Shipborne lidar investigations of aerosol fields in the atmosphere over Lake Baikal. Part 1. Longitudinal sections

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We present some results of lidar measurements of the altitude structure of aerosol fields based on the data array obtained during the shipborne mission on Lake Baikal in July–August 2002. Analysis of longitudinal and cross sections revealed a significant effect of local orography on the field structure. The correlation analysis of the altitude distribution of the optical depth along the ship route with the spatial profile of the Primorskii Ridge mountains was conducted. It was found that the highest correlation is observed in the lower atmospheric layer from 0.5 to 1.5-km height.

Baikal is a unique natural formation on our planet. UNESCO included it into the list of the objects of worldwide natural heritage, so the attention paid by scientific community to the change of environment in its area is understandable. In recent years special attention has been given to atmospheric investigations of the spatiotemporal structure of aerosol and gaseous fields as well as to trans-border transfer of admixtures, because one of the channels of anthropogenic impact on the lake is the atmosphere.

Large number of papers have been published to date on theoretical modeling of the processes of propagation, transformation and sedimentation of admixtures in the region of Lake Baikal,[1–7] as well as on the experimental study of the concentration of atmospheric admixtures at different parts of its area.[8–12] As applied to Lake Baikal, the processes of transfer and transformation of pollutants are modeled both on mesoregional scale and on the regional scale, taking into account the intensity and location of local industrial enterprises and those located up to 70 km far outside the lake coast.[1–5] The final purpose of such theoretical investigations, as it was rightly noted in Ref. 1, should be creation of adequate mathematical models of formation of the fields of concentrations of atmospheric admixtures taking into account specific physical-geographical conditions. The necessary stage in reaching this goal on prediction of the air state above Lake Baikal is verification of the models based on the data of observations.

Instrumental investigations of physical-chemical composition of Baikal aerosol by means of direct sampling have been carried out during quite a long time both at stationary sites and from research vessels.[8–16] The use of a research vessel allowed us to realize aerosol survey practically all over the area of the lake and to compare the results of field measurements with calculated, using a three-dimensional model,[2] mean fields of concentration of sulfur and nitrogen oxides, sulfates and nitrates.

As the authors of Ref. 2 consider the comparison has shown satisfactory agreement between theory and experiment. However, the comparison has been done using data on aerosol and gaseous admixtures only in the near-ground layer. The papers devoted to investigation of the vertical structure of admixtures over the lake are not numerous. The first ground-based lidar measurements over Baikal were discussed in Ref. 14 and those enabled us to reveal diurnal behavior of the vertical distribution of the scattering coefficient and corresponding autocorrelation matrices.

The data obtained allowed us to estimate the vertical size of wind circulation cells with the aerosol used as a tracer. The attempts to obtain two-dimensional pattern (vertical-horizontal) of admixture distribution over the lake were undertaken in Refs. 11 and 12 by means of sensors installed onboard an aircraft. However, in this case the observations were carried out only at heights between 400 and 900 m in the daytime because of the specific requirements to flights. Based on the aforementioned facts, it is quite clear that empirical data on vertical distribution over the lake representing at least two factors are necessary for complete verification of the models of the vertical structure of aerosol fields.

The first factor is the spatial one that accounts for the orography of the region. The leeward waves appear created by airflows to mountain ridge. They form ascending and descending air motions,[15,16] which actively affect the structure of aerosol field.

The second factor is time required for a single measurement of an atmospheric parameter. For example, in investigating the chemical composition of aerosol admixtures by sampling on filters, the exposure time in 10 to 12 hours.[1,8] So, only the mean characteristics can be considered. In case of measuring at a stationary site, these are daily mean concentrations. In the case of measurements with the instrumentation installed onboard a vessel during its motion, these are the concentration values spatially averaged over a region. For example, three parts of the lake are selected[1,8]: the northern one, middle part, and the southern one. Naturally, one should take into account the synoptic situation, so both wind direction and the type of air mass as a whole can change during that long time.

In general, the optical measurements are free of temporal limitations, because they allow obtaining instantaneous data on the state of the atmosphere at each point of space.

In July–August 2002 Baikal–02 multipurpose mission was carried out in order to obtain two-dimensional spatial sections of aerosol fields. A Loza-M single-frequency aerosol lidar[18] was installed onboard the Research Vessel *G. Titov* of Limnological Institute SB RAS. Sounding was carried out mainly in the regions of middle and southern parts of Baikal in order to obtain longitudinal (along the coastal line) and cross (from one coast to the opposite) sections. Organization of such an experiment allowed solving two important problems. The first one was in comparison of the profiles of scattering coefficient and their statistical characteristics in different parts of Baikal with similar data obtained earlier under stationary conditions.[14] The second problem was to investigate the effect of relief on the peculiarities in the vertical structure of aerosol field that is the most important thing in verifying the models.

In this paper we present first results of processing the data of sounding obtained during only two days of the shipborne mission – July 31 and August 1, 2002. One can conditionally divide the route of mission into several parts corresponding to the parts of the lake, different in their orography (Fig. 1).

The first part is longitudinal section obtained in the daytime since 11 a.m. until 5 p.m. in the region of Small Sea on July 31. The part of this route bounded by Ol'khon from one side and Primorskii ridge from the other side is characterized by most complicated orography with high-mountain part of the continental ridge.

The second part also was the longitudinal section, the most long in distance and time of all realized in the mission. This made the basis for selecting this route for processing in the first place. The route began at Ol'khonskie Vorota strait leading from the Small Sea, then along the coastal line and ended in the middle part of Baikal opposite to village Bol'shaya Goloustnaya. The time interval was evening and nighttime since 6:30 p.m. on July 31 until 3:20 a.m. on August 1.

In planning the third part of the route, the problem was stated to study the vertical sections of the boundary layer of Southern Baikal in cross direction along the Angara valley at north-west transfer of air masses from Irkutsk. The cross section was performed along the direction Tankhoi–Listvyanka in the morning on August 1.

The last, fourth section of this day was realized in the evening in the most polluted part of the atmosphere over Southern Baikal along the Listvyanka–Baikalsk line.

The general synoptic situation on this day was quite favorable from the standpoint of stable north-west transfer of air masses. In the night July 30–31 the cyclone moving to the north in the East Siberia, covered the entire region by its south periphery. It rained over the greatest part of Middle Baikal, the atmosphere was cleaned, and additional contrast of the vertical structure of the transferred aerosol was provided.

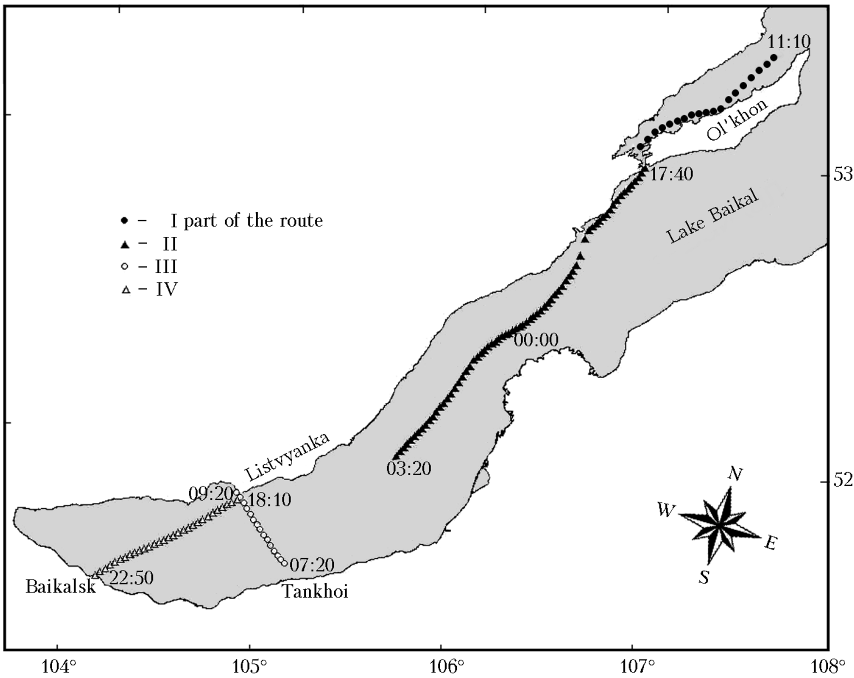

Fig. 1. Pattern of routes of the Research Vessel *G. Titov* on July 31 – August 1, 2002. Separate parts of the route are marked by different symbols.

In performing the route No. I, wind direction at all heights was approximately the same. The absolute value of wind speed increased from 5 m/s in the near-ground layer to 10 m/s at the heights of 1.5 to 3 km.

Synoptic situation on route II practically did not change until 4 a.m. on August 1, when some increase of wind speed with height was observed. The route No. III also was performed under these conditions. The last route No. IV was characterized by the change of air masses (mid-latitude and Arctic) and anomalous distribution of the absolute value of wind velocity over height. The value in the near-ground layer reached 15 m/s and at the upper boundary it was 5 m/s.

Let us consider the results obtained in the frameworks of solving the first problem. The selected profiles of the scattering coefficient σ at the selected routes of motion are shown in Fig. 2. In general, all profiles are similar, except for the dependences $\sigma(H)$ obtained on the route No. I in the region of Small Sea. Analysis of all data obtained along route No. I, including that shown in Fig. 2, shows that there are very wide variations of the values of $\sigma(H)$ profile with height both in lower and upper layers of the atmosphere. Obviously, it is related to the specific features of the region of observations, because in other cases (Fig. 2*b*–*d*) the variance of variations is not that high. The fact attracted our attention that anomalous behavior of $\sigma(H)$ is observed in all profiles in Fig. 2, because the scattering coefficient increases up to the height of 1 km. Such a distribution of admixtures in the lower layers was observed earlier both in lidar measuremetns[14] and from the data of direct sampling during airborne sounding, including comparison of the recent results of shipborne observations of gaseous and aerosol components of the atmosphere in the near-ground layer.[11]

To quantitatively estimate the relation between optical characteristics at the heights under study, statistical characteristics of $\sigma(H)$ were calculated, as in Ref. 14, in the form of normalized autocorrelation matrices $R(H)$ related to the selected types of routes. The matrices were calculated with the vertical resolution of 30 m.

The vertical behavior of autocorrelation matrices is shown in Fig. 3 depending on the region of observations, i.e. the number of the route. The number of the profiles used for calculating the matrices is also shown here. As the matrices can be essentially determined by the orographic conditions of the region of measurements independent time of day, one should analyze the peculiarities obtained earlier at Baikal under stationary conditions.[14] Then four time intervals were selected, which characterize the processes of transformation of the profiles in different time: morning (5 to 10 a.m.), daytime (11 a.m. to 5 p.m.), evening (6 until 10 p.m.) and nighttime (11 p.m. to 4 a.m.).

The matrices for these intervals have absolutely different view in different time of day. The differences are well seen, first of all, when comparing the data obtained in the nighttime and in the morning relative to other periods, in which the autocorrelation matrices monotonically decrease with height.

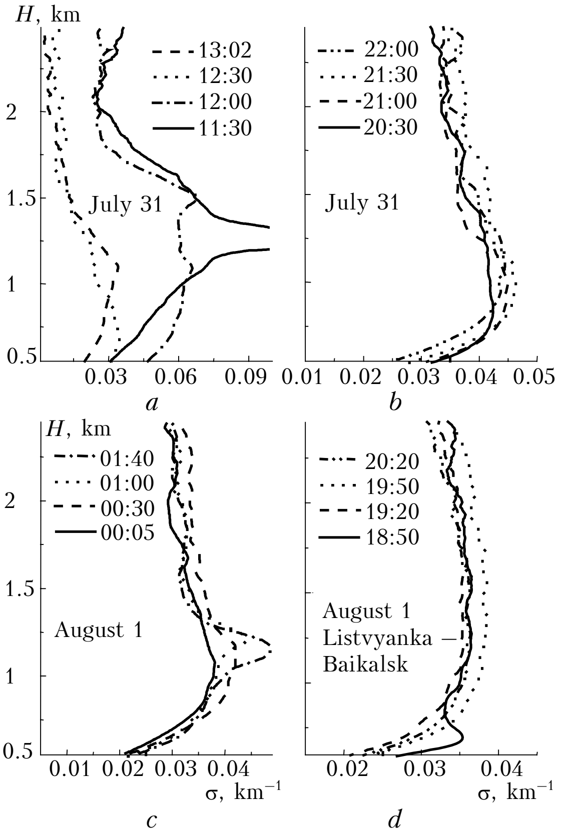

Fig. 2. Profiles of the scattering coefficient at the selected parts of the route: part I (*a*), part II (*b*, *c*); part IV (*d*).

Plots for the nighttime and morning intervals have shown the presence of well-seen dependence between variations of the scattering coefficients at the upper (1400–1500 m) and lower (300 m) boundaries, while the relation of $\sigma(H)$ between the values at the lower boundary and subsequent heights is not significant. It is an evidence of the common mechanism of formation of the vertical structure of $\sigma(H)$ caused by the specific features of the flux circulation in the atmosphere over the lake.[13,17] The turbulent exchange processes in the daytime and evening lead to more uniform stable relations between deviations of $\sigma(H)$ at all heights. The matrices presented for these time intervals are similar to the matrices obtained earlier under continental conditions,[19] and generally determine the behavior of the generalized autocorrelation matrix for the whole day. The height ranges are of interest, where concentration of all height dependences $R(H)$ is observed, and lower values of the scattering coefficient well correlate between each other ($R \geq 0.5$). It was supposed[20] to determine the height of the principal mixing layer by this criterion. In our case, it is the height of the layer with parameter correlation that is discussed in Ref. 19, which is 1800 m in daytime and 1500 m in the evening.

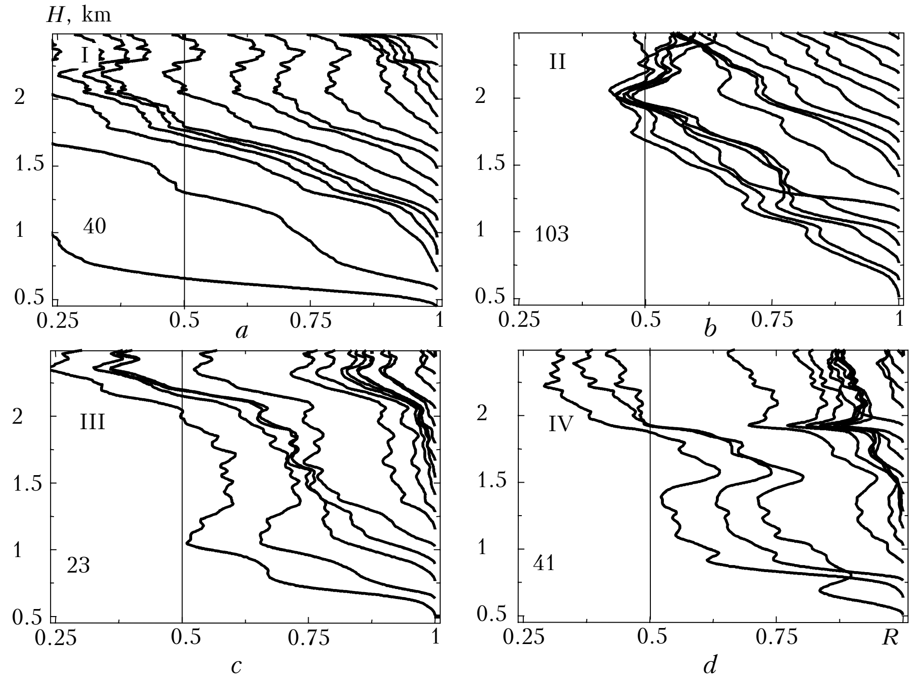

Fig. 3. Autocorrelation matrices of the vertical profile of the scattering coefficient at the selected parts of the route.

It is difficult to reveal the diurnal behavior in explicit form from data of shipborne measurements, because complex orography of the region is an additional factor affecting the vertical structure of aerosol field, as it will be shown below. It is seen in Fig. 3 that the matrices have different view depending on the region of measurements. As was supposed based even on the analysis of primary profiles σ(H) in Fig. 2, one should expect the least correlation between heights in the region of Small Sea (route I). It is also confirmed by vertical behavior of the autocorrelation matrix where the correlation coefficient at the height of 1 km decreases to the value less than 0.25 (Fig. 3*a*). These values at subsequent routes (Fig. 3*b*–*d*) always exceed the boundary value 0.5, but the vertical behavior of the matrices is different.

Monotonic decrease of correlation up to the height of 2 km is observed in data of the longest route II along the coastline. Correlation at the reference points of the lower 1-km high layer has the tendency toward increase in the height range from 2 to 2.5 km. It is an evidence of the fact that the principal flow at these heights affects lower layers favoring aerosol accumulation.

Subsequent routes III and IV corresponded to cross sections along the paths Tankhoi–Listvyanka and Listvyanka–Baikalsk. Analogous pattern is observed here, but the increase of the correlation functions is observed in the lower height range from 1 to 2 km, that is probably explained by lowering the relief of the mountain ridge in this part of Baikal.

As follows from the data presented, orography of the investigated region of Lake Baikal essentially affects the structure of the aerosol field. Let us consider this problem in a more detail by comparing the vertical profiles of the optical parameters along the route of the vessel with the corresponding profile of the coastline ridge relief.

Practically continuous (except for unfavorable weather conditions, such as low cloudiness, precipitation, strong gale wind) vertical sounding of the atmosphere was carried out during the days when the vessel moved. The returns of the lidar operating with the pulse repetition rate of 5 Hz were recorded as one-minute runs every 5 minutes. One run of sounding was stored as a data file with time reference, then it was referred to the spatial coordinates of the vessel position by means of the GPS (Global Positioning System) mobile system. The signals were processed and the vertical profiles of the scattering coefficient were retrieved for each shot according to the algorithms of processing the two-component (aerosol and molecular scattering) medium[21] with subsequent averaging within the limits of a measurement run. Then at the mean speed of the vessel of about 14 km/hour we obtained the spatial section of the profiles σ(H) with the vertical resolution of 8 m and horizontal resolution of ~ 1.3 km. Upper boundary of the section was ~ 3 km, and the lower boundary was ~ 0.5 km. The choice of the latter was mainly caused by the geometry of the lidar, which determined the dynamics of the lidar return.

Thus, two-dimensional sections of the aerosol field of the spatial scale from several meters (in one run) to hundreds kilometers and, in time, from minutes to days were recorded at sounding. The formed data array enables us to investigate the atmospheric phenomena connected with the aerosol transfer and circulation on the mesometeorological scale. Let us consider variations of the optical thickness τ in both the entire height range under investigation and within some layers as an example characterizing the change of the spatial structure of aerosol fields. The estimate based on the total optical thickness in the selected layers allows obtaining the one-dimension realizations at the characteristic heights.

The realizations of τ(*t*) obtained in three height ranges at sounding of the atmosphere along the route of the Research Vessel *G. Titov* on July 31 and August 1 are shown in Fig. 4. The route was performed from the middle (Small Sea) to the south end of Lake Baikal (Baikalsk) and covered the distance of $L \approx 300$ km. The first (in the vertical direction from the surface) realization of the values τ was obtained in the atmospheric layer from 0.5 to 1.5 km characteristic of the boundary layer. The second realization of τ was obtained in the intermediate layer from 1.5 to 2.2 km, and the third one – from 2.2 to 3 km. The last height is already characteristic of the lower level of free troposphere, where fluctuations of the optical characteristics of air masses undergo primary effect of the atmospheric processes of synoptic scale. As is seen in Fig. 4, the greatest variations of τ are observed in the boundary layer, and in the upper layers they are comparable in magnitude and have lower degree of variations. One should note essential non-stationarity of the process of fluctuations of the optical thickness in all height ranges. However, if selecting the characteristic temporal scales (of the order of 5 to 7 hours) in the limits of which the conditional stationarity is fulfilled and to take into account the factors of influence of only atmospheric phenomena, one can relate the variations of τ to processes of transfer of air masses on a subsynoptic scale.

Nevertheless, in the frameworks of the problem stated, let us first consider the effect of relief on the peculiarities of the spatial structure of aerosol field.

The dominant northwest wind direction with insignificant changes over height was observed during the experiment. Mountains of the Primorskii ridge were practically perpendicular to this direction, as is shown in Fig. 5. They are the highest obstacles for the airflow carrying anthropogenic aerosol from industrial regions of Irkutsk Region. In the first approximation one can suppose that the high-mountain relief of the ridge serves as a blocking filter on the way of transfer of admixtures in the boundary layer. Then subsequently one can expect that the structure of aerosol field assessed from the data of lidar sounding carried out on the route parallel to the ridge and not more than 20 km far from it, is spatially modulated depending on the profile of the high-mountain relief.

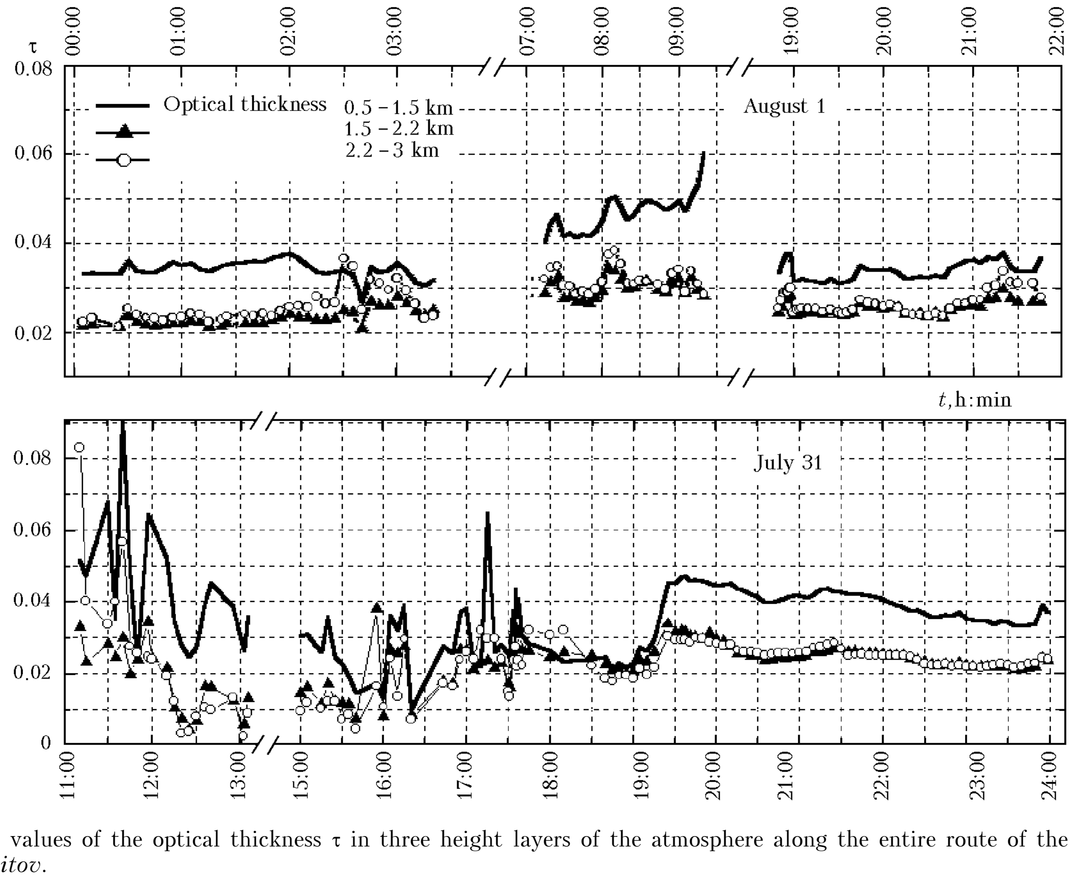

Fig. 4. The values of the optical thickness τ in three height layers of the atmosphere along the entire route of the Research Vessel *G. Titov*.

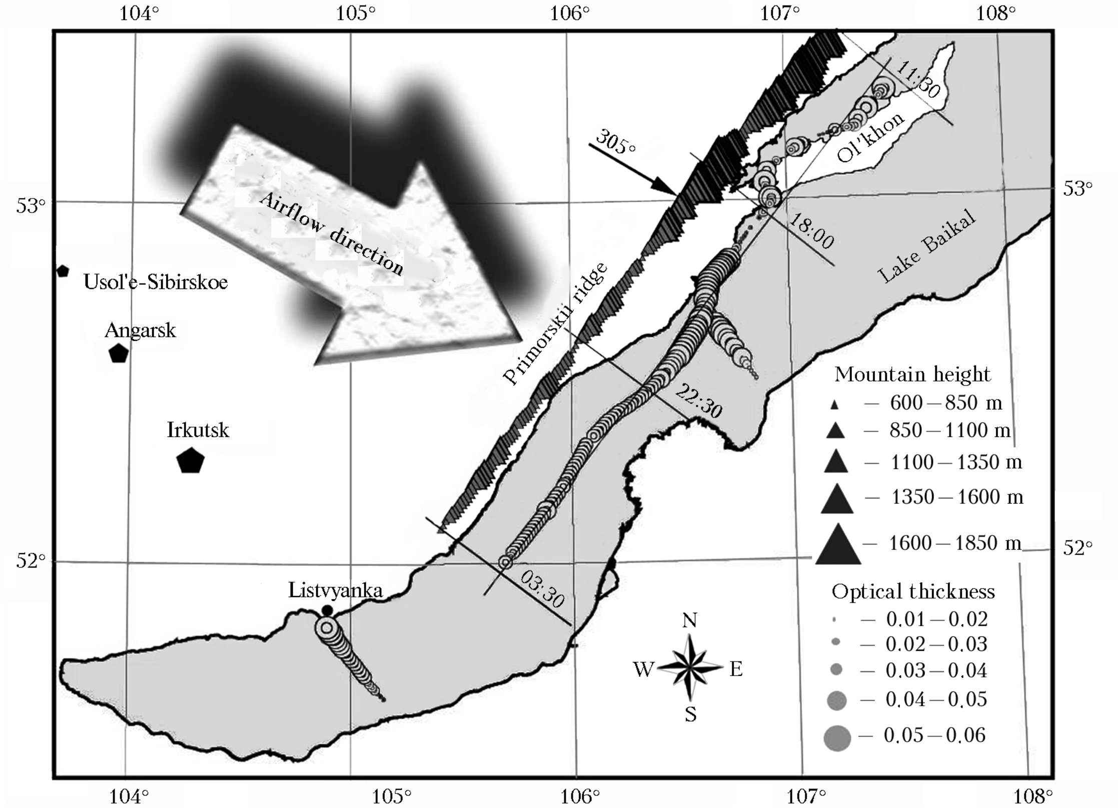

Fig. 5. Diagram of the shipborne experiment (the arrow shows the direction normal to the ridge).

Figure 5 shows the route of the research vessel with the values of the optical thickness τ of the boundary layer of the atmosphere marked by circles according to the scale calibrated in the units of τ. The vertical profile of the Primorskii ridge is shown by triangles according to the scale calibrated in the units of the ridge height.

The relief image was obtained from the data of GIS (geoinformation system) of high spatial resolution applying the software package for three-dimensional analysis. The single-dimensional realization of the profile was formed using the method of projection of the maximum values of height in the direction normal to the vertical plane of section along the ridge and in the 10-km wide relief lane.

Correlation of the mountain height and the spatial resolution of the optical thickness is seen in Fig. 5. In order to estimate such an effect in a more detail, let us consider correlation between the ridge height and τ at the selected heights, assuming that they have the stochastic nature. Let us preliminary prepare these data for correlation analysis. It lies in the standard procedures of statistical analysis – determination and removing of the mean value, i.e. “whitening” of the stochastic process and normalizing to the mean variance. Besides, in order to keep and reveal spatial correlation, it is necessary to preliminary refer the data and to calculate the subsequent projection of spatial points of realization of τ in the normal direction to the single-dimension section of the height profile of the relief. After determining the total length of the realizations, which is of the order of 200 km in our case, let us divide all realizations into equidistant readouts using the method of interpolation within the limits of the total number of points. Thus, the realizations of 150 readouts are obtained, with minimum spatial step of 1.33 km, that provides for the total length of the realization of 200 km.

The estimates of the correlation $\rho(H, \tau)$ are shown in Fig. 6. One should pay attention to the fact that the estimates of these functions along the entire distance are incorrect because of non-stationarity of realizations of τ along the entire time interval, as it was already noted above (see Fig. 4). Thus, the correlation window of the maximum number of shifts equal to 50 was selected after preliminary analysis. In scanning along the entire distance, the window covered characteristic time intervals where the condition of stationarity was fulfilled. It is indicative that the selected time scale (on the order of 5 hours) coincides with the scale of subsynoptic variations of the atmospheric phenomena determined above and is quite adequately described by synoptic report for the considered time period. The fact is not less important that subsequent position of the characteristic correlation scales along the sounding path coincides with the characteristic scale of variations of the height profile of the relief of Primorskii ridge. The revealed spatiotemporal scales are shown in Figs. 5 and 6.

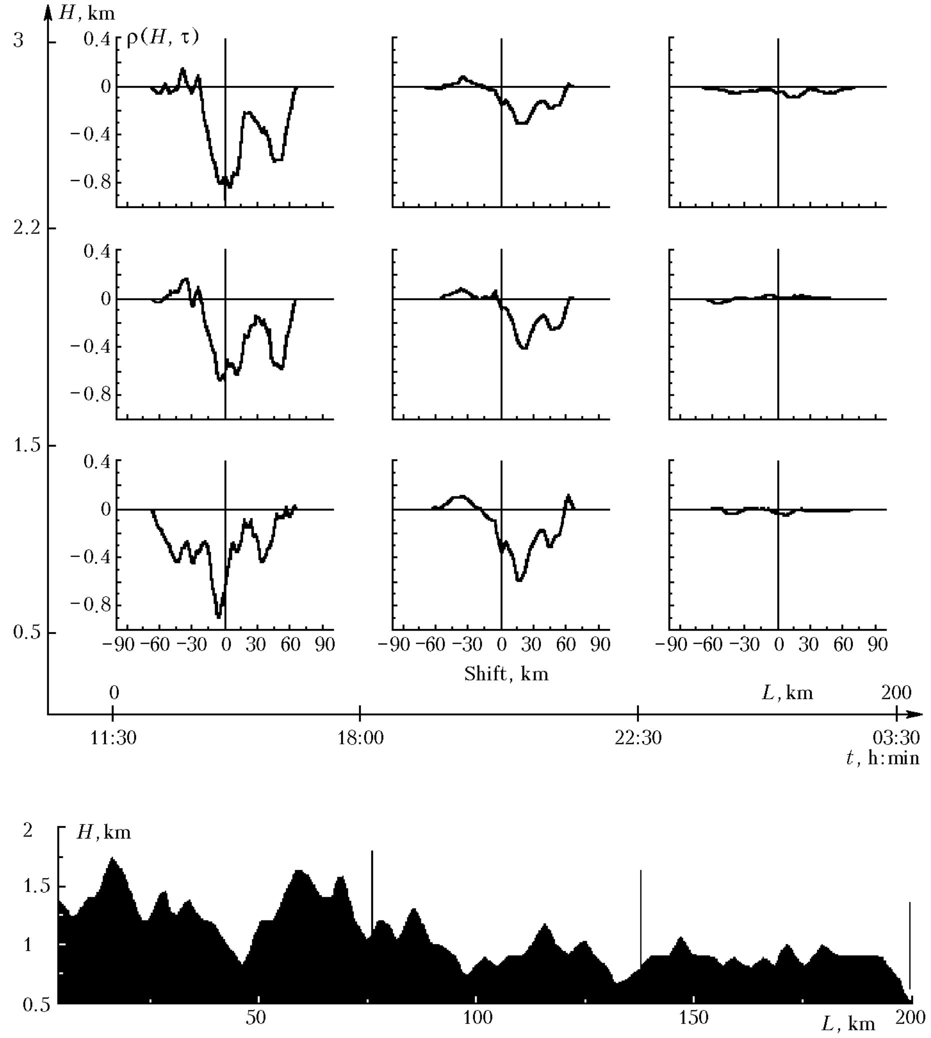

Fig. 6. Correlation function $\rho(H, \tau)$ of the height profile of mountains with spatial variations of the optical thickness.

As is well seen in Fig. 6, all functions $\rho(H, \tau)$ have negative values with different degree of significance, that is evidence of inverse correlation of the height profile of mountains with spatial variations of the optical thickness along the sounding path and quite adequately confirms the supposition made above at the statement of the problem. The errors in estimating the values of the correlation coefficients in main maximums do not exceed 30% for the first time interval since 11:30 a.m. until 6 p.m., and not more than 50% for the second time interval since 6 p.m. until 10:30 p.m. Secondary maximums of the coefficients $\rho(H, \tau)$ are not considered here because their small statistical significance. The absolute absence of correlation is observed for the third time interval since 10:30 p.m. until 3:30 a.m. It is mainly caused by the change of weather conditions at this time caused by intensification of anticyclone, corresponding weakening of the absolute value of the wind velocity with height, and change of its direction.

The decrease of correlation coefficients from the first time interval to the second is explained by a decrease of the absolute height of mountains and, respectively, weakening of their influence on the transferred airflow and by the destruction of correlation with variations of the measured optical thickness. The fact that such an influence is possible is confirmed by the shift of the maximum of correlation coefficient in the second time interval, because positive delay in the shift of the correlation function corresponds to the change of the airflow transfer direction from northwest to that from the west. It was estimated (using the diagram of projection of Fig. 5 to geographical grid) that the shift of 14 km corresponds to the change of direction by approximately 30°. The observed shift of 16 km in the second time interval corresponds to the shift of the airflow direction of 35° that is confirmed by the synoptic data.

It was revealed that spatial variations of the integral optical characteristics of the lowest layer show highest correlation with the relief profile if such a correlation occurs at all. In this connection, it is interesting to follow the spatial distribution of a differential parameter – scattering coefficient – along the route. The results of mapping the profiles of $\sigma(H)$ along Primorskii ridge are shown in Fig. 7. The section of aerosol field is represented by the intensity of blackening, the scale of which is shown in the upper part of Fig. 7. The schematic height profile of mountains of Primorskii ridge corresponding to the route of the vessel (parts I and II) is shown in the lower part of Fig. 7.

The view of the aerosol section is a variegated mosaic pattern. The well pronounced cell vortex structure of aerosol field is observed in the beginning of the route since 11:30 a.m. until 6:30 p.m. in the region of Small Sea. It is diagnosed by the relative constancy of the scattering coefficients over height inside the cell and variations of the horizontal size of the cells from 1.5 to 8 km.

As moving away from the Small Sea, since 6:30 p.m. (Fig. 7*b*,*c*) the vortex structure of the field is destroyed, it becomes more homogeneous in the end of the route. Such a structure is characteristic of the airflow flowing to the mountain ridge perpendicular to it, in this case, the so-called obstacle waves appear on the leeward side.[15]

The behavior of small-scale disturbances of the flow is described in Ref. 22. It strongly depends on the following factors: (1) vertical profile of wind velocity; (2) factor of stability of the atmosphere; (3) shape of the obstacle. The airflow at weak wind smoothly moves over the ridge forming the flat wave – laminar flow. The stagnant vortex is formed at the leeward side at more strong wind, and as the vertical lapse rate of wind velocity increases, the sequence of stagnant waves is formed. As was noted,[22] appearance of leeward waves is possible for low ridges (1 km) at horizontal wind velocity not less than 7 m/s at the ridge level and from 15 m/s for the 4-km high ridges.

Theory of leeward waves was considered[23] for the case of airflow flowing around the ridge of the shape of semi-cylinder, and the solution of the problem was suggested by means of introducing the dimensionless parameter ξ_0:

$$\xi_0 = \omega H_{\rm mean}/U_{\rm mean},$$

where ω is the Brent–Vaysal frequency of gravitation oscillations which has the order of 10^{-2} sec^{-1}; $H_{\rm mean}$ is the mean height of the ridge; $U_{\rm mean}$ is the mean velocity of the disturbed flow.

It was obtained resulting from calculations that leeward waves appearing at $\xi_0 < 0.4$ are very weak, and the closed vortices are formed behind the ridge at $\xi_0 > 1$–2. Assuming the vertical lapse rate of temperature to be constant 0.65°/100 m, because it was not measured, one can calculate the parameter ξ_0 in our case. For the Small Sea part of the route (Fig. 7*a*) $H_{\rm mean} = 1350$ m; $U_{\rm mean} = 8$ m/s, then $\xi_0 \approx 2$. The characteristics of the next parts are $H_{\rm mean} = 990$ m; $U_{\rm mean} = 7$ m/s, $\xi_0 \approx 1.5$ (Fig. 7*b*) and $H_{\rm mean} = 850$ m; $U_{\rm mean} = 9$ m/s, $\xi_0 \approx 1.0$ (Fig. 7*c*).

Thus, in general, the experimentally obtained structure of aerosol field (see Fig. 7) is in satisfactory agreement with the results of theory of leeward waves.[15,23] At the same time, theories of airflow over mountains are mathematically complicated, require taking into account many factors (the presence of inversions, stratification, etc.) so one can consider this conclusion only as the first approximation.

The data obtained are in fact only the starting point for special experiments aimed at solving this problem. In the second part of the paper authors plan to consider the peculiarities of distribution of aerosol fields on the basis of lidar cross sections in different parts of Lake Baikal.

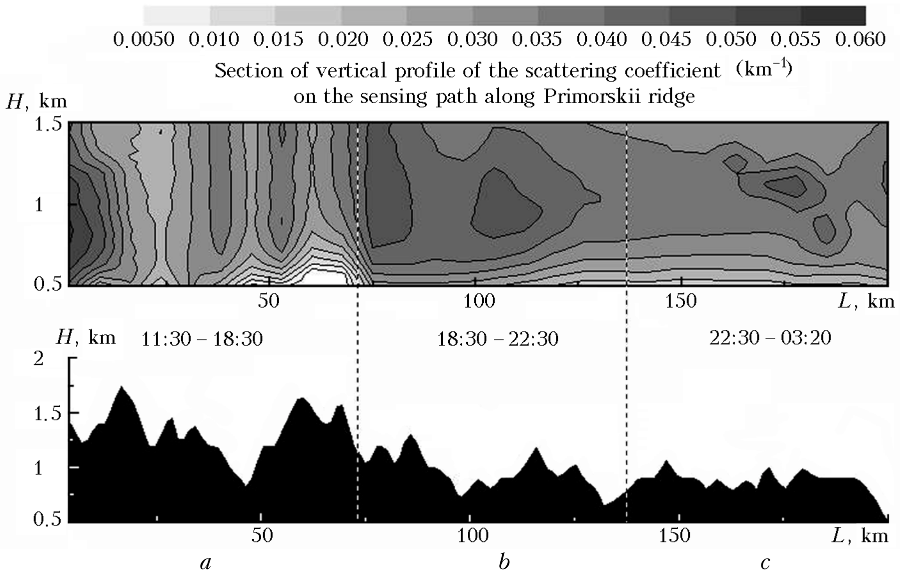

Fig. 7. Comparison of the vertical sections $\sigma(H, L)$ and mountains along the ridge.

Acknowledgments

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