Spatiotemporal statistics of small-scale turbulence in the near-ground atmospheric layer from measurements with a set of ultrasonic sensors

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We present here some results of a series of field atmospheric experiments with 12 acoustic computer-controllable sensors. The experiments were conducted to study in detail the turbulence structure of the lowest atmospheric layer. The measurement data were accumulated during the experiments using different schemes of the sensors spatial arrangement in horizontal and vertical planes. Based on the measurements obtained, some spatiotemporal characteristics of wind and temperature fields as well as their dependence on the measurement altitude and thermal stratification of the ground layer are discussed.

The near-ground atmospheric layer, occupying several tens of meters above the Earth's surface, may exemplify the turbulent translation stream. Its properties, including effect of atmospheric stratification on the turbulence dynamics, have been thoroughly studied in Refs. 1 and 2. Nevertheless, there are a number of problems yet unresolved because of the lack of corresponding experimental data. It is primarily because until very recently only the revolving-cup anemometers and mercury thermometers were the basic meters used in the experimental investigations of the atmospheric turbulence. As known, these standard meteorological instruments introduce significant measurement errors due to their low response time and due to the influence of solar radiation.

In recent time the acoustic meters of wind speed and air temperature have begun to be used in atmospheric investigations.[3] They allow one to improve significantly the measurement time and accuracy, what plays a decisive role in recognition of subtle effects in the structure of turbulent fields.

Experimentally, the statistical characteristics of the atmospheric turbulence are most commonly measured from time series of wind and temperature fluctuations. The measured temporal realizations are usually transformed into "spatial" ones with the help of the Taylor hypothesis. Such an approach assumes that within the boundary layer the stream is stationary and horizontally homogeneous. As known, the degree of certainty for the obtained spatial characteristics therewith depends on the degree to which the conditions of the stationarity and homogeneity keep true for the fields of velocity and temperature under study. "ut in the real atmosphere such conditions do fulfill rather seldom.[1] So, the experimental data on spatial structure of wind and temperature fields obtained by means of many-point pulsation measurements with the low-inertia instruments are of great interest both for testing and verification of different theoretical ideas in modeling the turbulence and for a lot of particular practical problems.

In order to study spatiotemporal structure of the atmospheric turbulence, a complex of instrumentation has been developed, consisting of a set of ultrasonic meters of wind speed and temperature arranged in various spatial configurations in the atmospheric ground layer with the help of a system of masts. The set includes 12 identical ultrasonic single-component sensors of wind speed and temperature. It enabled us, to obtain, in addition to time (frequency) statistical characteristics, the spatial ones for wind and temperature fields free of assumptions on according to hypothesis of frozen turbulence.

In combination with the single-component sensors we used the acoustic meteostation[4] which enables one to simultaneously measure the temperature and three components of the wind. We failed to find in literature similar examples of simultaneous use of a lot of acoustic sensors in atmospheric measurements. A significant complexity and relatively high cost of such instruments can, most likely, explain it. The aim of this paper is to demonstrate the capabilities of the complex we have developed for investigation of the spatiotemporal structure of turbulence by means of long-term automated, high-accuracy, low-inertia, synchronous, many-point spatial measurements of the temperature and wind velocity in the near-ground layer. Some statistical characteristics of the near-ground layer turbulence, measured with that complex, are considered as the examples of our results.

Experiment

In our experiments we have used two schemes of the sensors arrangement in space. All the 12 sensors were arranged along one line or in three groups placed

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along three mutually perpendicular rows at a 1 m interval between the adjacent sensors. The acoustic meteostation was usually deployed at the level of the bottom sensor at a distance of 1 m on windward side. The temperature and one component of the wind velocity (depending on axial orientation of the sensors) were measured with all the 12 sensors sinchronously with the meteostation, which measured the temperature and three components of the wind velocity as well as mean values of pressure and air humidity. Thus, each series of measurements involved 28 records of simultaneous measurements. Readouts from the sensors were taken at a 4 Hz frequency. Single data sample comprised 4096 points. The scheme of the experiment and the instrumentation complex, as a whole, have been described in Ref. 5 in a more detail.

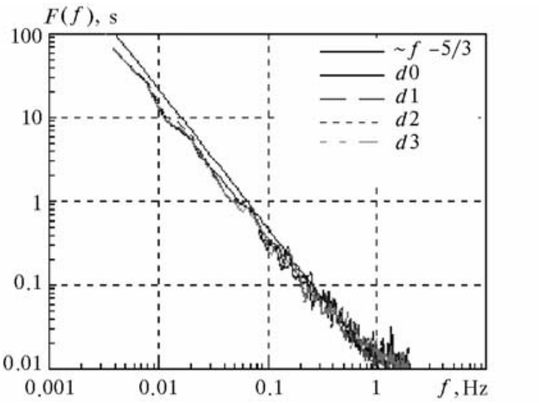
The measurement data were recorded on the hard disk of a computer after their partial real-time processing. The averaging was performed over the whole length of each realization, what took about 17 minutes. Then the recorded data were subjected to more careful analysis and statistical processing. We have analyzed 50 series of measurement data. The following statistical characteristics were calculated for each series: mean values of temperature and wind velocity; variance, scewness, kurtosis, autospectrum, autocorrelation function at the point of location of each sensor, as well as the cross-correlation functions, spectra of coherence, and phase spectra for the sensors situated at a distance of 1 to 11 m from each other. " esides, from the data of ultrasonic meteostation, the single-point moments of the temperature and three components of wind velocity were calculated as well as vertical turbulent fluxes of momentum $\tau = \langle u'w' \rangle$ and heat $H = \langle t'w' \rangle$. Among the calculated parameters there were the scale of velocity (rate of friction) $u^* = \sqrt{-\langle u'w' \rangle}$, the scale of temperature $T^* = -\langle t'w' \rangle / u^*$, and Obukhov scale $L = -\langle T \rangle (u^*)^2/(0.4\, gT^*)$, where u', v', w', and t' are the fluctuations of longitudinal, transverse, and vertical components of the wind velocity and the temperature; $\langle T \rangle$ is the mean value of absolute temperature; and g is the acceleration of gravity.

Thus, quite an extensive and diverse information on statistical properties of spatiotemporal structure of temperature and wind fields of the near-ground atmospheric layer was obtained in each measurement series. Unfortunately, it is rather difficult to analyze the whole complex of measured and computed parameters and their interconnections within the frames of a single paper. So, we will treat, using our data, only some statistical characteristics and their behavior depending on the stratification conditions.

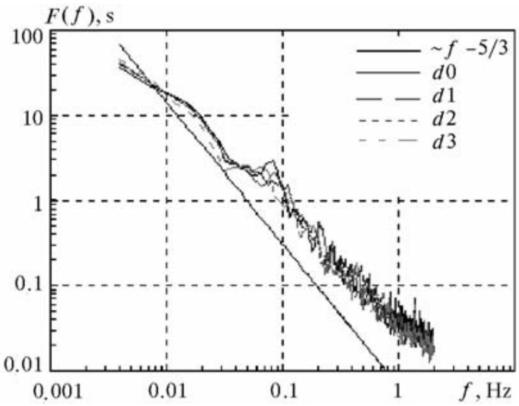
Spectral characteristics

The spectra of wind velocity within the near-ground atmospheric layer reflect the anisotropy of turbulent fluctuations caused by the effect of a hard boundary. When passing to smaller scales, the influence of the boundary gradually decreases, under conditions of neutral or stable stratification and fluctuations become more isotropic, and spectra of the velocity components reach the equilibrium interval. This phenomenon is well known and has been verified in numerous experiments available from the literature. The low-frequency limit, starting from which the universal behavior of the spectra is observed, is therewith different for different components of wind velocity and temperature. It is determined by the corresponding scales of inhomogeneities and depends on a number of factors, in particular, on the height of the observation point and on meteorological situation.

Figures 1–3 depict some examples of frequency spectra for longitudinal, transverse, and vertical components of the wind velocity (a) and simultaneously measured spectra of temperature (b). Each figure presents four spectral curves corresponding to four sensors ($d0$ – $d3$) spaced 1 m apart. Certain difference observed between the spectra is due to spatial variability of turbulent fluctuations on that distance. For horizontal components of the wind velocity (longitudinal and transverse) the agreement between the measured spectra and the "−5/3" law is good enough.



a



b

Fig. 1. Frequency spectra for the longitudinal component of wind velocity (a) and temperature (b).

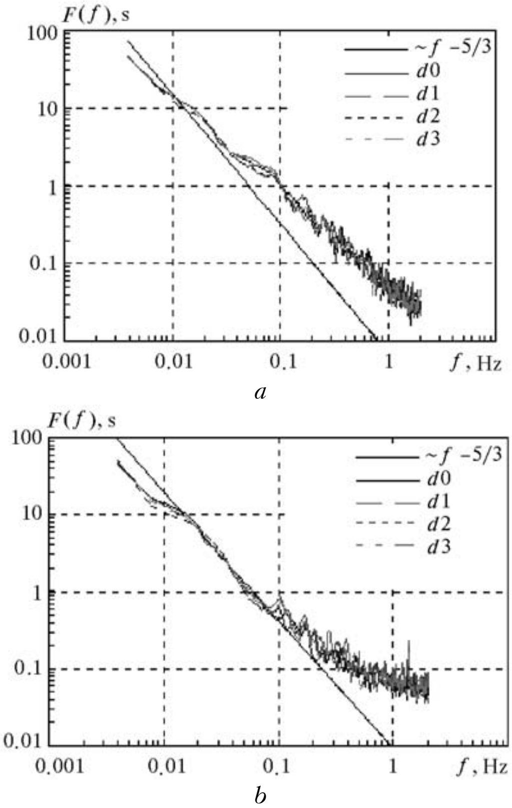


Fig. 2. Frequency spectra for the transverse component of wind velocity (*a*) and temperature (*b*).

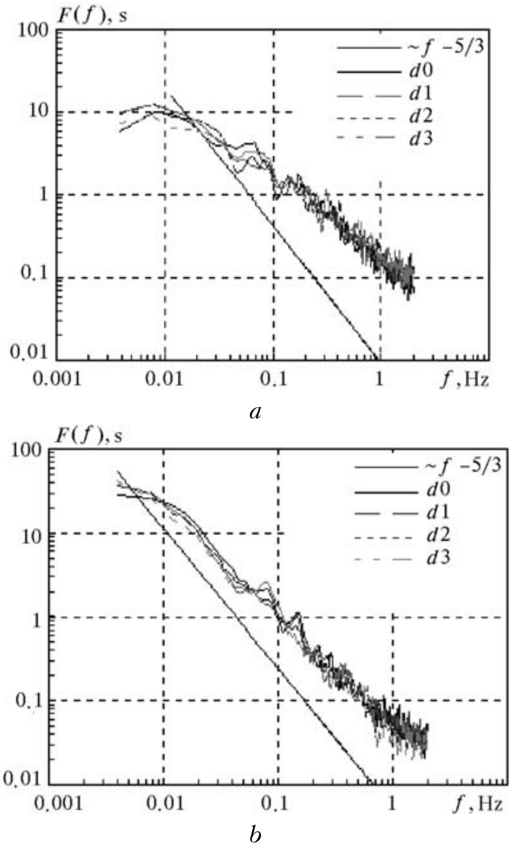


Fig. 3. Frequency spectra for the vertical component of wind velocity (*a*) and temperature (*b*).

The energy in high-frequency spectral region for the vertical component of the wind velocity vector is greater compared with the theoretically predicted. Possible explanation of this fact may be in the generation of turbulence by the wind shear, which is not taken into account by the isotropic model of Kolmogorov turbulence.

Spatiotemporal correlation

The plots depicted in Fig. 4 present spatiotemporal correlation between the longitudinal components of the wind velocity and temperature for the case of measurement points spaced in a horizontal plane.

This is an example of strongly unstable stratification (the Obukhov scale $L = -0.737$ m). Under this conditions the correlation functions fall off most slowly. In this case we can see a good agreement between the shifts of maxima of correlation between the temperature and longitudinal speed, i.e., the velocity field transports the temperature field as a "conservative admixture." For a comparison, dotted lines in the figure show spatiotemporal correlation functions for longitudinal component of wind velocity obtained with the use of Taylor's hypothesis of frozen atmosphere and the data from only one (the first) ultrasonic sensor, when time lag of the correlation maxima position is determined as $\tau_3 = R/v_R$, where v_R is the mean wind velocity along the sensors' spacing line. In the given case v_R is 0.75 m/s and the angle between the line of sensors and the direction of the mean horizontal of wind is 76° (i.e., the direction of arranging the measurement points in space is close to the transverse one).

So, it is seen from Fig. 4, that the shape of curves, as well as the magnitude and position of maxima of the spatiotemporal correlation, calculated assuming the turbulence to be "frozen" and obtained from many-point measurements, do not correspond to each other already at the distance R equal to several meters. It is also seen, that as the distance between the sensors increases, the correlation for temperature decreases much faster then for wind. This testifies that the main contribution to the temperature correlation comes from inhomogeneities of the scale that is less than the characteristic scale of longitudinal velocity. Inasmuch the generation of temperature fluctuations under unstable stratification is mainly due to fluctuations of the vertical component of wind velocity, the temperature correlation behavior better corresponds to the behavior of correlation functions of the vertical component rather than the longitudinal one. The corresponding correlation functions for vertical component and temperature in a horizontal plane, obtained under weakly unstable stratification ($L = -60.7$ m) are presented in Fig. 5.

It should be noted that in the case of stable stratification within the near-ground layer, the correlation for both the velocity and temperature decrease practically to zero already at a distance of several meters.

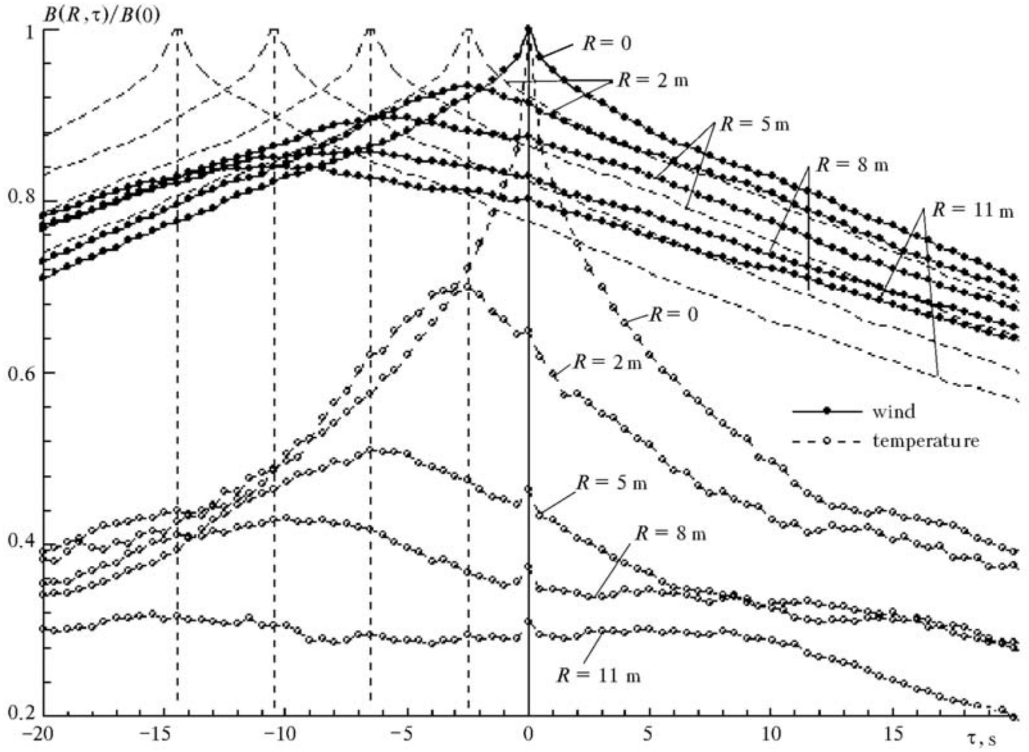


Fig. 4. Spatiotemporal correlation for the longitudinal component of wind velocity and temperature in a horizontal plane.

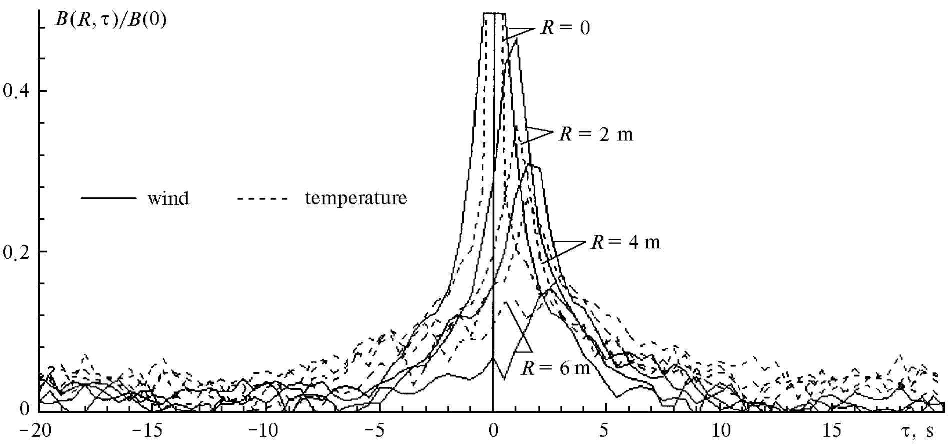


Fig. 5. Spatiotemporal correlation for the vertical component of wind velocity and temperature in a horizontal plane.

Spatial inhomogeneity of the wind velocity and temperature fields may be estimated from variation of the spatial correlation functions, when a pair of the observation points is displaced equidistantly in one direction (Fig. 6), as in Fig. 4 (at a shift of the initial reference point by the distance R in a horizontal direction). The sensors were spaced 1 m apart along one line at a height of 2.5 m above the ground surface. Figures *1* to *12* denote the curves corresponding to the case when thus numbered sensor (from 1 to 12) was used as a reference one, i.e., the sensor relative to which the correlation was computed.

As seen from Fig. 6, the horizontal homogeneity of the temperature field in this realization does not extend thus far as in the velocity field. (This is one more explanation for faster decay of the temperature correlation in Fig. 4).

In accordance with Ref. 2, the altitude correlation of the longitudinal component of wind velocity depends not only on the distance between measurement levels, but on the height of the initial level, relative to which the correlation is calculated, and on the direction of the displacement (up or down) as well.

Figure 7 presents the dependences of the coefficients of spatial correlation for the sensors spaced 1 m apart vertically within the near-ground layer and numbered from top to bottom. Curve *1* in Fig. 7 shows the decrease in the coefficient of spatial correlation between the first and other sensors at an increase in the distance between them from top down; curve *12* demonstrates the correlation behavior relative to the bottom (the twelfth) sensor at increasing distance from bottom upwards.

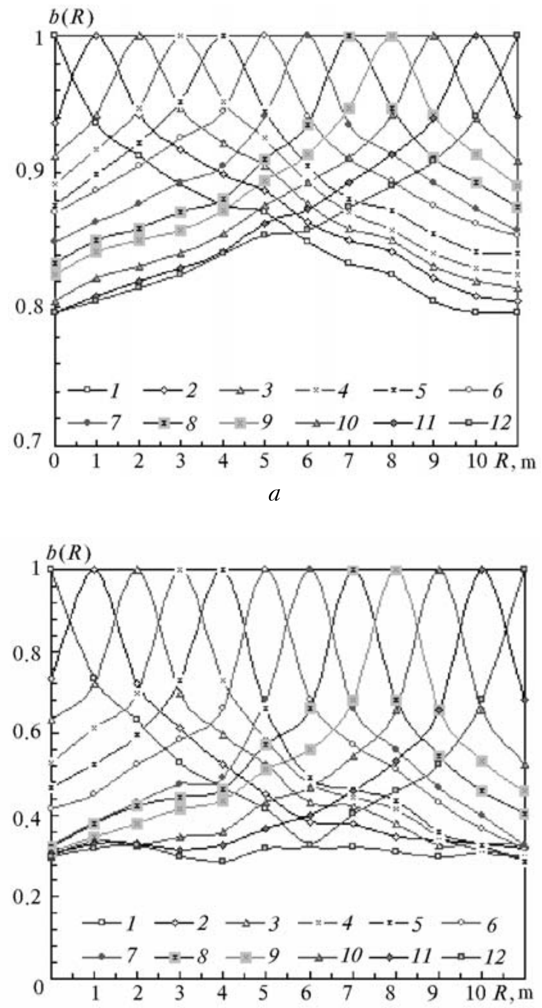


Fig. 6. Spatial correlation for the longitudinal component of wind velocity (*a*) and temperature (*b*) in a horizontal plane.

The above-presented case takes place under conditions of a very stable stratification (the Obukhov scale L = 6.68 m). It is seen, for example, that curves *1* and *12* in Fig. 7*a*, corresponding to heights of 13.5 and 2.5 m and to downward and upward reference directions, respectively, significantly differ from each other. The height correlation of temperature in Fig. 7*b*, is of an irregular character and breaks already at the distance of 1–2 m. This may be caused by wave movements arising in the near-ground layer under stable stratification and, as noted in Ref. 1, their coexistence with the fluctuations of turbulent origin distorts general situation and hampers interpretation of measurements. All this demonstrates the complexity of structure and strong spatial inhomogeneity of the turbulence in vertical direction, particularly, under conditions of stable stratification. Now this type of stratification is the least understood. The principal difficulty is in the fact that the intensity of turbulent fluctuations of the measured parameters is here the weakest. With the use of standard anemometers, spectral analysis and correlation estimates are hampered because of noises, so the results become uncertain. Therefore, the use of the measurement complex we have developed for this purpose is very promising due to higher accuracy of the acoustic measurements.

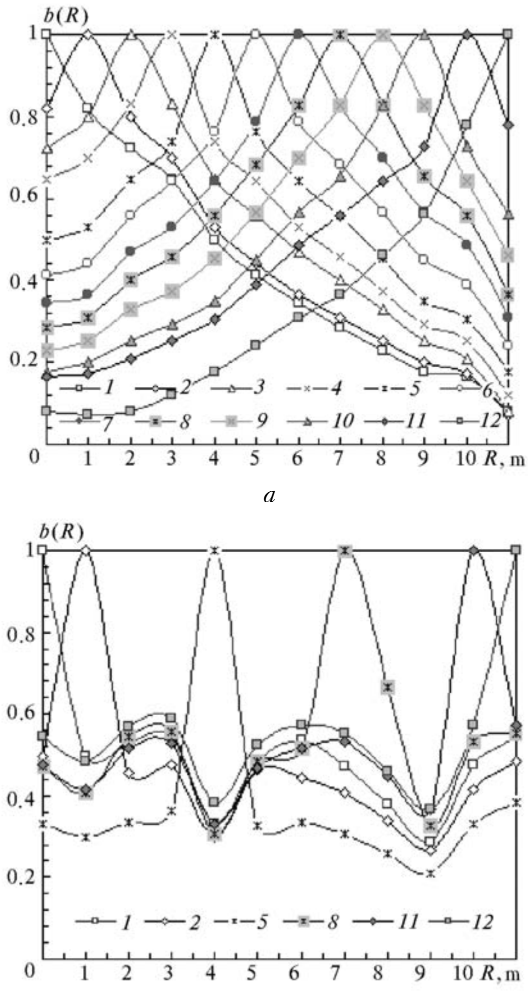


Fig. 7. Spatial correlation for the longitudinal component of wind velocity and temperature along the vertical direction (the designations are the same as in Fig. 6).

Statistical moments of the third and forth orders

The normal distribution law is used in many theoretical papers on simulation of temperature and wind velocity fluctuations. It is stated in Ref. 2 that the distribution of fluctuations for all the three components under standard conditions and assuming their stationarity obeys the laws close to the normal law. The experiments show it to be quite true to life for fluctuations of the horizontal velocity within the inertial interval, i.e., when the conditions of the experiment correspond to isotropic Kolmogorov turbulence approximation. "ut in the case when the interval extends to the low-frequency range (energy region) or if we consider the vertical component of wind velocity, the distribution differs from the Gaussian.

The quantitative measure of the difference between this and standard distribution is the scewness

$$As_{\rm v} = \langle V^3\rangle/\sigma_{\rm v}^3 \qquad (1)$$

and the kurtosis

$$Ek_{\rm v} = \langle V^4\rangle/\sigma_{\rm v}^4 - 3. \qquad (2)$$

It is noted in Ref. 1 that the scewness and the kurtosis of vertical velocity fluctuations and their dependence on the stability and altitude are very important characteristics, but, unfortunately, there is very little available information on actual values of these parameters. Some sparse experimental data on the scewness values in the near-ground layer have been generalized in Ref. 6. The values 0.3 for unstable and −0.2 for stable stratification are presented there. "esides there is formula describing the variation of scewness of fluctuation of the wind vertical component $As_{{\rm v}z}$

$$As_{{\rm v}z} = \frac{-0.77\, z/L}{(1 - 15\, z/L)^{-1/4} - 1.8\, z/L} + 0.1, \qquad (3)$$

where z is the height of measurement and L is the Obukhov scale. According to data from Ref. 7, in the case of unstable stratification $As_{{\rm v}z} = 0.63$ and $Ek_{{\rm v}z} = 0.17$.

Figures 8 and 9 present the experimental values of the scewness and kurtosis, respectively, depending on the parameter of stability z/L for vertical component w, temperature t, and the wind speed module ${\rm mod}V = \sqrt{u^2 + {\rm v}^2 + w^2}$, as well as a calculation by formula (3) and linear approximate expressions obtained from our measurements.

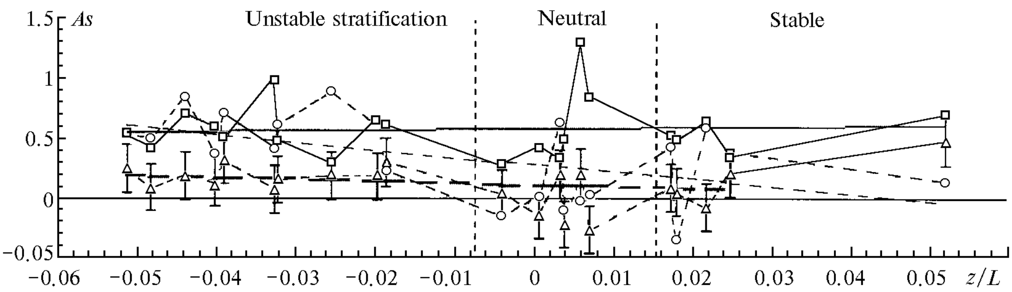


Fig. 8. The dependence of the scewness of velocity and temperature fluctuations on the type of stratification. - - Δ - - − w; - - o - - − t; —□— − mod$V$; — — − Eq. (3); - - - - − $As\ t = -6.2089\ z/L + 0.2803$; —— − As mod$V = 0.4718\ z/L + 0.574$.

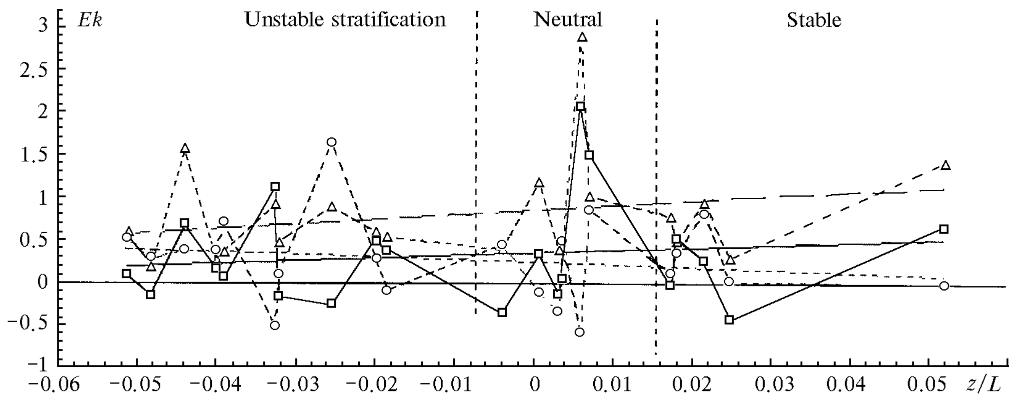


Fig. 9. The dependence of the kurtosis of velocity and temperature fluctuations on the type of stratification. - - Δ - - − w; - - o - - − t; —□— − mod$V$; — — − $Ek\,w = 5.3949\,z/L + 0.8484$; - - - - − $Ek\ t = -2.9603\ z/L + 0.2452$; —— − Ek mod$V = 3.2265\ z/L + 0.3616$.

In the case of unstable stratification, the scewness of the distribution of fluctuations of vertical velocity component is positive (remind, that in case of normal distribution the scewness and kurtosis are equal to zero). On the average, under typical day-time conditions with the prevailing upward directed velocity fluctuations $As_{{\rm v}z}$ is close to 0.2. With the increase of stability the scewness decreases, because at stable stratification the turbulence energy is consumed for overcoming the buoyancy force, and the probability of positive spikes for the vertical wind component to occur decreases. A good agreement between the values calculated by formula (3) and our measurements is seen. The behavior of scewness of the temperature fluctuations qualitatively corresponds to that of the vertical wind component, but it is characterized by somewhat greater positive values in the region of instability and a faster decay to negative ones in the region of neutral and stable stratification. As is seen from Fig. 8, the experimental points for the wind speed are characterized by a significant, on the average, scatter $As_{\mathrm{mod}\,V} \approx 0.5–0.6$. Within the instability range, the positive scewness for the velocity module means that the probability of the wind intensification relative to some given level is greater than the probability of its weakening.

The data presented in Fig. 9 show that the kurtosis of the velocity fluctuations distribution is, on the average, positive, i.e., this distribution is more "sharp" (with more high and spiky top), and the probability density of small fluctuations therewith is increased compared with the normal distribution. The magnitude of the mean kurtosis for vertical component in this case is greater than for the velocity module. Most likely, this overestimation is due to lower homogeneity of the velocity field in vertical direction as compared with the horizontal one, and the deviations from the normal distribution manifest themselves there to a greater extent.

Whereas the scewness decreases from positive values to negative both for w and t as the stability grows (i.e., the asymmetry of distributions changes similarly), the behavior of the kurtosis of velocity fluctuations is opposite to its behavior for temperature fluctuations. The distribution w has a tendency to an increase in the probability density in the case of weak fluctuations (relative to the normal distribution) at all types of stratification.

Thus, the assumption of Gaussian probability distribution for fluctuations of the vertical component of wind velocity does not work for the near-ground atmospheric layer. Actual distribution of vertical velocities in unstable near-ground layer is asymmetrical to the scewness coefficient ranging from 0.2 to 0.3 and the kurtosis (0.5 – 0.8). These circumstances should be taken into account when the laws of distribution are applied to describing the wind velocity fluctuations in developing and substantiating the optical methods for sensing, as well as to description of the optical wave propagation through the atmosphere. Adequate consideration of an asymmetric distribution of the velocities in simulating the statistical characteristics of meteorological quantities will provide for better agreement between the calculated and measured data.

Acknowledgments

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