Lidar investigations of the vertical structure of aerosol fields in the atmosphere in the Lake Baikal basin

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In this paper we present the results of investigations into the structure of vertical profiles of the scattering coefficient in the atmospheric boundary layer over Lake Baikal. In our analysis we used the data obtained with a lidar during the field campaign on round the clock observations of the atmosphere over Lake Baikal in summer of 1998. It was found that aerosol fields over Lake Baikal have a rather complicated structure that is caused by peculiar features of the air mass circulation in a mountain valley. The estimates of the vertical size of circulation cells gave their lower boundary to be at about 300 m height while the upper one being at 1000 to 1300 m above the surface.

Lake Baikal is one of the unique natural objects and, as mentioned in many international scientific programs, it is a natural laboratory for studying the environmental and climate changes.[1] Therefore, it is understandable that much attention is now being paid to the study of possible mechanisms of its pollution. Among those there are pollution through the atmosphere–lake system, due to transfer of air and sedimentation of admixtures produced by industrial enterprises situated both in the immediate proximity of the lake and significantly far from it.

Until recently investigations of aerosol and gas admixtures have been carried out mainly in the near-ground layer using the *in situ* monitoring tools deployed either at several sites along the coast[2] or onboard research vessels in order to study composition of the air in the near-water layer over the lake.[3,4]

The region of Lake Baikal is characterized by the significant orographic and thermal inhomogeneities that lead to specific interaction between local winds and the main air mass stream over this terrain. The phenomenon of air circulation over Lake Baikal depression contour was first revealed from airborne observations. It is a toroidal vortex formed due to the joint action of two factors, namely, the thermal instability and the channel effect.[5]

The further airborne observations of the emissions from Baikal Pulp and Paper Mill demonstrated quite a complicated spatial distribution of the aerosol content over the atmosphere above Lake Baikal. The presence of such a circulation favors vertical stratification of the admixtures and transfer of them along the coastal line at many tens of kilometers.[6]

The teams from the Institute of Atmospheric Optics, Tomsk, have carried out regular lidar observations over the vertical structure of aerosol fields in the lower troposphere usually in spring and summer. Measurements are conducted in the round-the-clock mode every 1 or 2 hours what allows one to follow the dynamics of vertical profiles of the scattering coefficient during a day. High spatial resolution (7.5 to 15 m) of lidar measurements makes a basis for studying more fine details in the vertical structure of aerosol fields as compared to airborne nephelometric observations, especially at low heights at nighttime.[7]

As known, the mechanism of transformation of the vertical profile of scattering coefficient of one and the same air mass is caused by the diurnal variation of the thermal regime of the near-ground layer of the atmosphere. This results in that the scattering coefficient values in the near-ground layer first increase after the sunrise, and the layers above and up to the height of the boundary layer are intensely filled up with aerosol. Then, as it follows from the concept of the internal (IML) and principal (PML) mixing layers,[8] the aerosol first fills the internal layer and only then penetrates the upper boundary $H_{\rm PML}$.

Beginning from noontime the temperature gradually decreases that leads to the suppression of the turbulent exchange and, hence, to a decrease in the scattering coefficient of the upper layers and to the accumulation of aerosol in the lower layers.

It was shown in Ref. 9 based on the statistical analysis of the mean values of the scattering coefficients $\sigma(H)$ and autocorrelation matrices calculated for different synoptic conditions and seasons that the height $H_{\rm IML}$ reaches 500–600 m, and the $H_{\rm PML}$ – 1200 to 1400 m.

In this connection, it is interesting to follow up the peculiarities in vertical structure of the aerosol fields over other regions, namely, in the depression contour of Baikal Lake because of the specific air mass circulation there.

For this purpose, we have selected the background region near Boyarsk settlement characterized by the absence of big industrial enterprises nearby. The biggest industrial enterprise, the Baikal Pulp and Paper Mill is approximately 150 km far from the observation site. In recent years (1998–1999), the Institute undertakes complex field missions in this region, with the use of different instrumentation, including a “LOZA–M” compact scanning aerosol lidar (λ = 0.53 μm). It should be noted that according to data obtained using ground-

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based and airborne aerosol complexes[6,10] the atmosphere over Lake Baikal is characterized by very low values of the aerosol scattering coefficient. Nevertheless, the aerosol sampling stations situated even near small villages can characterize the regional aerosol background only in summer because in winter there is observed a strong influence of the local heating sources on the aerosol overburden of the atmosphere.[2] The presence of an aerosol layer can immediately be recorded against this background by the spikes on the otherwise smooth lidar returns.

We observed such a pattern already in the first field mission in 1998. The measurements were carried out hourly round-the-clock. The lidar sounded the atmosphere both along horizontal and vertical directions with the spatial resolution of 7.5 m, i.e., 24 vertical profiles of the aerosol scattering coefficient were recorded during a day. Figure 1 illustrates this situation by the fragment of a vertical section of the aerosol field recorded during one measurement cycle. Shown in the figure are the square range corrected lidar returns. The brightness scale of the intensity of thus corrected returns is shown in the upper part of the figure. The data presented in this figure were acquired at 10 and 11 a.m. LT. As follows from earlier measurements,[9] the formation of vertical aerosol fields undergoes the most intense dynamics during this time interval. As seen from the upper part of Fig. 1 (taken at 10 a.m.) two well-pronounced layers, at the heights of ~ 500 and 1250 m are observed in the vertical stratification, that well agrees with the boundaries of the internal and the principal mixing layers.

The measurement cycle that followed this one showed an intense filling of the atmosphere with aerosol through the entire height range of measurements. The filling occurred both from the lower boundary upwards and from the upper boundary downwards. The latter fact is a good confirmation of the inverse distribution of an admixture along the vertical direction observed earlier at airborne sounding and caused by the specific features of air streams over the Lake Baikal depression contour.[11]

Let us consider in more detail the diurnal behavior of vertical profiles of the aerosol scattering coefficient $\sigma(H)$ (the profile of the molecular scattering coefficient was assumed to be known from model estimates[12]).

We have selected only clear sunny days from the whole array of data acquired in the second half of June 1998, i.e., without precipitation that normally violate the regularities of the diurnal behavior.

The diurnal behavior of the vertical distribution of the aerosol scattering coefficient observed on July 29–30 is shown in Fig. 2. Although the soundings have been done hourly up to 2.2–2.4 km, we present the data only up to 1.6 km and in a 2-hour period that, however, does not lead to any loss of generality. The numbers in the upper part of the figure show the local time of measurements, and the mean values of the scattering coefficient σ_0 shown in the lower part of the figure are the values measured with the lidar on a 1.5-km-long horizontal path. The lower boundary of the profiles is taken to be at 285 m, in order to exclude the effect of the blind zone of the lidar and its geometric function, which could introduce significant errors to $\sigma(H)$ at low values of it.

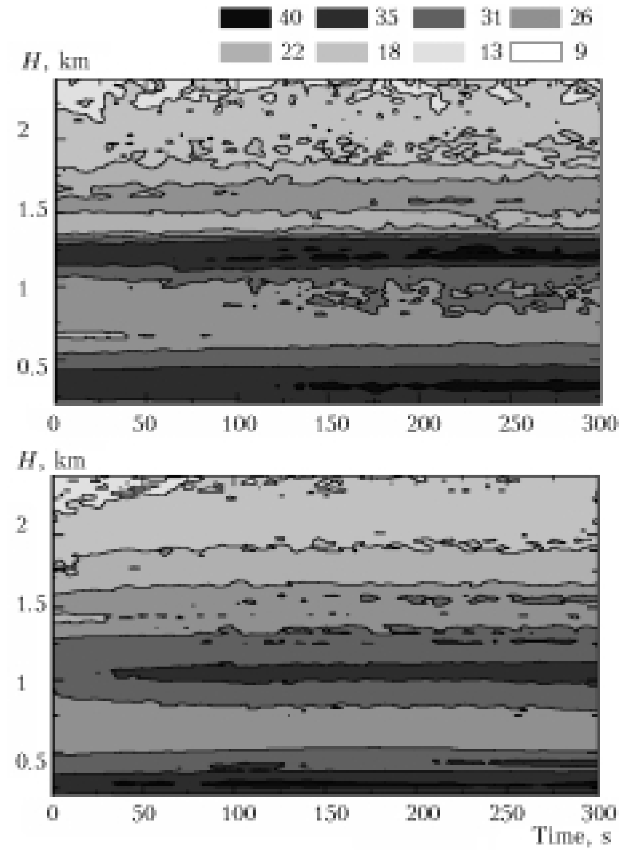

Fig. 1. Spatiotemporal structure of aerosol fields retrieved from the lidar returns. The measurements were conducted on July 29, 1998 the upper part at 10 a.m., the lower at 11 a.m.

The time at 6 a.m., i.e., just after the sunrise was chosen as the initial point. The first cycle of sounding showed quite a complicated distribution of $\sigma(H)$. According to gradients in this profile, one can isolate the following characteristic height ranges: at 200–400, 400–800, 800–1200, and 1200–1600 m heights. The gradient of $\sigma(H)$ even changes its sign in the range from 800 to 1200 m, i.e., the scattering coefficient increases with height. Next measurements (at 8 and 10 a.m.) showed yet more pronounced stratification caused by intensification of the turbulent exchange after the sunrise. Two well-pronounced layers can be isolated at the heights near approximately 300 and 1200 m. The vertical distribution $\sigma(H)$ has neutral height behavior in the range heights from 600 to 1100 m. The pattern becomes smoothed near the noon because of the increase in the aerosol filling of the entire height range with simultaneous decrease of the $\sigma(H)$ gradient. Starting from 3 p.m., the intensity of the turbulent exchange gradually decreases, the upper layers are destroyed what leads to the aerosol accumulation in lower layers and the observed stratification becomes smoother. Obviously, one can take the 4 p.m. time as the "point of equilibrium," when no characteristic deviations are observed in the vertical profiles $\sigma(H)$, and the near-ground value σ_0 decreases after reaching maximum near the noon. According to the diurnal behavior of thermal regime of the boundary layer of the atmosphere in the mid-latitude summer, the increase of the rate of temperature decrease with height is observed since 5 p.m. until sunset.[13]

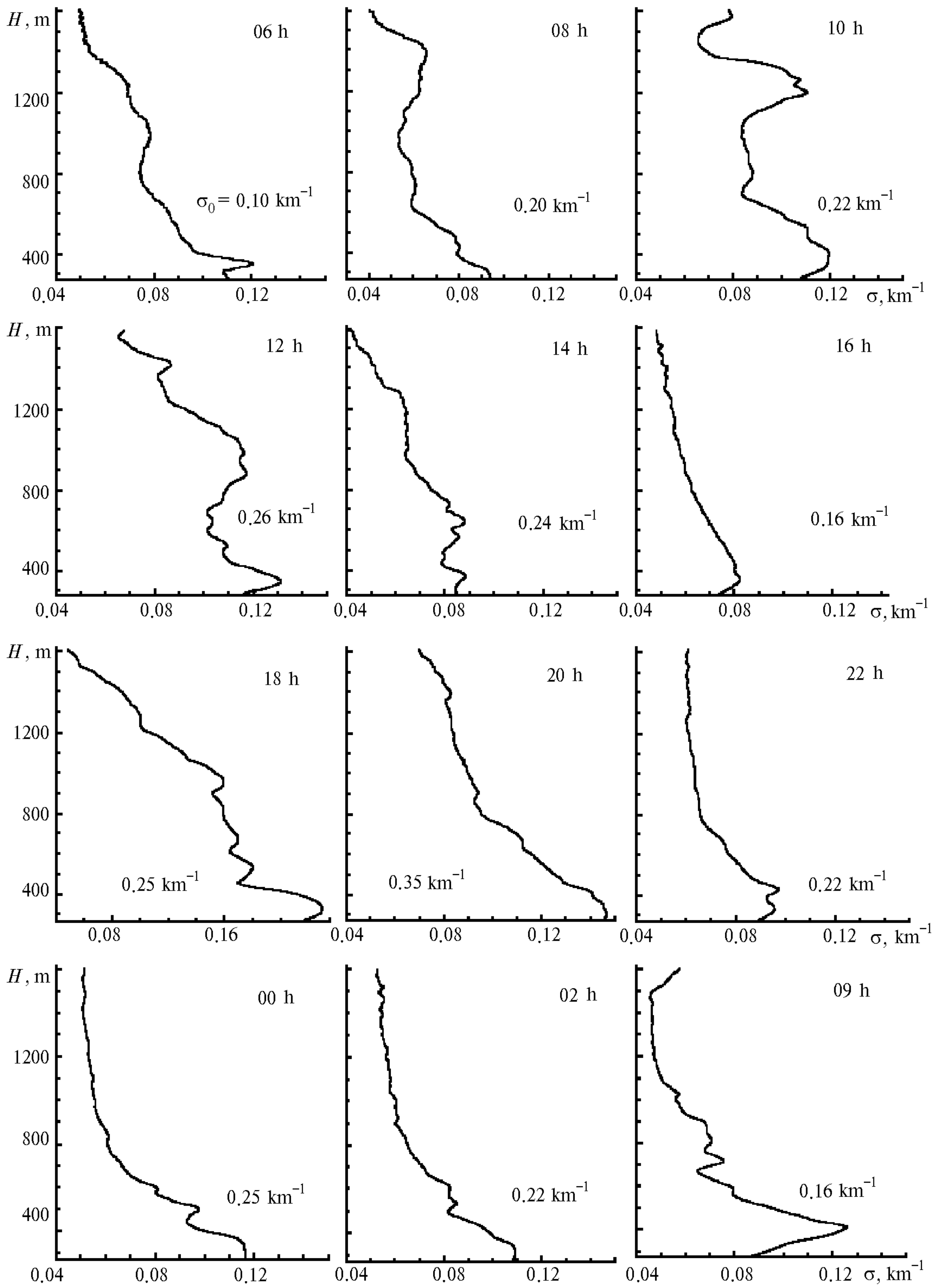

Fig. 2. Diurnal behavior of the vertical distribution of the scattering coefficient measured on July 29–30, 1998. The time of the beginning of measurements is shown in the upper part of the plots, the near-ground value of the scattering coefficient is shown at the figure bottom.

First, at 6 p.m., it leads to an increase in the rate of σ(*H*) decrease in the upper height range (1000–1600 m) and then in the entire selected range (8 p.m.). One should note that the second maximum in the near-ground values σ_0 is observed just at this time. This was earlier[10] revealed when studying the number density of particles in the atmosphere over Baikal Lake in the end of July 1991. Then, based on measurement data acquired at 10 and 12 p.m., one should isolate three height regions at 800 to 1600, 500 to 800 and 200 to 500 m characterized by their own gradients.

The nighttime and daytime measurements that followed on July 30 are not presented in the paper. The reason for this is that those are similar to the diurnal behavior of the vertical distribution of σ(*H*) described above, with only small variations. Let us present only one profile obtained at 9 a.m. on July 30, which repeats the general features of the data acquired at 8 a.m. and 10 a.m. on July 29.

Thus, the series of measurements shows the presence of a complicated structure of the vertical profile σ(*H*) caused by the inverse behavior of the aerosol content in the height range from 1200 to 1400 and from 200 to 400 m, and, in the majority of events, the neutral behavior in the height region from 500 to 800 m.

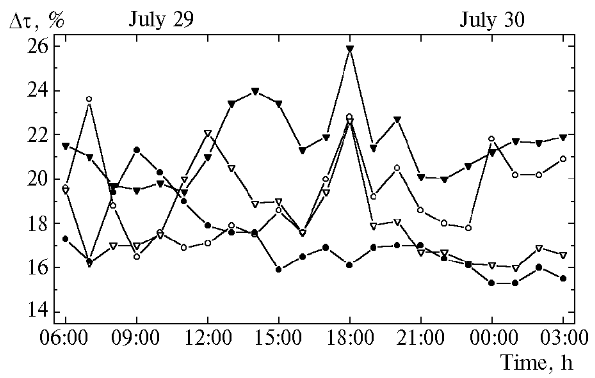

Fig. 3. Diurnal behavior of the contribution (in percent) coming from different height ranges to the total optical thickness: open circles are for the 200 to 500 m layer, filled triangles for 500 to 800 m region, open triangles for the heights of 800 to 1100 m, and dots for the layer between 1100 and 1400 m heights.

In this connection, it is interesting to estimate, on the same time scale, what is the percentage of the contribution to the total optical thickness coming from different height ranges. The whole height range from 200 up to 1400 m was divided into the 300-m-long parts. Diurnal behavior of the contribution Δτ from different height ranges to the total value τ is shown in Fig. 3. The most complicated pattern is observed in the morning. The lower layers make the greatest contribution here, but the contrary situation is observed already at 9 a.m.: the minimum values of Δτ from the lower range of 200–500 m heights and the maximum values coming from the upper layer. The steady increase of the optical thickness of the middle part of the boundary layer is observed starting from this time accompanied by the simultaneous decrease of the contribution coming from the upper layers. The difference between them near the noon and in the evening is about 10%. This tendency remains up to the end of measurements, and physical meaning of the variations of the diurnal behavior of Δτ was considered when describing Fig. 2.

To quantitatively estimate the relations between the optical parameters of the atmosphere at different heights, let us consider statistical properties of the profiles σ(*H*) presented by the normalized autocorrelation matrices *R*(*H*). The correlation matrices were calculated for the height range from 0.28 to 2 km with the spatial resolution of 30 m using approximately 400 profiles of the scattering coefficient.

Let us consider the diurnal variations in the behavior of *R*(*H*) shown in Fig. 4. According to the dynamics of σ(*H*) behavior shown in Fig. 2, we have isolated four time-intervals characteristic of the processes of transformation of the profiles at different time, namely, the morning (5–10 a.m.), daytime (11 a.m.–5 p.m.), evening (6–10 p.m.), and nighttime (11 p.m.–4 a.m.). As is seen from Fig. 4, matrices *R*(*H*) are principally different at different time of a day. The differences are seen, first of all, when comparing the data obtained in the nighttime and in the morning with the data acquired in other periods (Fig. 4*b*, *c*), in which the autocorrelation functions monotonically decrease with height.

The plots for the nighttime and morning (Figs. 4*a* and *d*) show the presence of certain correlation between the variations of the scattering coefficient at the upper (1400–1500 m) and lower (300 m) boundaries of the range, while the correlation between σ(*H*) at the lower boundary and subsequent height being insignificant. It is evidence of one mechanism of formation of the vertical structure of σ(*H*) by the breeze circulation of air over the lake[14] and the channel effect[15] leading to the appearance of the spiral coastal vortex revealed[5,16] at airborne observations under different synoptic conditions in 1991–1996 and from the balloon-borne sounding in the next years.[16] The turbulent exchange in the daytime and in the evening leads to a more uniform and stable correlation between the deviations of σ(*H*) at different heights. The matrices presented for these time intervals (Figs. 4*b* and *c*) are similar to that calculated using the data obtained earlier under continental conditions[9] and, on the whole, determine the behavior of the generalized autocorrelation matrix for the whole day (Fig. 4*e*). The height ranges attract attention where dense concentration of all curves *R*(*H*) is observed, and the scattering coefficient values at altitudes below these heights well correlate with each other ($R \geq 0.5$). Authors of Ref. 8 suggested to define the height of the principal mixing layer based on this criterion. In our case, this height is 1800 m in the daytime and 1500 m in the evening.

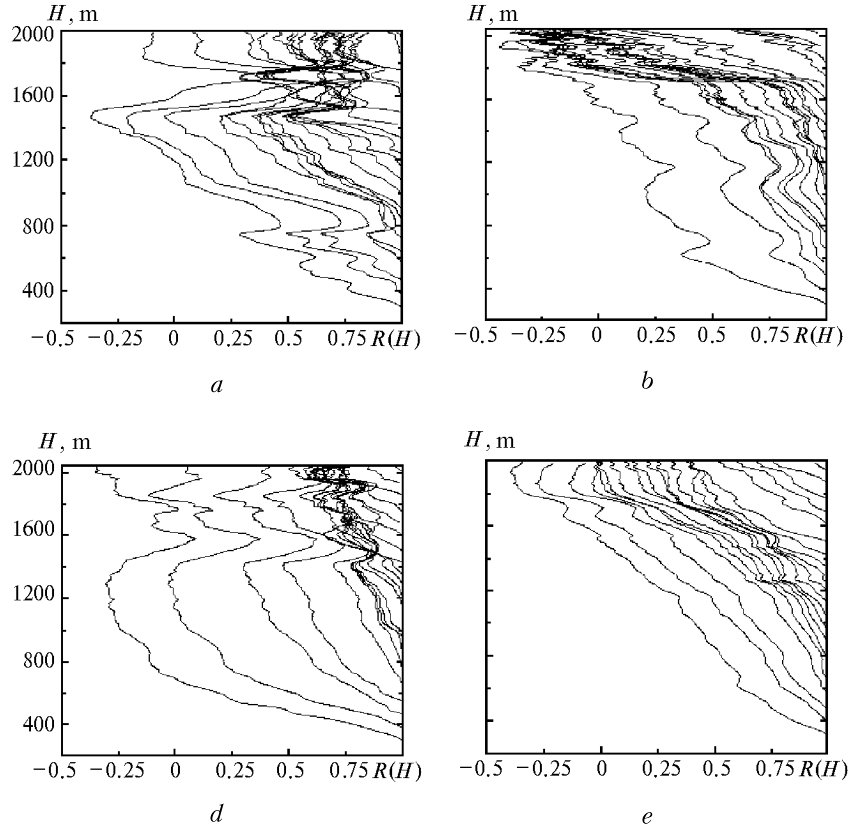

Fig. 4. Vertical behavior of the autocorrelation matrices at different time of a day: 5–10 a.m. (*a*), 11 a.m. – 5 p.m. (*b*), 6–10 p.m. (*c*), 11 p.m. – 4 a.m. (*d*) and whole day (*e*).

Thus, the lidar observations made it possible to reveal the pattern of correlation of variations of the aerosol optical characteristics at the boundaries of the height range 0.28–1.4 km that most likely is caused by the toroidal breeze thermal vortex at the dominating air mass transfer from the west.[5] If one supposes that its lower boundary is at the above-mentioned height, the weak correlation should be observed between the vertical variations of $\sigma(H)$ and the data of ground-based measurements. To clarify this supposition, we calculated the autocorrelation functions $R(0, H)$, where the values σ_0 were taken from the data of sounding along a horizontal path in each measurement cycle. The calculated results are shown in Fig. 5 for the same time intervals as in Fig. 4. Two groups of data can be isolated here: daytime-evening and nighttime-morning. Practically, no correlation is observed in the first group (Fig. 5, curves *2* and *3*) in the entire height range. Significant correlation is observed in the nighttime only up to $H = 500$ m, it is even negative for other heights and comes to the range of small positive values only at the upper boundary. It is interesting to mention the increase of $R(0, H)$ up to maximum values of 0.75 in the height range up to 400 m. In addition to the data from Fig. 3*d* it is an evidence of the transfer of admixtures from the upper boundary (source) to the lower one where its accumulation with the subsequent sedimentation to the near-ground layer occurs. The contrary situation is illustrated by the curve *1* in Fig. 5 for the morning hours.

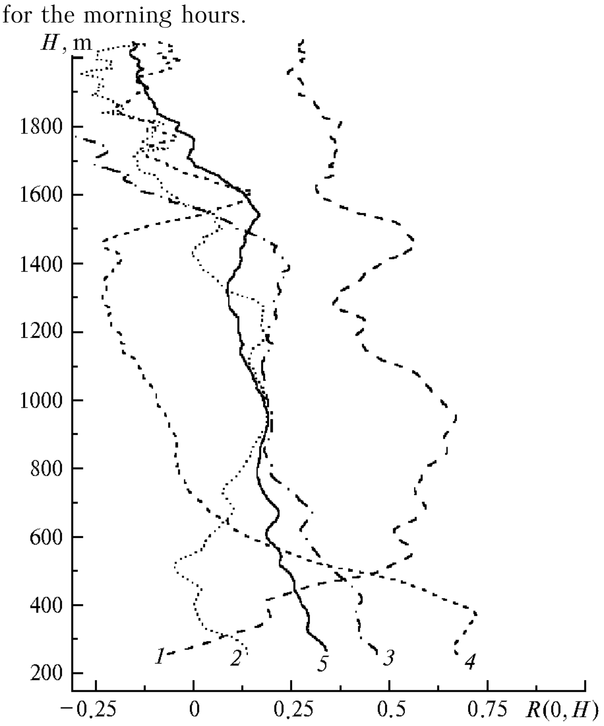

Fig. 5. Vertical behavior of the autocorrelation function $R(0, H)$ for different time of a day: 5 – 10 a.m. (curve *1*), 11 a.m. – 5 p.m. (*2*), 6–10 p.m. (*3*), 11 p.m. – 4 a.m. (*4*) and whole day (*5*).

On the whole, the analysis of the results presented is the evidence of a complicated structure of the profiles σ(H) observed during a day that is caused by the specific features in the air circulation in the boundary layer of the depression contour of the lake. The diagram of the vertical distribution of the absolute value of wind velocity obtained from the data of balloon-pilot sounding and the aerosol scattering coefficient obtained by the lidar (in the morning) are shown in Fig. 6. These distributions make it possible to estimate the vertical size of the circulation cells. Their lower boundary is at the height H_{min} = 300 m, and the upper one is at H_{max} = 1100-1300 m. The cell center corresponding to the minimum values of the wind velocity and the scattering coefficient is near the height H_c = 700-800 m. The range of the boundary heights is in a good agreement with the data of aerological observations carried out in previous years.[16]

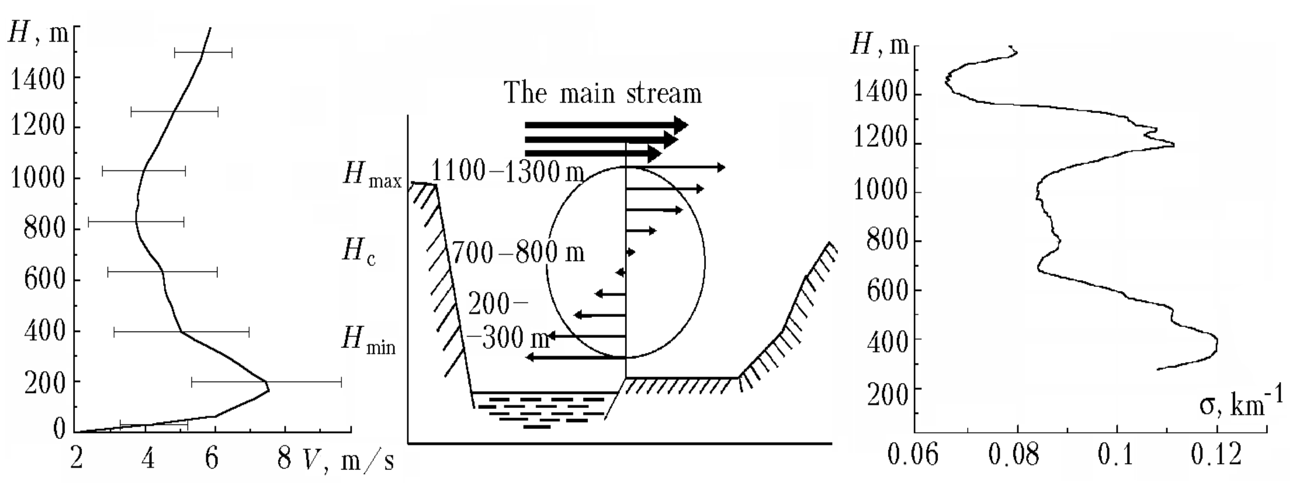

Fig. 6. The diagram of the vertical distribution of absolute value of wind velocity and the scattering coefficient in a circulation cell. Mean value of the wind velocity during the period of observations (*a*), model of the wind circulation cell[16] (*b*), and the distribution of σ(*H*) obtained by the lidar in the morning (*c*).

For a conclusion, we would like to thank all the participants of the "Baikal" field mission, especially scientists from Buryat Institute of Natural Sciences, on the field site of which the measurements were carried out.

Further complex processing of all data obtained during the field campaign and statement of special experiments will favor a more detailed understanding of the nature of physical processes occurring in the atmosphere over Lake Baikal.

Acknowledgments

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