# Analysis of wind field structure in the lower atmosphere on the Lake Baikal shore

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The paper discusses the results of remote acoustic sensing aimed at retrieving the wind velocity profiles in the lower troposphere performed on the southwestern shore of Lake Baikal. Measurements were conducted since June 26 until July 16 of 2001. Peculiarities of the flow structure in various situations are considered. Wind direction histograms (wind roses) at different heights, including the surface layer, are presented. Characteristic directions of mean flows are revealed for the whole period of measurements and for the daytime and nighttime periods separately.

In recent decade, the Institute of Atmospheric Optics has organized several research missions into the Lake Baikal region. One of the goals of these missions was to study peculiarities of air mass motion in the lake hollow. Closed air circulation along the lake perimeter was revealed in 1991 from the results of airborne sensing of the lower troposphere.[1] Later on[2,3] detailed airborne and balloon-borne observations were conducted and the experimental findings gave rise to the hypothesis about the structure of the circulating flow as an elongated tore moving along the lake shore and turning clockwise around its axis if viewed downstream.[3] Its characteristic vertical size is 700–1000 m, and the height of the lower boundary is 200–400 m.

The research mission organized in summer 2001 was aimed at refining specific features of air circulation over Lake Baikal. Local and remote diagnostics of the atmospheric boundary layer was conducted with the measurement facilities of the Institute of Atmospheric Optics (IAO). For detailed investigation of the structure of the lower troposphere, the mission was equipped with the Volna-3 sodar[4] along with the Meteo-2 ultrasonic weather station made at the IAO.[5] The sodar was operated from June 26 until July 16 of 2001. The total operation time was about 400 hours. The studied parameter was the structure of temperature turbulence in the height range from 40 to 730 m above the ground level. In the presence of this type of turbulence, we measured wind velocity profiles with the intervals of 13–15 m in height and about 15–17 s in time. The ultrasonic weather station installed 10 m far from the shoreline at the height of 4 m provided measurements of the wind velocity and direction, air temperature, humidity, and pressure with the periodicity of about 10 times a second. It should be noted that the data presented here on the time-height distribution of the wind vector over the Lake Baikal shore are likely unique. We do not know other that detailed measurements.

The measurement site was located on the southwest shore of the Lake Baikal with the coordinates 51°54′N and 105°03′E. The shoreline was directed roughly from the northeast to the southwest (55–235°). The orography of the region was characterized by the presence of mountainsides bounding the shore almost from the shoreline. The sodar was installed at a mouth of a small ravine, the length of whose gentle part was less than 1 km. The height of slopes bounding the observation site did not exceed 200–250 m. The height of mountains at the distance of several kilometers from the shore was 800–900 m. A larger ravine affecting significantly air flows in this area was located about 1.5 km to the northeast from the observation site. The length of its gentle part into the heart of the mountainous territory was no less than 10 km, and its width in the mouth was up to 800 m.

The synoptic situation varied significantly for the period of observations. Atmospheric pressure changed widely. The air temperature also varied rather widely during a day under fine weather conditions. The relative air humidity could change by tens percent for a short time. The temperature of the surface water near the shore was relatively stable and varied within (8.5 ± 2.5)°C. To illustrate the variability of the weather conditions at the observation site, Fig. 1 depicts the plots of the near-surface pressure $P$, air temperature $T$, and relative humidity $u$ for the period from June 26 to July 3 of 2001.

The landscape effect leads to the formation of a rather complicated space-time pattern of flows of different thermodynamic atmospheric parameters. The permanently operated ultrasonic weather station provided for the possibility of observing their fine structure directly in the surface layer. In particular, 20 to 40 min long airflows with the temperature difference of 6–8°C from the ambient air temperature moving from the ravine were observed rather often. Sometimes they resembled foehn. As known, foehn arises as air masses cross a mountain ridge. For it to arise, the air

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humidity should be such that water vapor condensates with heat release as the air mass rises up to a ridge top. Then the air mass crossing the ridge has higher temperature and the decreased relative humidity. Figures 1*d* and *e* illustrate an episode that took place at night of July 1–2. One can see three relatively short flows of heated air moving downward along the ravine (see Fig. 1*d*). The first of them was accompanied by a decrease in the humidity (see Fig. 1*e*), i.e., presumably by the foehn effect.

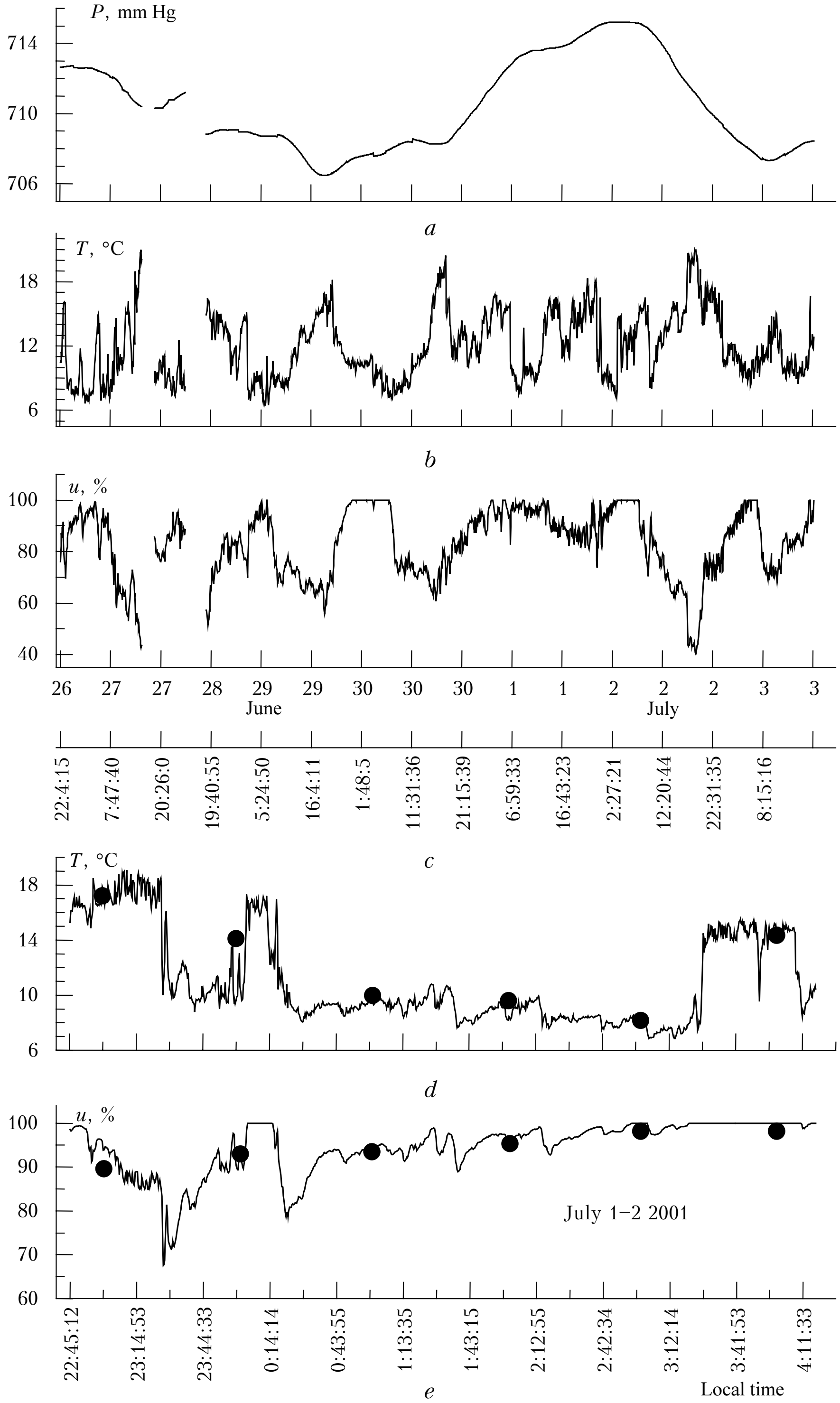


**Fig. 1.** Time dependence of weather parameters measured by the Meteo-2 weather station: the scan from 22:04 06/26/2001 to 18:22 07/03/2001 with 5-min averaging of atmospheric pressure (*a*), temperature (*b*), and relative humidity (*c*) of air; the scan from 22:45 07/01/2001 to 4:17 07/02/2001 with 30-s averaging of temperature (*d*) and relative humidity (*e*) of air. Circles are for the data obtained with standard meteorological equipment.

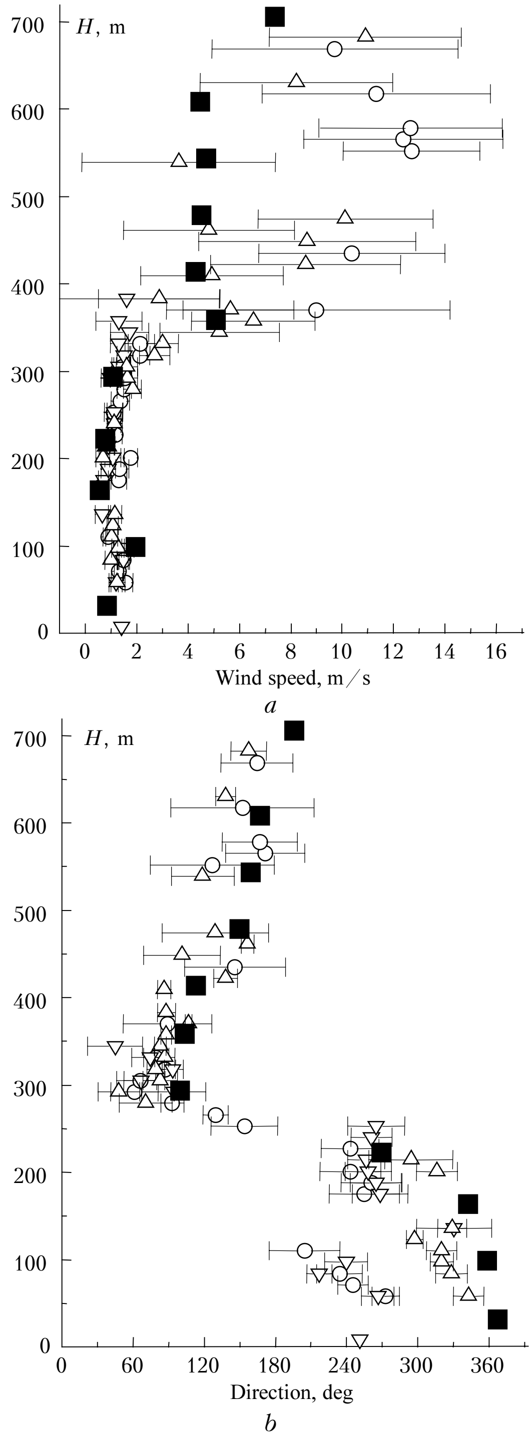


**Fig. 2.** Altitude profiles of wind speed (*a*) and direction (*b*) obtained on July 3, 2001; balloon (launched at 03:27 L.T.) measurements (closed squares) and sodar measurements (open signs: ○ – 03:24, ∇ – 03:34, Δ – 03:43). The lowest points in sodar profiles for 03:34 are 5-min averaged Meteo-2 data.

In the process of standard weather observations, our colleagues from the Laboratory of Optical Weather of the IAO have launched more than 30 balloons for measurement of the structure of wind flows up to the height $H = 3$–4 km. Figure 2 compares one balloon and three sodar profiles of wind speed and direction. The corresponding balloon was launched at night of July 3 2001 at 03:27 L.T. The launching point was on the shore 1.5 km to the northeast from the sodar. The bottom point of the balloon wind direction profile (Fig. 2*b*) corresponds to 367° in spite of 7° to keep the smoothness of the altitude behavior of this parameter. The wind profiles centered at 03:34 include also the Meteo-2 data (the lowest point of the corresponding profile). The sodar data were averaged over 10-min intervals, whose centers are shown in Fig. 2. They are supplemented with the 90% confidence intervals. It can be seen that, in spite of some discrepancies, the balloon and sodar profiles agree quite well.

The results measured are now being thoroughly analyzed in the Laboratory of Optical Weather to refine peculiarities of mesoscale circulation along the Lake Baikal shoreline. In this paper, we present only some results on the revealed peculiarities of the wind field structure obtained using acoustic sensing.

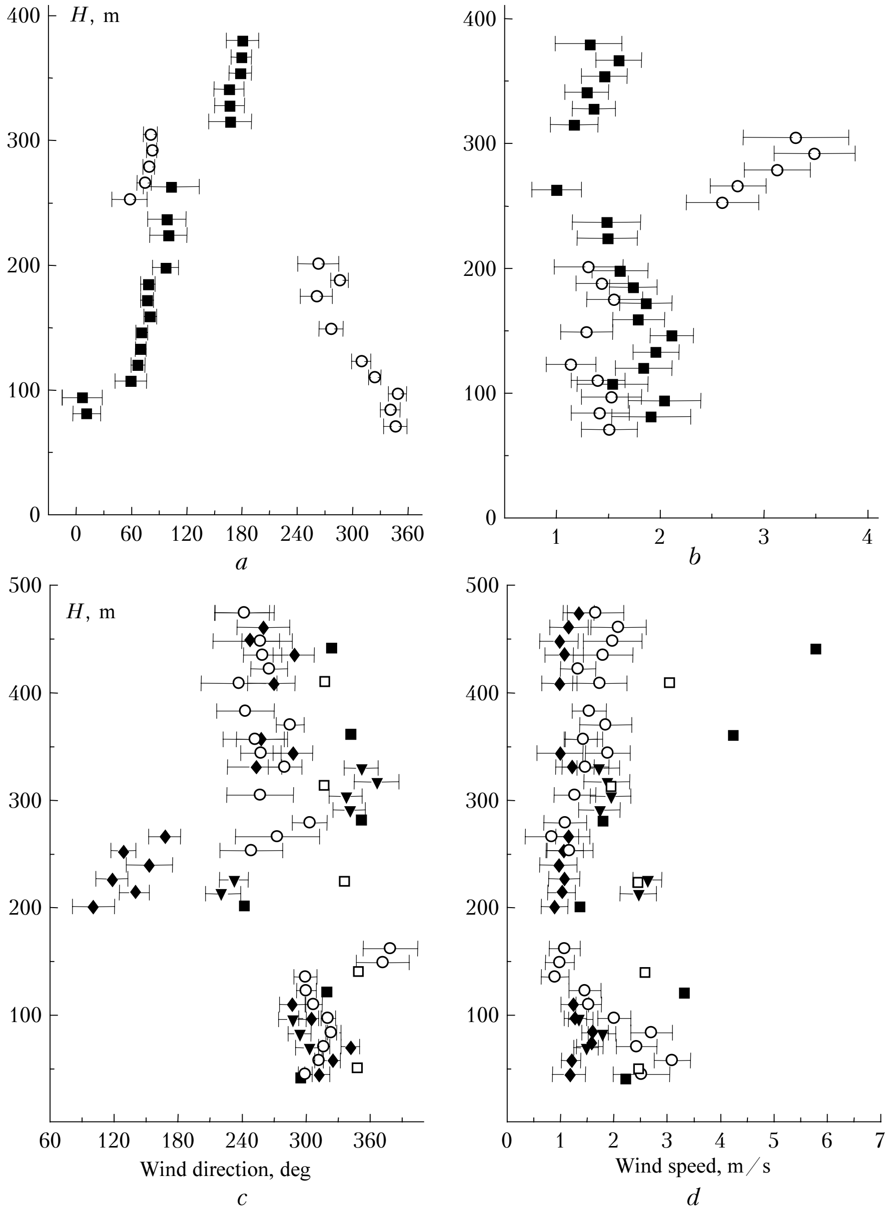
The turbulent structure of the temperature field measured with the sodar varied widely in space and time. We failed to reveal a clear diurnal dynamics in the development of turbulent zones. We often observed a layered structure, which occurred in both day- and night-time. The highest turbulence intensity was observed up to the heights of 300–350 m. The majority of sensing data were obtained just in this height range. Signals were received from the heights higher than 350–400 m as well, but their intensity was usually low. The sodar was installed near the mission camp, and the noise level was rather high in daytime, thus decreasing the height potential of restoration of wind velocity profiles.

The complicated structure of the turbulence field recorded by the sodar reflects the complexity of the processes occurring in the boundary layer during a day. Combination of the effects of mountain-valley and breeze circulations leads to mixing of air masses with different thermodynamic properties and to establishment of rather specific turbulent fields and mean flows. For example, according to observations in Tomsk, stepwise in height, but stable in time changes in the wind direction occur only in the case of front occlusion. However, under conditions of Lake Baikal we observed stepwise changes in the wind direction many times.

Let us present several examples with complex and rather stable wind profiles. The main shift in the wind direction in the first episode shown in Fig. 2 occurs at the height of 260–280 m. The flow direction changes smoothly with the distance from the boundary. It is worth noting also that direction drifts in time in the bottom part of the profile. We can assume that this is a manifestation of the Stokes processes in the ravine, in whose mouth the sodar was installed. This situation is rather typical for the stepwise change in the flow direction. In particular, Figs. 3*a* and *b* demonstrate two episodes, one of which (July 3) is a continuation of the situation depicted in Fig. 2, which indicates the stability of the flow structure in time. The second episode (June 30) demonstrates the three-layer structure of the flow with small jumps in direction at the heights about 100 and 260 m. It is characteristic that the lower and the upper layers in this episode have almost opposite flow directions resembling breeze circulation, while the medium layer moves almost normally to them along the shoreline. In the main characteristics, this flow structure resembles the small-scale circulation described in Ref. 3, but has much smaller vertical dimensions and occurs in nighttime.

In the episodes of July 3 shown in Figs. 2 and 3*a* and *b*, we can also see the ordered motion along the shoreline with the simultaneous indications of breeze circulation. The distinguishing feature here is the almost opposite direction of the flow at the heights of 200 (in the angle sector of 260–270°) and 300 m (in the angle sector of 80–90°). Now it is difficult to give a comprehensive explanation of this flow structure. We can only assume that a marked role here belongs to the heat and mass exchange processes between the near-surface air layer and the extended valley of B. Koty River.

One more example of a complex structure of the wind flow with rather stable characteristics is a "submerged jet," when some atmospheric layer moving in one direction contains a flow with the other direction.



*a* *b*

*c* *d*

**Fig. 3.** Height profiles of the wind speed and direction obtained from balloon-borne and acoustic sensing data. Figs. *a* and *b*: sodar measurements (○ – 07/03/2001 at 6:55, ■ – 06/30/2001 at 01:33); Figs. *c* and *d*: balloon measurements (■ – 07/01/2001 launched at 00:00, □ – 07/11/2001 launched at 06:00) and sodar measurements (▼ – 07/01/2001 at 00:00, ◆ – 07/11/2001 at 5:40, ○ – 07/11/2001 at 06:00). All sodar profiles are obtained with 10-min averaging. Horizontal bars correspond to 90% confidence intervals.

Two episodes with such situations are shown in Figs. 3*c* and *d*, and in both cases the sodar data are given in comparison with the balloon data. On July 1 balloon observations were conducted just at the time, when a submerged jet occurred. For the episode of July 11 (Figs. 3*c* and *d*) there are two 10-min averaged sodar profiles of the wind speed and direction, one of which (05:40) shows the jet at the height of 200–270 m with the direction shift by 160–180°. The second profile (06:00) demonstrates the close agreement with the simultaneous balloon data, but has no marked jet. Analysis of these and other measurement results shows that the lifetime of submerged jets is much shorter than that of the layers with the direction shifts considered above. The short lifetime likely reflects the local character of sources generating this structure of the wind flow.

The short period of observations does not allow thorough investigation of the regularities inherent in the processes of formation and destruction of the complicated structure of the wind flow above the observation site. Nevertheless, we tried to systematize the material obtained and separate out the most characteristic flow directions in the lower part of the atmospheric boundary layer. For this purpose, we used the observations, including the Meteo-2 data, to construct wind direction histograms (wind roses) for different heights.

Figure 4 shows the histograms for the heights from 4 to 400 m. To draw the wind roses, we first averaged the sodar data over 10-min intervals and then entered in the histograms. The frequencies, with which the flow direction fell in some or other angle sector, are plotted as an ordinate. The histogram step on the abscissa is 10° for the sodar and 5° for Meteo-2. The Meteo-2 results were used without averaging, therefore large frequencies are present on the ordinate. To ensure the reliability of restoration of the wind direction, only the cases with the high signal-to-noise ratio were included in the processing. Therefore, at high altitudes, the number of experimental results falling in the histograms was much smaller.

From the data shown in Fig. 4, we can draw the following conclusions about the wind conditions during the whole period of observations:

– *characteristic wind directions, that is, the directions that occurred most often in the sensing process, were revealed;*

– *characteristic wind directions vary with altitude;*

– *the higher the altitude, the less pronounced are the characteristic directions (the latter conclusion may be a consequence of deficient experimental data).*

The further analysis of the wind rose was performed with separation of measurements by the day/night principle. Wind measurements from 06:00 to 20:00 L.T. were classified as daytime ones and others – as nighttime. This gradation is rather conditional, but it allowed us to draw some conclusions on the diurnal behavior of the characteristic wind directions at different altitudes.

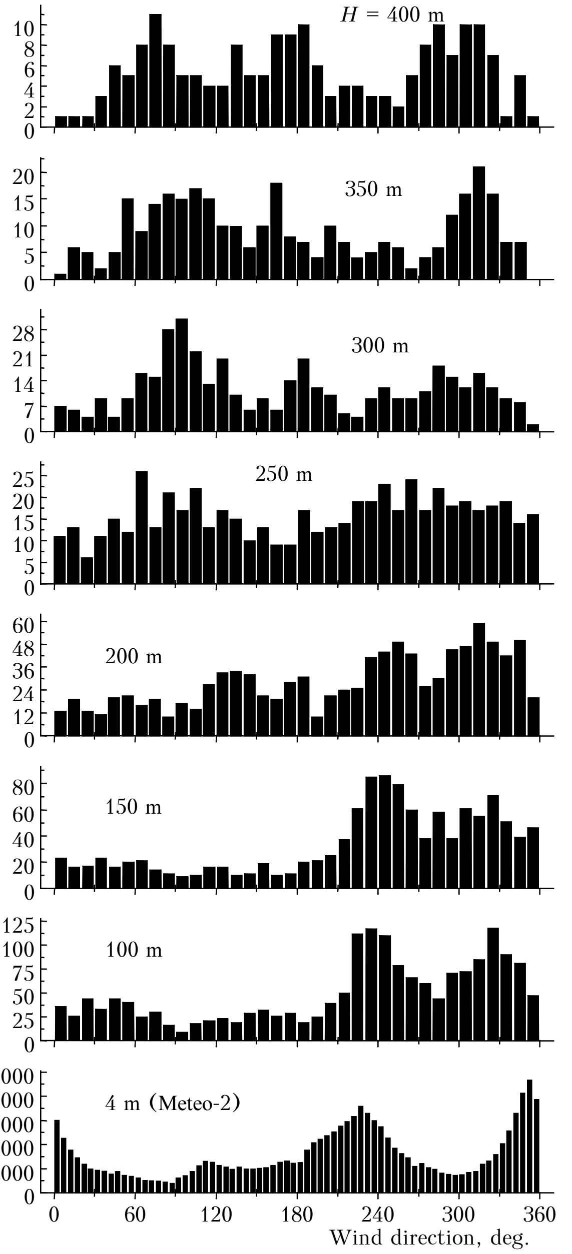


**Fig. 4.** Wind direction histograms drawn based on sodar measurements with 10-min averaging and the step of 10° for the observation period from 06/26/2001 to 07/16/2001 and on measurements at the Meteo-2 ultrasonic weather station from 06/26/2001 to 07/03/2001 with the measurement frequency of 10 Hz and the direction step of 5°.

Figure 5*a* shows the wind direction histograms for the *daytime conditions*. These are as follows:

at low altitudes, the main direction falls in the sector of 220–250° (sectors mentioned in this paper are only tentative); as the altitude increases, the flow unidirectionality breaks;

at the height of 300 m the flow direction in the angle sector of 80–100° predominates;

in the atmospheric layer below 100 m the flows from the lake (angle sector of 100–180°) are observed;

in daytime the simultaneous presence of flows from the directions of 220–250 and 80–100° at different heights is unlikely.

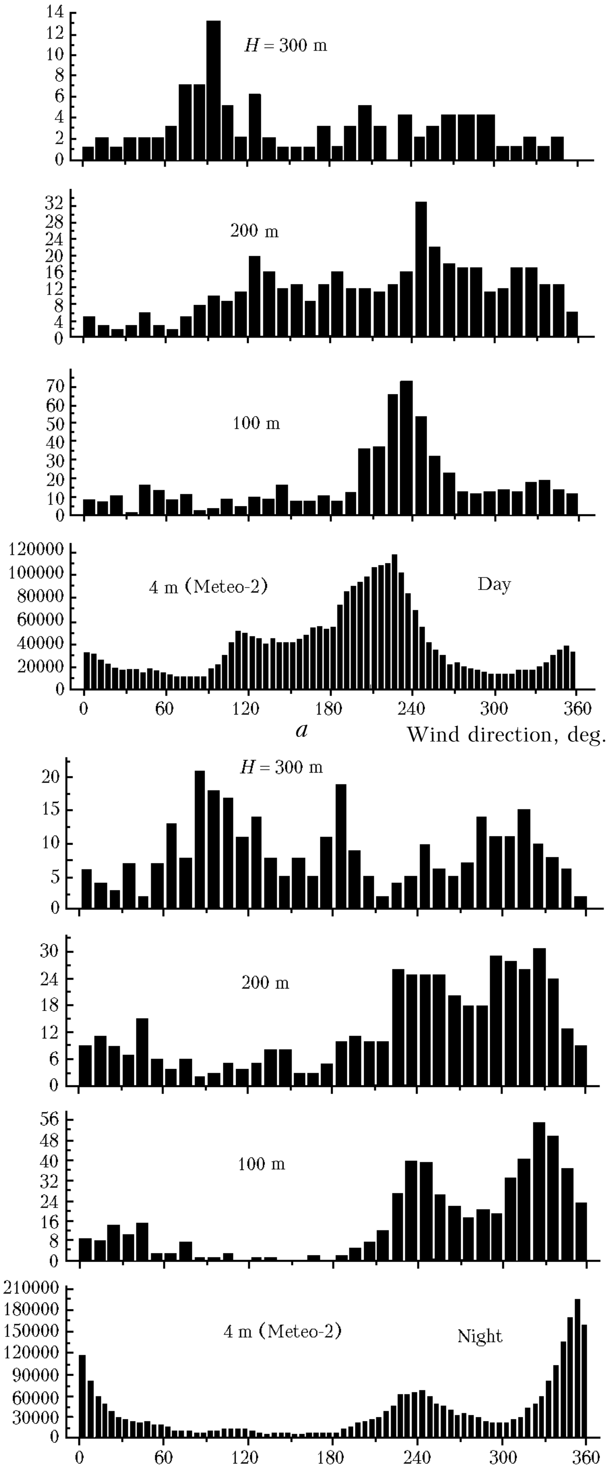


**Fig. 5.** Wind direction histograms at different heights as calculated for the daytime (*a*) and nighttime (*b*) conditions. Processing models are the same as in Fig. 4.

Classical daytime breeze circulation is absent in this case. Maybe, the sodar failed to reach the height, where air masses move from the land to the lake (angle sector of 330–360°).

Figure 5*b* shows the wind direction histograms for the *nighttime conditions*. They have the following characteristic features:

the Meteo-2 station clearly observes gravity flows along the ravine toward the lake (angle sector of 340–360–20°);

the wind from the lake is almost absent in the lower atmosphere in nighttime;

two sectors of flow directions (220–270 and 300–350°) dominate at low heights;

as the height increases, the wind rose becomes more uniform;

three characteristic directions (80–120, 180–200, and 280–340°) are clearly seen at the height of 300 m;

only the flows from the sectors of 80–120 and 220–250 or 80–120 and 300–350° could exist simultaneously at different heights; other combinations of characteristic directions were observed far more rarely and had short lifetimes.

Comparison of the daytime and nighttime wind direction histograms demonstrates that there are significant differences in the flow structure, especially, at the heights up to 200–250 m. This is probably connected with the local orography, since it is just the height of surrounding mountain. Recall that the shoreline at the observation point corresponded roughly to the direction of 55 to 235°.

The above results of acoustic sensing of the wind speed and direction in the lower part of the atmospheric boundary layer can be used not only for refining the structure of mesoscale circulation along the Lake Baikal shoreline, but also it can be used as a basis for the development of models of air mass motion in the “lake – ravine” system.

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