Investigation of wind velocity variations on mesometeorological scale from sodar observations

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The results of remote acoustic sounding of the wind velocity in the atmospheric boundary layer are analyzed. Oscillation spectra of the absolute value of the horizontal wind velocity of mesometeorological scale are considered. The statistics of wind velocity distributions with periods of 20–250 min, as well as the statistics of significant amplitudes of oscillations at these periods, has been studied using the numerical bandpass filtering. Both summer and winter measurements are included in analysis. Daytime and nighttime conditions are considered separately. To increase the reliability of estimates for amplitudes and periods of regular oscillations of wind velocity, "spectral reliability thresholds" corresponding to the chosen significance level are used. A group of basic oscillation periods in some time intervals is found.

The study of heat and gas exchange processes in the atmospheric boundary layer plays an important role in development of methods and algorithms for prediction of the state of the environment. The wind field is one of the main objects of investigation. Atmospheric motions with characteristic periods of variation of about 24 hours, as well as turbulent components having the scales from several minutes and shorter, are studied quite thoroughly now. The first-priority interest to these motions is caused by the fact that the main part of the energy of atmospheric motions is concentrated just in them.

An intermediate range, namely, the region of mesometeorological minimum in the spectra of velocities of atmospheric motions, is studied much more poorly. This fact is also reflected in equations describing atmospheric dynamic processes, in which the wind velocity field is usually represented as a sum of some average value (often constant in time) and a turbulent component. However, for problems of mesometeorological scale, when the solution is sought for time intervals from several tens of minutes to several hours (from few to several tens of kilometers), such a representation of the wind velocity field may appear not absolutely correct, because regular field variations of a comparable scale exist. In recent years, certain attention is paid to analysis of such processes, in particular, due to development of remote tools for diagnostics of the atmospheric boundary layer (ABL), which allow wind vector profiles to be reconstructed with high spatial and temporal resolution.

Taking into account the urgency of the problem to be considered, the main goals of this work were the spectral analysis of the absolute value of the horizontal wind velocity V_m (hereinafter, wind velocity) at different ABL levels and revealing and systematization of significant (in value) spectral peaks in the range of periods from tens to hundreds of minutes at stable and unstable stratification under summer and winter conditions. For analysis, we used the results of wind velocity measurements by the sodar of the Institute of Atmospheric Optics SB RAS in Tomsk suburbs (Akademgorodok).

Estimation of the spectral composition of wind velocity based on remote acoustic sounding has some features associated with the finite spatiotemporal resolution inherent in a Doppler sodar.

First, the sodar technology of obtaining the information about wind vector profiles uses the combination of vector projections on the directions of sounding by three differently directed antennas (one of which is usually oriented vertically). The scatter in positions of atmospheric volumes, from which the sodar receives signals by different channels (antennas), may be tens and hundreds of meters in the horizontal plane depending on the altitude of measurements. This means that the wind vector components are determined at different spatial points. Consequently, some spatial filtering of the wind vector components takes place.

Second, a significant role is played by finiteness of the atmospheric volume, the signals are received from. Longitudinal dimensions of this volume depend on the duration of the sounding pulse and may be up to tens of meters. Transversal dimensions are connected with the width of the directional pattern of sodar antennas and increase with altitude, achieving hundreds of meters at long ranges. Therefore, the Doppler frequency shift of the received signal is caused by some average motion of a rather large atmospheric volume, the signal comes from, that is, a low-frequency "volume" filter takes place.

Third, measurements are usually carried out with the use of sodars (including the IAO sodar) operating in the mode of turn-by-turn transmission/reception of signals by different antennas. The total period of operation of three measuring channels to obtain

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one "instantaneous" profile of the wind vector is Δt = 12–15 s, which is adequate to a low-frequency time filter. Taking into account the reasons listed above, we analyzed the wind velocity spectra for periods of oscillation longer than 20 min, which, in our opinion, are already beyond the influence of the technology of data obtaining.

To reveal the regular frequency components of wind velocity oscillations from the total random array of V_m (including measurement errors as well), we used the approach described in Ref. 1. It consists essentially in determination of peaks of the unsmoothed power spectrum of a studied sample, which exceed some threshold value G_q corresponding to the chosen level of significance q. In this paper, for clearer interpretation of significant spectral peaks of the wind velocity and new spectral thresholds A_q, we use estimates of amplitude spectra for harmonics $f_k = k/N\Delta t$:

$$A(f_k) = \left| \frac{2}{N} \sum_{n=0}^{N-1} V_m(n\Delta t) \exp(-j2\pi kn/N) \right|,$$

where in the general case k = 0, 1, ..., $N/2$, N is the number of readings in the processed realization $V_m(n\Delta t)$. In this case, the values of significant $A(f_k)$ roughly correspond to amplitudes of ordinary harmonic oscillations.

Find the threshold A_q assuming that $V_m(n\Delta t)$ is the discrete white noise with the variance σ^2. Then, using the results of Ref. 2, we can show that at $N > 1000$, used here, the readings of $A(f_k)$ for $k = 1, 2, ..., N/2 - 1$ are Rayleigh random values regardless of the form of the initial distribution of V_m and have the distribution function $F_1(z) = 1 - \exp(-z^2N/4\sigma^2)$, $z > 0$. The probability that all independent $A(f_k)$, $k = 1, 2, ..., N/2 - 1$, do not exceed some value z is $F_\Sigma(z) = [1 - \exp(-z^2N/4\sigma^2)]^{N/2-1}$. Consequently, the probability that at least one reading of the amplitude spectrum of the white noise $A(f_k)$ exceeds z is determined by the equation $Q(z) = 1 - F_\Sigma(z)$. Solving the equation $Q(A_q) = q$, where A_q is the threshold of detection of a regular component corresponding to the significance level q in the mixture $V_m(n\Delta t)$, we obtain

$$A_q = 2\sigma\sqrt{-\ln[1 - (1 - q)^{2/(N-2)}]/N}.$$

In this case, the value of σ for $N > 1000$ used can be replaced with the sampled standard deviation of the realization $V_m(n\Delta t)$ [Ref. 1].

Thus, the readings of the amplitude spectra, for which $A(f_k) > A_q$ is fulfilled, can be considered as spectral peaks of the corresponding regular oscillations of the wind velocity V_m, rather than its fluctuations, with the probability $1 - q$. As a value of q, we took q = 0.01. To exclude the distorting influence of low-frequency trends (for example, the diurnal behavior of V_m) on the spectral region of the analyzed periods, the high-frequency filtering is necessary. This filtering is performed by using synthesized discrete filters with the finite pulse characteristic.[3] In this case, to exclude transient effects during the data filtering, the analyzed temporal region begins from the reading $n = M_2/2$, where M_2 is the half-length of the pulse characteristics. In what follows, for better illustration we pass from the frequencies f_k to the corresponding period of oscillation p.

Our earlier investigation of oscillations V_m was restricted to the maximal period of about 4 h (numerical filters with a passband Δp = 20–250 min at a half-power level with M_2 = 1000 were used). The main analysis was performed for an altitude of 130 m (one of discrete measurement altitudes). This altitude was selected from the following reasons: (a) episodes selected for the analysis ensured the continuity of estimates of the wind velocity at this altitude (at high altitudes, sodar signals were absent in some episodes, especially, at night time), (b) the influence of surface roughness (orography, plants, and buildings) is weak at this level, (c) the absence of signals reflected from local objects (neighbor buildings) and capable to distort estimates of the wind velocity is guaranteed.

In analysis of the spectra of wind oscillations in the summer period, it was taken into account that under the anticyclonic conditions there are two time intervals with relatively stationary conditions in ABL. The first interval corresponds to stable stratification and takes place at night time. The second interval is associated with daytime convection. The duration of these intervals is 8–10 h. The ABL structure and processes in ABL at different stratification differ markedly. That is why we have performed the comparative analysis of day and night situations. A total of 137 episodes (June–July of different years; altitude of 130 m; 65 episodes for day time with a total duration of about 700 h and 72 episodes in night period with a total duration of 810 h) were included in processing. The analysis has shown that in summer day the spectral amplitudes exceeded their A_q thresholds in only 45 of 65 processed episodes, which makes up about 70% of all the cases. For summer night time, such an excess was observed roughly in 76% episodes (55 of 72).

In winter, the temperature profiles determining the type of the ABL stratification at an observation site not always strictly correspond to the time of day. In addition, the period of surface insolation in December and January is 6 to 8 hours for Tomsk, and therefore the separation of winter episodes into nighttime and daytime ones is quite conditional. A total of 96 winter episodes (December–January of different years; altitude of 130 m; 43 episodes at day time with a total duration of 416 h and 53 episodes at night time with a total duration of about 600 h) were analyzed. In winter day, oscillations of the significant amplitude were observed in about 72% of episodes (31 of 43), while in winter night they were observed only in 62% (33 episodes of 53). That is, oscillations with amplitudes above the spectral confidence threshold A_q are observed most rarely in a winter night among all the situations considered.

The main task of this work was to systematize significant periods and amplitudes of oscillation of the wind velocity. In the calculated spectra, all peaks exceeding the threshold A_q were selected. The period of oscillations, whose spectral amplitude $A(p)$ exceeded all others in the considered episode, was taken as a main period of oscillations. Examples of the spectra and the corresponding time scans of the wind velocity V_m filtered in the 20–250 min band are shown in Fig. 1. In particular, Figure 1*b* depicts the spectrum, in which besides the main period of 30 min with a spectral amplitude of 0.48 m/s two other peaks exceed the threshold A_q = 0.35 m/s. At the same time, Figure 1*d* shows the spectrum, in which several peaks are pronounced, but no one of them exceeds the threshold A_q = 0.47 m/s. Such spectra were excluded from the following analysis.

The systematization was based on the histogram technology, that is, the frequency (in percent), with which periods (or spectral amplitudes) fell within some or other time interval (or amplitude range), was estimated. A step of 20 min was taken for construction of histograms of periods of oscillations. This step was selected as optimal, because it, on the one hand, smoothed possible random shifts of peak positions in the spectra and, on the other hand, provided a rather high resolution for analysis of processes of different scale. The step of histograms of spectral amplitudes was 0.1 m/s. These characteristics on the below figures are represented in the so-called polygonal form, that is, centers of the upper bases of columns of the histogram are connected by straight lines. This representation is used in practice for better illustration of the studied distributions compared to the ordinary histogram representation.

Analysis of periods of oscillation for an altitude of 130 m

Before discussing the results of systematization of periods of oscillation, we will consider the statistics of amplitude thresholds A_q, because they form the basis for selection of the periods of significant oscillations. The analysis of histograms of the thresholds has shown that in the most cases they have values of 0.2–0.7 m/s (Fig. 2) with the maximal frequency of falling within the range 0.3–0.5 m/s.

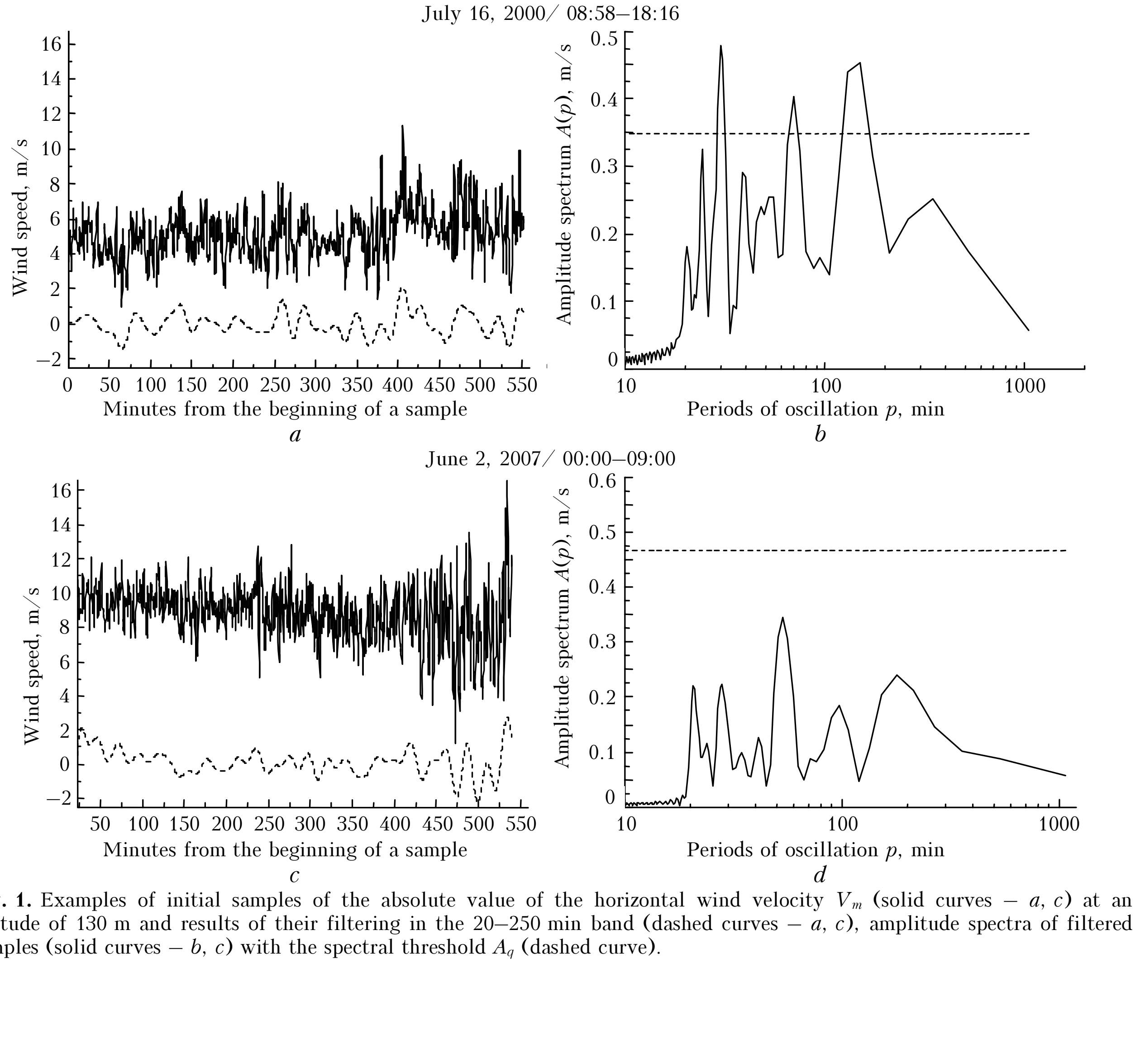

Fig. 1. Examples of initial samples of the absolute value of the horizontal wind velocity V_m (solid curves – *a*, *c*) at an altitude of 130 m and results of their filtering in the 20–250 min band (dashed curves – *a*, *c*), amplitude spectra of filtered samples (solid curves – *b*, *c*) with the spectral threshold A_q (dashed curve).

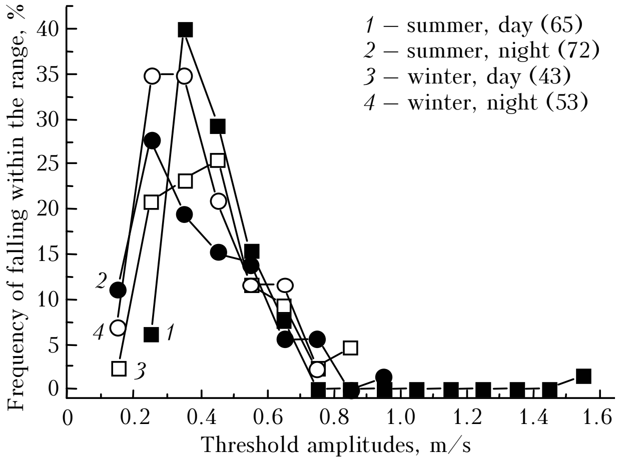

Fig. 2. Histograms of thresholds A_q at an altitude of 130 m for winter, summer, day, and night (polygonal representation). The total number of samples included in processing is given in parentheses.

There is a shift between the daytime and nighttime intervals of observation both for summer and for winter. Daytime thresholds are somewhat higher. This is likely explained by the higher level of the ambient acoustic noise in day time than in night. Remind that noise affects the quality of sodar estimates of the wind velocity and, consequently, the value of the spectral threshold A_q.

Let us consider the results of analysis of the *main periods of oscillation* of the wind velocity (denoted below as p_0). These results are shown in Fig. 3*a*.

At summer day time, the most part of p_0 is concentrated in the range 20–60 min (curve *1*). A total of 47% of cases fall within this range. Two more ranges with marked concentration of p_0 can be separated, namely, the range of 80–120 min, accounting for about 28% of cases, and the range of 140–180 min, responsible for up to 14% of all values of p_0. In contrast to day time, at summer night the main oscillations of the wind velocity occur most often with periods from 80 min and longer. About 75% of cases (curve *2*) fall within this range. In this case, as well as in day time, the periods of 80–120 min (a total of up to 36% of cases) and 140–180 min (a total of about 33% of cases) are clearly seen. The suppression of the range of 20–60 min in summer night is likely connected with the influence of the nighttime temperature inversion, namely, the atmospheric layer with the very stable stratification. This is also confirmed by analysis of the periods p_0 in winter, when the stable stratification is observed in Tomsk not only at night, but also in day time.

According to Fig. 3*a* in winter day the main periods of oscillation are concentrated in the range 40–180 min. A total of up to 90% of cases fall within this range (curve *3*). In this range both in winter and in summer, we can separate the ranges 80–120 min (a total of about 30% of cases) and 140–180 min (a total of about 25%) with certain reliability. To be noted is the narrow range 60–80 min accounting for about 20% of cases. The increased occurrence of the main oscillations of wind velocity in this range of periods is a distinctive feature of winter daytime conditions. As to the winter night, the histogram of the main periods of oscillation demonstrates the obvious prevalence of the range 80–120 min (curve *4*). It accounts for up to 50% of all episodes. In other ranges, the frequency of occurrence of p_0 does not exceed 6–9%.

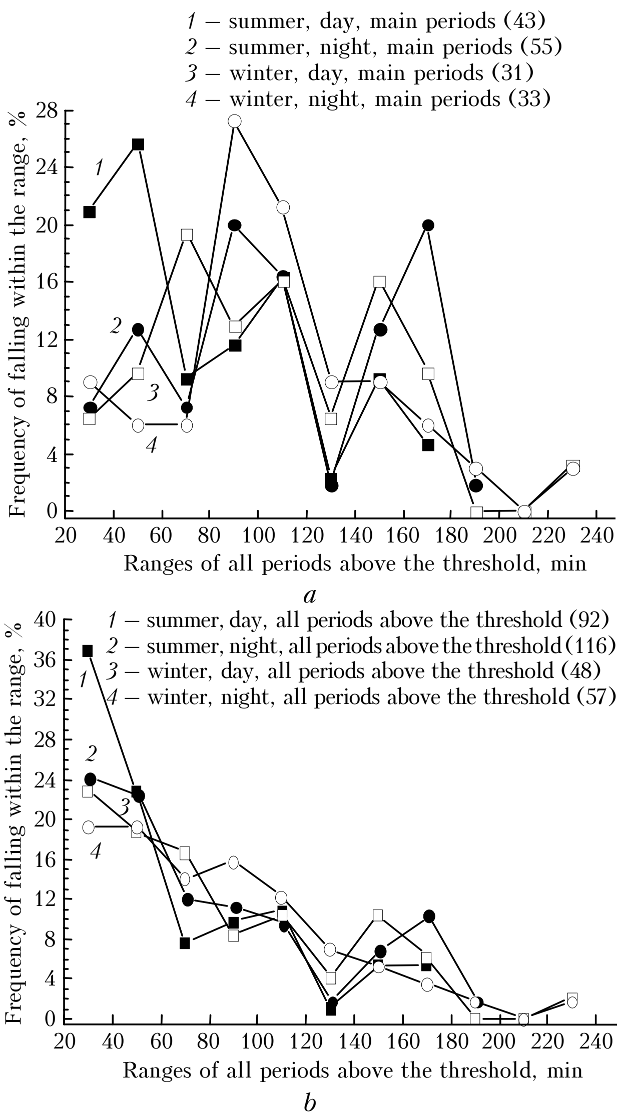

Fig. 3. Histograms of periods of oscillation: (*a*) periods of main oscillations; (*b*) all periods, whose amplitude exceeds the threshold A_q. The number of peaks included in analysis is given in parentheses.

Summarizing the results of the analysis, we can conclude that the ranges 20–40, 80–120, and 140–180 min accounting for the most part of periods of wind velocity oscillations are clearly seen. The range 20–40 min is obviously connected with the type of ABL stratification, because it is pronounced only in summer day, when strong instability takes place in the lower part of ABL.

It should be noted that the low frequencies of falling of the periods p_0 within the range 20–40 min under the conditions of stable stratification do not mean that there are few oscillations with such periods. This fact indicates only that oscillations of wind velocity with the *highest* mean amplitudes occur in the "slower" spectral ranges. In general, the range 20–40 min remains filled with other oscillations, whose spectral amplitude is higher than the threshold, but lower than the main maximum. This is demonstrated in Fig. 3*b*, which shows histograms of all periods exceeding the threshold A_q (including the main periods p_0). Consideration of all oscillations with amplitudes above the threshold not only saturates the range 40–60 min, but also masks markedly the range 80–120 min. It becomes less pronounced. At the same time, the range 140–180 min continues to be clearly seen (except for winter night).

Analysis of oscillation amplitudes for an altitude of 130 m

In summer day, the peaks of spectral amplitudes of main periods of oscillation $A(p_0)$ are concentrated in the range 0.3–0.7 m/s. It accounts for nearly 75% of cases. In general, $A(p_0)$ do not exceed 1.6 m/s. In summer night, the range of $A(p_0)$ is somewhat wider: 0.2–1.0 m/s. It accounts for up to 90% of all cases. The maximal values of $A(p_0)$ achieve 2.1 m/s in night, markedly exceeding the daytime maxima, although being few in number. This statistics is illustrated by histograms shown in Fig. 4*a*.

This figure also shows the results for the winter conditions. In winter day, the amplitudes of the main periods $A(p_0)$ are concentrated in the range 0.2–0.7 m/s. It accounts for up to 70% of cases. The maximal values of $A(p_0)$ achieve 2.4 m/s. Some features of the histogram shown by curve *3* in Fig. 4*a* should be noted. There are two pronounced ranges of amplitudes: 0.2–0.4 and 0.5–0.7 m/s. Amplitudes most often fall just within these ranges (32 and 30%, respectively). In addition, amplitudes are concentrated in the range 0.9–1.1 m/s, although it accounts for only up to 13% of cases. The histogram for winter night (curve *4* in Fig. 4*a*) demonstrates the similar behavior: histogram fragmentation in the ranges mentioned above is observed as well. It can be noted that in winter night the oscillations, whose amplitude exceeds 0.8 m/s, have a somewhat higher "specific weight" than in winter day. However, the maximal values of $A(p_0)$ at both night and day do not exceed 2.4 m/s.

Summarizing the results of the analysis, we can conclude that the most oscillations of the absolute value of the horizontal wind velocity at the main periods occur with the spectral amplitudes of 0.2–0.7 m/s in any season and at any time. However, there are some differences. In particular, wind velocity oscillations with significant amplitude are observed more often in winter. In addition, the winter histograms of oscillation amplitudes have a rather "fine" structure manifesting itself in formation of ranges, oscillations are grouped in.

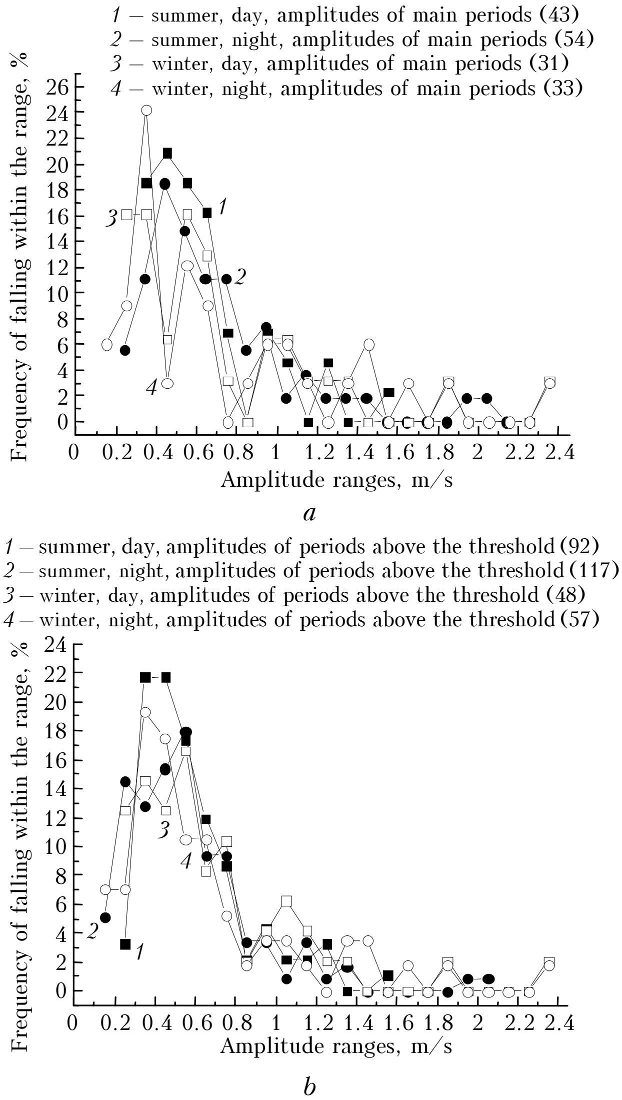

Fig. 4. Histograms of oscillation amplitudes: (*a*) amplitudes of main oscillations; (*b*) all amplitudes exceeding the threshold A_q. The number of peaks included in the analysis is given in parentheses.

The inclusion of all amplitudes exceeding the spectral threshold A_q in the analysis significantly fills the amplitude range 0.2–0.7 m/s and extends it to the level of 0.8 m/s (Fig. 4*b*). Thus, about 85% of cases fall within this level in summer (in both day and night). In winter day, about 65% of amplitudes do not exceed this level, and in winter night this number is 77%. Consideration of additional oscillations of the wind velocity leads to the smoothing of the fine structure of histograms mentioned above, and the ranges 0.2–0.4 and 0.5–0.7 m/s become not so pronounced.

Narrow-band filtering of oscillations at an altitude of 130 m

Using the narrow-band numerical filtering separating the range including the interesting period of oscillations from the whole spectrum, we have studied the temporal concordance of occurrence of different harmonic in spectra. It has been found that different periods of oscillation could both occur simultaneously and alternate each other during the period of observation. We failed to find some regularity in the order of their occurrence and alternation.

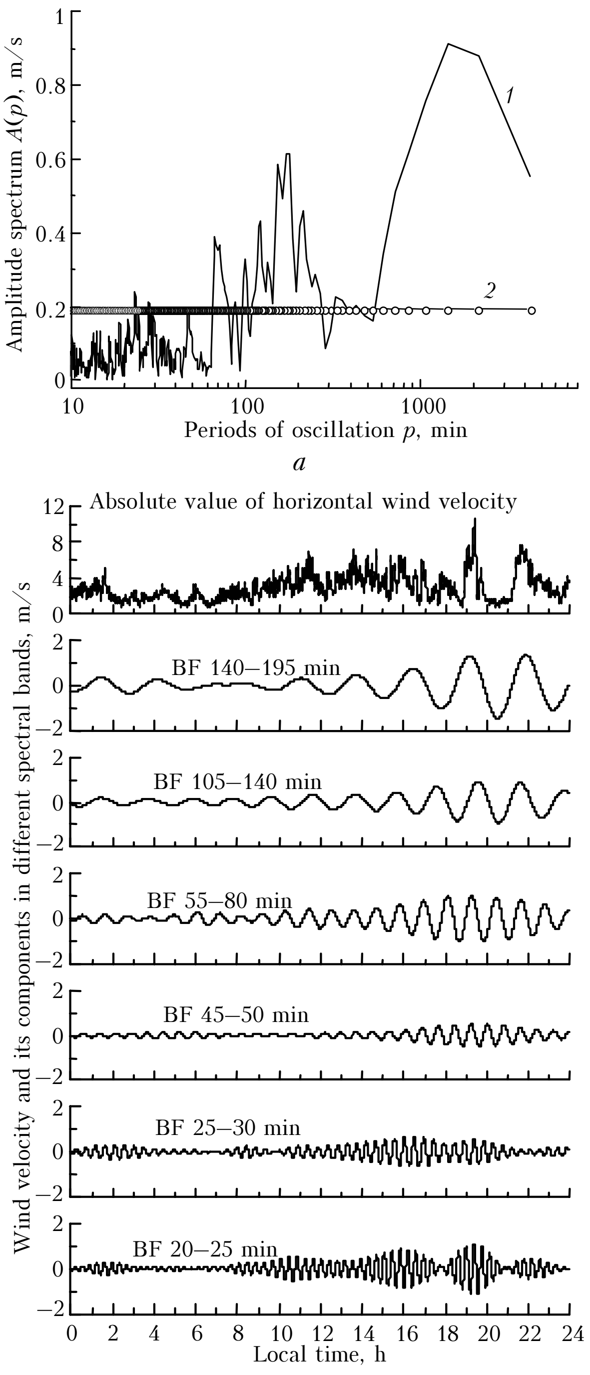

Fig. 5. Amplitude spectrum of the absolute value (*1*) of the horizontal wind velocity at an altitude of 130 m obtained on June 14, 2007 (00:00–24:00) (*a*) and results of numerical bandpass filtering of velocity in several spectral ranges (*b*); (*2*) spectral threshold A_q (0.19 m/s).

This is true for both winter and summer periods. The results of bandpass filtering (BF) of oscillations in different spectral bands obtained from 24-hour period of observation on June 14, 2007, at an altitude of 130 m are exemplified in Fig. 5.

In this case, there are many oscillations exceeding the threshold A_q. The highest oscillation amplitudes take place in the later half of a day. In other episodes or at other altitudes, time intervals with high oscillations of the absolute value of wind velocity may be different. It should be also noted that in the case of long (several days) stationary meteorological conditions a diurnal peak is pronounced in the spectra of the absolute value of horizontal wind velocity.

Comparison of spectra of oscillations at different altitudes

In addition to analysis of wind velocity characteristics at an altitude of 130 m, we have compared the spectra obtained at different altitudes. The results obtained suggest that the spectra of oscillations can change with altitude, but the positions of the main peaks and most of significant peaks usually coincide. It is interesting to estimate synchronism in wind velocity oscillations at different altitudes. The narrow-band filtering of the initial samples was applied for analysis. Figures 6*a, c* show the spectra of wind velocity of nearly the same type in different days for altitudes of 100, 130, and 160 m, but having different concordance of wind velocity oscillations at different altitudes. Thus, Figure 6*b* shows deviations of the wind velocity from the average value in the 55–85 min band. One can clearly see high synchronism of velocity variations in this band at all altitudes and nearly in the whole range of observations. A different situation is illustrated in Fig. 6*d*, which shows the results of wind filtering in the 85–140 min band for other episode. In this case, a phase shift takes place between oscillations at different altitudes. Similar situations were also observed in other cases, when the same oscillation mode at different altitudes differed significantly in the amplitude and had a phase shift achieving 180°. Such situations take place both in winter and in summer, at day and night time.

Conclusions

From the results of spectral analysis of the absolute value of horizontal wind velocity within the atmospheric boundary layer, we can draw the following conclusions:

– variations of the wind velocity in ABL may have significant (in amplitude) periodic components of mesometeorological scale; this is observed both in winter and in summer at any time at stable and unstable stratification;

– in the spectra of oscillations of the wind velocity at main harmonics of mesometeorological scale, the ranges 20–40, 80–120, and 140–180 min,

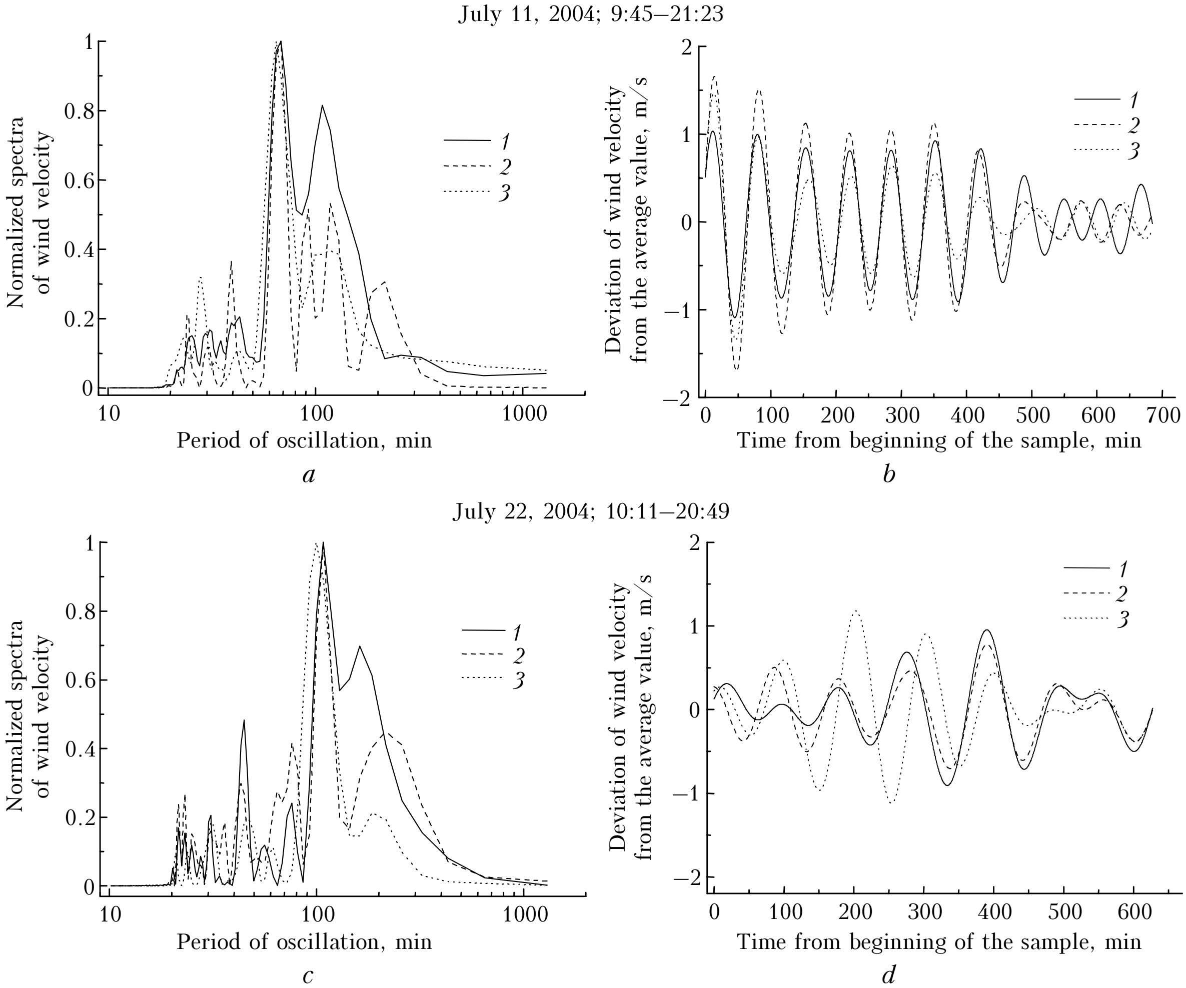

Fig. 6. Normalized spectra of the absolute value of the horizontal wind velocity in the summer period (*a*, *c*) obtained using the numerical filtering in the 20–250 min band and results of the narrow-band filtering of the initial samples of wind velocity (*b*, *d*). Spectra of wind velocity (*a*) and results of filtering (*b*) in the 55–85 min band at altitudes of 100 (*1*), 130 (*2*), and 160 m (*3*); spectra of wind velocity (*c*) and results of filtering (*d*) in the 85–140 min band at the same altitudes.

within which the main oscillations of the wind velocity fall most often, are clearly seen; the range 20–40 min is obviously connected with the type of ABL stratification, because it is "saturated" only in summer day, when strong instability is observed in the lower part of ABL;

– oscillations of the wind velocity at the main periods occur most often with the spectral amplitudes of 0.2–0.7 m/s in all seasons and at any time; oscillations with the significant amplitude are observed most often in winter;

– if several harmonics of mesometeorological scale with comparable amplitudes are present in spectra, the corresponding variations of the wind velocity may occur both simultaneously and in different time intervals;

– oscillations spectra may vary with altitude, but the positions of the main peaks and most of significant peaks usually coincide; oscillations at different altitudes may occur both synchronously and with a significant phase shift.

These conclusions characterize only measurements conducted in the Tomsk suburbs. For other observation sites, features characterizing the spectra of wind velocity of mesometeorological scale may be different.

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