorological station No. 3 was mounted on a 5 m mast and was capable of recording with a frequency of 2 Hz three components of the wind velocity and temperature in air volume of 0.03 m^2. The laser radar was at a distance 240 m from the meteorological station, and its sounding path was in the immediate vicinity of the meteorological station. Lidar sounding wavelength was 532 nm. Short laser pulses with 10 ns duration ensure 1.5 m spatial resolution. The diameter of a beam was equal to 0.15 m. Sounding was conducted synchronously with the operation of meteorological station with a frequency of 2 Hz.

We notice that the accuracy of tuning of a lidar strobe to an anemometer was approximately equal to half the step of digitization of an analog–to–digital converter (ADC) of the lidar. Frequency of ADC operation was 20 MHz. It ensures 7.5 m spatial resolution, and the anemometer was located between two strobes (No. 32 and No. 33). To increase reliability of results, the cross–spectra were calculated for both strobes, and then they were averaged. Any aerosol inhomogeneity makes its contribution to the spectrum of lidar signal fluctuations on a frequency f, being directly proportional to the velocity of this inhomogeneity and inversely proportional to its size. Setting the maximum frequency of the frequency range of cross–spectra under study equal to f_2 corresponding to a spatial scale of 7.5 m, we determine its value. Aerosol inhomogeneities whose dimensions are less than 7.5 m will affect the time spectra at frequencies $f_2 > \langle v\rangle/7.5$ Hz, where $\langle v\rangle$ is the average wind velocity. As a rule, the average wind velocity at a height of 5 m exceeds 1 m/s. . Hence, $f_2 = 0.13$ Hz. We notice that approximately 80 per cent of the turbulent flows of impurities is concentrated at frequencies below 0.1 Hz. The minimum frequency of spectra depends on the total length of realization and an averaging of spectral estimations over frequency and intervals of realization.[16] In our experiment, total length of every realization was 2048 readings taken with a frequency of 2 Hz (17 min). The averaging was conducted over 64 intervals of realizations overlapped by one half to decrease the errors of spectral estimations.[16] As a result, frequency resolution of spectra was equal to 0.016 Hz, and hence f_1=0.016 Hz.

Two more acoustic meteorological stations were used for the estimation of a gradient Richardson number, describing the degree of thermal stability of the atmosphere. These stations were at heights of 2 and 10 meters. The experiment was conducted from July till September 1993 in Zarechnyi Poligon of the Institute of Atmospheric Optics above a smooth field sown with oats. Fifty runs of measurements were conducted. In order to cover the widest range of variation of the number Ri, the measurements were conducted at different time of the day.

The obtained series of data represented the time series, which were then processed on a computer. Data of any series were input into the computer, and gross instrumental errors were eliminated with the use of the Chebyshev inequality. Then recalculation of horizontal components of wind velocity with respect to the direction of average wind velocity was performed so that the average value of longitudinal component $\langle u \rangle$ coincided with the average modulus of velocity, and the average cross component $\langle v \rangle = 0$. Further the operator looked through all series, and in the case of failures of equipment, nonstationarity, etc. the data were rejected fully or partly by means of trancation of part of realization of poor quality and its reduction. After ellimination of trend by high–frequency polynomial filtration,[16] the data were subjected to the Fourier analysis with the use of the procedure of fast Fourier transform[16] (FFT). The effect of leakage was decreased with the use of the GEO (Goodman–Enochson–Otnes) window[16] after calculation of the Fourier coefficients.

In parallel with the calculation of auto– and cross–spectra, the averages of all quantities, theirs variances, turbulent flows of momentum and heat, spectra of coherence and phase, Monin–Obukhov length, and other quantities were calculated. The results were tabulated and filed on a hard disk of a computer. The program of processing made it possible to operate with files easily, to obtain the final results selecting the given characteristics, and to plot their dependences.

In the study of the atmospheric surface layer and investigation of behavior of average values and statistical characteristics of meteorological parameters, the Monin–Obukhov similarity theory is commonly used. This theory makes it possible to use dimensionless velocity, temperature, and height above the Earth's surface. By this theory, within the surface layer (whose height is of the order of 50 m) the vertical flows of the momentum $\rho\langle u'w'\rangle$ and heat $c_p\,\rho\langle w'T'\rangle$ are considered to be constants. This makes it possible to obtain the measuring scales of velocity $u_* = \sqrt{\langle u'w'\rangle}$ (friction velocity), temperature $T_*=\langle w'\,T'\rangle/\kappa\,u_*$, and length $L=u_*^2\langle T\rangle/(\kappa^2\,g\,T_*)$ (Monin–Obukhov length). Introduction of these scales enables one to systematize experimental data; moreover, dimensionless height $\xi = z/L$ represents the parameter of hydrostatic stability unambiguously related with the gradient Richardson number[17] Ri:

$$\mathrm{Ri} = (g/\langle T\rangle)\left[\left(\frac{\partial\langle T\rangle}{\partial z} + \gamma_{\mathrm{a}}\right)\Big/\left(\frac{\partial\langle u\rangle}{\partial z}\right)^2\right],$$

where g is the acceleration of free fall, $\langle T\rangle$ is the average temperature, γ_{a} is the dry adiabatic temperature gradient, and z is height. The form of the dependence of Ri on ξ is well known[17]; therefore, we considered it logical to plot such dependences for each meteorological station *a priori* and to compare it with our data.[17] As a result, we obtained that the graph of the number Ri calculated from the gradients recorded at of meteorological stations No. 1 and No. 3 was in closest agreement with the true dependence. Therefore, the parameter was defined as the average value $(\xi_1 + \xi_2)/2$.

Study of slope of autospectra as functions of the number Ri revealed that lidar data were more noisy than the data of meteorological stations. This is explained by the effect of intense background illumination in the daytime and by instability of lidar operation. The experimental spectrum may be considered as superposition of the Kolmogorov spectrum (or close to it) and white noise. The normalized spectrum is shown in Fig. 2 (curve *2*). This realization (W8) was recorded on July 26, 1993 at 20:30, LT.

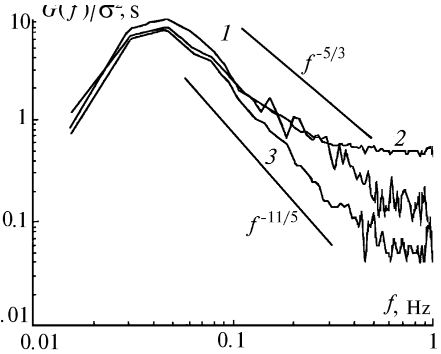

FIG. 2. Normalized autospectra of fluctuations of longitudinal component of the velocity (curve 1), lidar return signal (curve 2), and corrected spectrum of lidar return signal (curve 3).

We note that the statistical error of lidar spectra of fluctuations on the whole was less than the error of wind spectrum (curve *1*), since for estimation of spectra of lidar return signal, the averaging of the spectral estimations was conducted over thirty strobes of lidar return signal at once. The first and the last strobes were at a distance 7.5×29|218 m apart, meteorological station No. 3 was in the middle. Such procedure is quite acceptable, since the time of averaging (of realization) was much greater than the time interval of the order of $218/\langle u\rangle = 1 \ldots 3$ min, and the field was homogeneous and sufficiently large.

The effect of the noise spectrum on of the slope of the autospectra of lidar return signal fluctuations was eliminated with the use of the following procedure of spectrum correction. It was assumed that at high frequencies close to the Nyquist frequency (1 Hz), the spectrum was primarily determined by the noise. It is true, since the spectrum of the valid signal falls off according to the quadratic law, whereas the noise spectrum remains constant. On the same basis we assume that the initial spectrum at high frequencies is primarily determined by the valid signal. Starting from the $-5/3$ law, the value of the spectrum of valid signal at the Nyquist frequency was predicted, then the difference between the initial spectrum and the predicted value was taken to be noise power and was subtracted from the entire initial spectrum. The result of subtraction was the corrected spectrum of lidar return signal (curve *3*). From our point of view, such a simple method of correction used to obtain preliminary results turned out to be efficient.

All results of estimation of the slope m of the autospectra (f^{-m}) are shown in Fig. 3. Triangles (*1*) are for the slope of spectrum of the longitudinal component of wind velocity, crosses (*2*) are for the initial spectral estimations of lidar return signal, and squares (*3*) are for the corrected estimations.

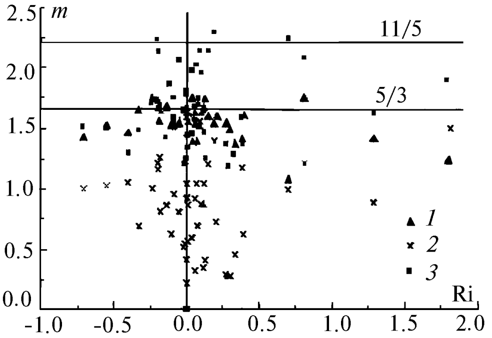

FIG. 3. Graph of slope m of autospectra (f^{-m}) *of longitudinal component of velocity (1), lidar return signal (2), and corrected spectrum of lidar return signal* (3). *Realization W8 on July 26, 1993, 20:30 LT.* Ri = + 0.09.

This graph confirms the results obtained in Ref. 12 for the autospectra of lidar return signal. All spectra of velocity had slope close to 5/3. This is not the case for the spectra of lidar return signal.

We note that the spectra shown in Fig. 2 correspond to the stable state of the atmosphere (Ri =+0.09), and the slope of the corrected spectrum of lidar return signal is close to 11/5. In addition, the slope $m = 11/5$ does not always correspond to the stable conditions (Ri > 0). This fact may be attributed to the presence of descending convective air flows within the atmospheric boundary layer, transporting the aerosol inhomogeneities formed under the stable conditions in the upper part of the boundary layer to the Earth's surface.[18]

Now we proceed to the analysis of cross–spectra. We compare the cross–spectra of temperature–wind velocity and cross–spectra of lidar signal–velocity. We consider the spectra representing expansion in frequencies of turbulent flows of heat and aerosol particles.

Realizing that fluctuations in lidar return signal only approximately describe the fluctuations in aerosol particle content in the volume under study and still considering that they are primarily determined by the pulsations of particle content, we identify these two notions. Therefore, denoting by F' the fluctuations in lidar return signal, we mean by the quantities $\langle F'u'\rangle$ and $\langle F'w'\rangle$ and by theirs spectral expansions (cospectra) $C_{Fu}(f)$ and $C_{Fw}(f)$ the horizontal and vertical turbulent flows of aerosol particles, respectively.

In Fig. 4, cospectra of horizontal and vertical flows of heat and particles are shown for the above–mentioned realization W8.

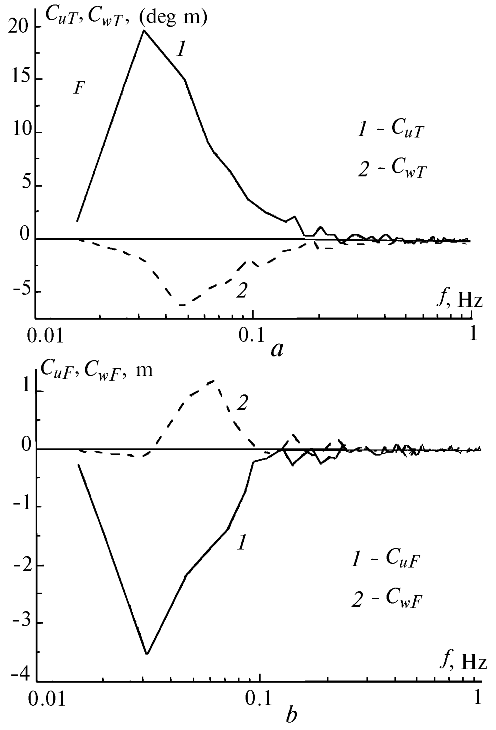

FIG. 4. Cospectra of flows of heat (a) and aerosol particle content (b). Curves 1 are for horizontal flows, and curves 2 are for vertical flows. Realization W8 on July 26, 1993, 20:30 LT. Ri = +0.09.

Considering the horizontal and vertical turbulent flows of a particular impurity, we would like to remind the reader some of their properties. First, these flows differ from zero only in the presence of vertical gradient of the given impurity. Second, if we take the upward direction for vertical flow and the forward direction for horizontal flow as positive ones, then these flows will always have opposite signs. For example, when stratification is unstable (Ri < 0), and positive fluctuation of velocity vertical component $w' > 0$ occur, the warmer air parcel rises up, and we observe the positive fluctuations of temperature $T' > 0$. In this case, the horizontal velocity turns out to be less than the average velocity at this height, since average velocity always grows with increase of height, and consequently $u' < 0$. Hence it follows that $\langle uT\rangle/\langle wT'\rangle < 0$. This inequality will also be satisfied for $w' < 0$ and analogous consideration with Ri > 0.

The cospectra in Fig. 4 corroborate the above reasoning. We note that the character of cospectra for particles (Fig. 4*b*) is similar to the behavior of the corresponding cospectra for heat (Fig. 4*a*). We are reminded, that due to stable thermal stratification, the vertical flow of heat was directed downward, and the horizontal flow — forward.

When stratification is unstable, flows alter their direction, and the fact that turbulent horizontal flow is counter to the average flow means that the total amount of heat transported by air through a given area reduces exactly by the value of negative horizontal turbulent flow. Such is the influence of the atmospheric turbulence. The same is also true for aerosol particles.

In view of the conditions of our experiment mentioned above, the flows were calculated in the frequency range from f_1 = 0.016 Hz to f_2= 0.13 Hz corresponding to aerosol inhomogeneities from 10 to 200 m for wind velocity varying from 1 to 3 m/s. To this end, the cospectra were integrated over a frequency range $f_1 - f_2$. Horizontal and vertical turbulent flows of heat were calculated from the formulae

$$H_h^* = \int_{f_1}^{f_2} C_{uT}(f)\, df/u^*, \tag{5}$$

$$H_v^* = \int_{f_1}^{f_2} C_{wT}(f)\, df/u^*. \tag{6}$$

In these formulae, the constants c_p and ρ were omitted. The horizontal and the vertical turbulent flows of aerosol particles were analogously calculated from the formulae

$$A_h^* = \int_{f_1}^{f_2} C_{uF}(f)\, df, \tag{7}$$

$$A_v^* = \int_{f_1}^{f_2} C_{wF}(f)\, df. \tag{8}$$

The obtained dependences for flows of heat do not contradict numerous data published in the literature[1,2,13]; moreover, change of signs of flows H_h^* and H_v^* in Fig. 5 occurs at $\xi = 0$.

All obtained results of estimation of H_h^* and H_v^* are shown in Figs. 5*a* and *b* as functions of ξ. Corresponding turbulent flows for aerosol particles A_h^* and A_v^* are shown in Figs. 6*a* and *b*. All graphs may be considered as correlative; moreover, the character of the dependence of any of them is followed unambiguously. For this reason, we can draw regression curves, which are shown in figures by solid lines. For calculation of the regression curves, algebraic polynomial of eighth degree was used.

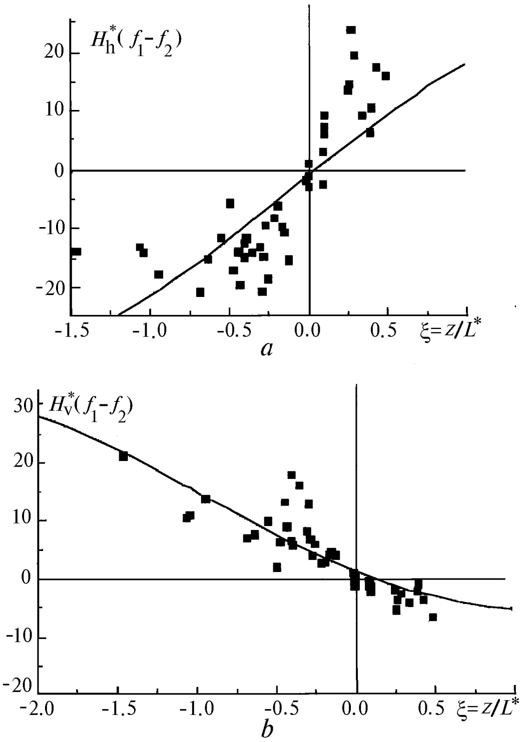

FIG. 5. Dependences of horizontal (a) and vertical (b) turbulent flows of heat in a frequency range (f_1–f_2) as functions of a local parameter of hydrostatic stability $\xi = z/L$. Solid lines show the regression curves.

Analogous functions for aerosol flows A_h^* and A_v^* behave somewhat differently. The decrease of A_v^* with increased instability attracts our attention, and even change of sign of flow at $\xi < -0.6$. At stable thermal stratification (ξ>0), flow A_v^* has a tendency to increase; however, at $\xi > +0.5$ there are not enough points to judge unambiguously about the form of the dependence A_v^* ($\xi > 0$). There is only one value of A_v^* at $\xi = +1$ (it is not shown in the figure) which is close to zero. We may assume for the moment that at large positive ξ the flow A_v^* vanishes. This assumption calls for experimental test. The horizontal flow A_v^*, as it must be, behaves opposite to the flow A_v^*.

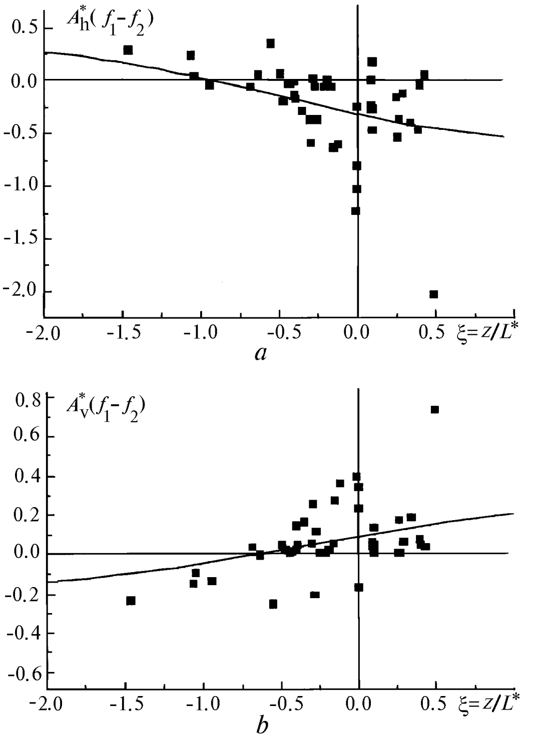

FIG. 6. Dependences of horizontal (a) and vertical (b) turbulent flows of aerosol particles in a frequency range (f_1 — f_2) as functions of local parameter of hydrostatic stability $\xi = z/L$. Solid lines are for the regression curves.

Physical explanation of the obtained result, in our opinion, is the following. Aerosol particles are usually generated near the Earth's surface.[19] The Earth's surface, as a generator of aerosol,[8] has finite power, since for appreciable increase of aerosol number density in air it takes several hours. Therefore, the convective air flows at $\xi < 0$ may likely smooth but the vertical aerosol altitude profile very fast and thereby decrease the gradient of aerosol number density and consequently reduce the vertical turbulent flow of aerosol particles. The fact of change of sign and consequently direction of turbulent flow at $\xi < -0.6$ is of particular interest, because it means the change of sign of the gradient of the number density of aerosol particles, i.e. testifies the increase of aerosol number density in the upper part of the atmospheric surface layer. Undoubtedly, the obtained results are preliminary. They call for future experimental verification and theoretical analysis, the more so that they do not agree with the data of Ref. 10.

In Fig. 7*a* and *b*, the ratios of the horizontal and vertical turbulent flows for heat H_h^*/H_v^* and particles A_h^*/A_v^* are shown Dependence of H_h^*/H_v^* shown in Fig. 7*a* agrees well with the data of Ref. 2. Analyzing the dependence A_h^*/A_v^* shown in Fig. 7*b*, we note that in some series the positive values of ratios of flows occurred. This fact contradicts physics and testifies low accuracy of determination of A_h^* and A_v^* in the experiment. Linear regression in Fig. 7*b* allows us to make only qualitative conclusion that, on average, A_h^*=—1.2 A_v^*, i.e. the turbulent horizontal flow of particles is approximately equal to the vertical flow with opposite sign. If we make a comparison with turbulent heat transfer, then horizontal and vertical heat flows become compared to each other at $\xi < -1$.

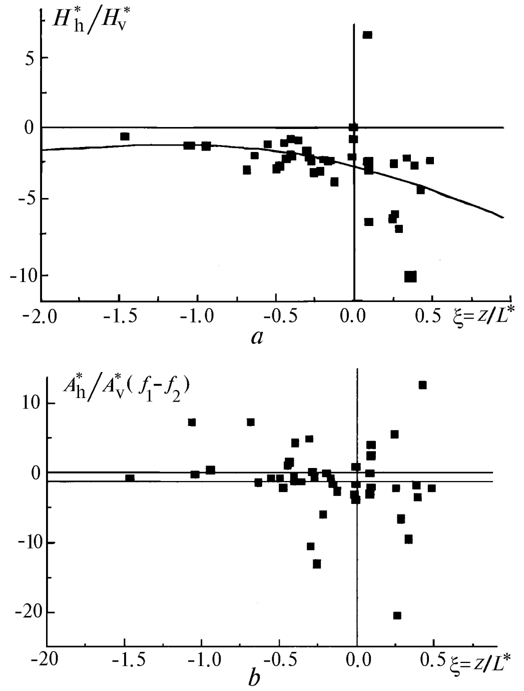

FIG. 7. Ratios of horizontal (a) and vertical (b) turbulent flows of heat (a) and aerosol particles (b) in a frequency range (f_1 — f_2) as functions of local parameter of hydrostatic stability $\xi = z/L$. Solid lines show the regression curves.

To summarize our results have corroborated the autospectrum slope corresponding to the Boljiano—Monin spectrum (the —11/5 law) and simultaneously differing from the velocity spectrum, which is always Kolmogorov (the —5/3 law) in the air surface layer.

Data of the laser—acoustic experiment have revealed so far the qualitative principal difference in the behavior of vertical and horizontal turbulent flows of heat and aerosol particles: the vertical turbulent flow of particles falls off with the increase of a the degree of thermal instability.

The results of data processing also pointed out disadvantages of the lidar method of investigation of pulsations of aerosol content caused by the low signal—to—noise ratio. It makes calibration and estimation of the gradient of particle number density difficult. The last circumstance is extremely important for calculation of the coefficient of turbulent exchange for aerosol particles.

The obtained results will make it possible to design an experiment optimally and to answer the above—formulated questions.

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