Transparency by Secchi disk and water temperature in Southern Baikal

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Based on long-term observations carried out from onboard scientific research vessels, relationships have been established between transparency by Secchi disk and temperature of upper water layer in Southern Baikal. Peculiarities of the relationships in different hydrological seasons and factors caused these peculiarities have been discussed. In summer and autumn, negative correlation between parameters is due to the influence of temperature on phytoplankton growth. The reason of positive correlation in spring and early winter is the effect of water temperature on the intensity of vertical mixing. The relationships established allow revealing long-term trend in transparency by Secchi disk during the warming period in 1940–2000. Data on transparency measurements of 1950–1987 confirm the conclusion that transparency increases in spring months and decreases in summer and autumn.

Introduction

One of the most informative indices of optical and biological properties of upper layers of water reservoirs is the transparency by Secchi disk Z_S (the depth of limiting visibility of a standard white disk). In seas and pelagic zones of deep and large lakes it mainly depends on the organic suspension concentration determined by the phytoplankton content. Lake Baikal is characterized by significant seasonal Z_S variations with maximum up to 40 m in spring and late autumn under active vertical water mixing and minimum of 5–8 m in winter, summer, and autumn months,[1] when phytoplankton grows and the stratification makes difficult the exchange between upper water and pure internal water.

The water temperature T does not exert some direct effect on the transparency by Secchi disk, but it affects directly the content of suspension in upper layers of the lake. This is connected with the role of the temperature as a positive factor of phytoplankton growth as well as its influence on conditions of suspension distribution and vertical exchange depending on the depth.[2] The purpose of this work is to analyze relationships between Z_S and T in hydrological seasons distinguished by conditions of the stratification and vertical exchange.[3,4]

Data and methods

Observations of 1970–1979 at the deep-water trench Listvenichnoye–Tankhoy in Southern Baikal in 3 and 7 km from the west (stations 1 and 2) and east (stations 5 and 4) lakesides, as well as in the center of the trench (station 3) are taken as a basis. In the analysis, 452 simultaneous measurements of the water surface temperature and transparency (from 86 to 94 for each station) were used.

Parameter values averaged over the observation period changed slightly at the trench. The temperature decreased in spring (by 4°C) and increased in summer (by 2°C) near the east lakeside, the lake center was colder (0.6–0.9°C) in autumn. The transparency decreased (by 0.9–5.5 m) to the east lakeside in all seasons. These distribution peculiarities are due to hydrological conditions of the region as well as the presence of inhabited localities, main tributaries, and shoals along the east lakeside, which are additional sources of heat (in summer and autumn) and suspension.

Relationships between Z_S and T were analyzed for the following periods: spring convection in May–June from ice destruction to the transition of the water surface T through its value 3.96°C corresponding to the water maximal density, for summer warming-up (July – the middle of September), and autumn cooling to T transition through 3.96°C (September – November) with stable stratification of upper layers in the lake. Previously, the initial data were averaged over individual temperature intervals (from 0.5°C for May–June to 1°C for July–August and September–October) in order to decrease the influence of inhomogeneities in distribution of T and phytoplankton,[5] as well as accidental measurement errors.

Analytical power and linear equations for relations between Z_S and T were obtained for all stations in individual periods (Table 1). Correlation coefficients of the relations turned out to be high and significant for all considered periods. The plots of Z_S variations as function of T in different hydrological seasons are shown in Fig. 1 by the examples of stations 1–3.

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Table 1. Relations between Z_S and T for the trench Listvenichnoye–Tankhoy in Southern Baikal

Station No.	May–June		July–August		September–November	
	Linear (1) or power (2) equation					
	1	2	1	2	1	2
1	$7T + 0.7$ $\sigma = \pm 4.7$ $r = 0.85$	$6T^2 - 7T + 43$ $\sigma = \pm 2.5$ $\rho = 0.96$	$-0.9T + 17$ $\sigma = \pm 3.4$ $r = -0.78$	$0.2T^2 - 5T + 33$ $\sigma = \pm 1.9$ $\rho = 0.94$	$-0.8T + 16$ $\sigma = \pm 2.5$ $r = -0.83$	$0.3T^2 - 5T + 33$ $\sigma = \pm 1.2$ $\rho = 0.97$
2	$3T + 10$ $\sigma = \pm 6.6$ $r = 0.71$	$5T^2 - 23T + 40$ $\sigma = \pm 3.8$ $\rho = 0.93$	$-0.8T + 16$ $\sigma = \pm 3.3$ $r = -0.81$	$0.2T^2 - 5T + 34$ $\sigma = \pm 2.3$ $\rho = 0.93$	$-0.9T + 17$ $\sigma = \pm 3.7$ $r = -0.75$	$0.2T^2 - 4T + 30$ $\sigma = \pm 3.2$ $\rho = 0.83$
3	$5T + 3$ $\sigma = \pm 5.2$ $r = 0.77$	$5T^2 - 24T + 40$ $\sigma = \pm 3.5$ $\rho = 0.92$	$-0.7T + 16$ $\sigma = \pm 4.3$ $r = -0.64$	$0.2T^2 - 5T + 36$ $\sigma = \pm 3.3$ $\rho = 0.85$	$-1T + 17$ $\sigma = \pm 2.1$ $r = -0.91$	$0.2T^2 - 4T + 29$ $\sigma = \pm 0.9$ $\rho = 0.99$
4	$3T + 10$ $\sigma = \pm 5.2$ $r = 0.42$	$7T^2 - 35T + 50$ $\sigma = \pm 2.6$ $\rho = 0.93$	$-0.7T + 17$ $\sigma = \pm 3.2$ $r = -0.77$	$0.2T^2 - 4T + 31$ $\sigma = \pm 1.5$ $\rho = 0.96$	$-0.8T + 15$ $\sigma = \pm 2.8$ $r = -0.74$	$0.3T^2 - 5T + 32$ $\sigma = \pm 1.1$ $\rho = 0.97$
5	$3T + 7$ $\sigma = \pm 3.3$ $r = 0.76$	$T^2 - 4T + 14$ $\sigma = \pm 2.9$ $\rho = 0.85$	$-0.6T + 15$ $\sigma = \pm 2.7$ $r = -0.76$	$0.1T^2 - 4T + 30$ $\sigma = \pm 2.2$ $\rho = 0.86$	$-0.3T + 10$ $\sigma = \pm 1.3$ $r = -0.65$	$0.0T^2 - T + 12$ $\sigma = \pm 1.3$ $\rho = 0.65$

N o t e. σ is the computation error; r is the correlation coefficient of the linear dependence; ρ is the correlation coefficient of the power dependence.

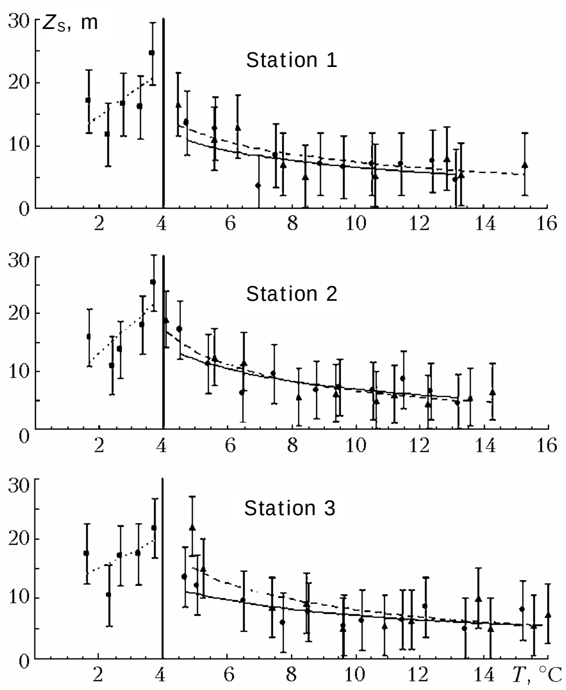

Fig. 1. Relation of the transparency by Secchi disk and the water surface temperature at stations 1–3 at the trench Listvenichnoye–Tankhoy in different hydrological seasons (ÿ – spring, þ – summer, ı – autumn), trend lines (dotted line for spring, dashed line for summer, and solid line for autumn) at the confidence level of 95%.

Analysis of the results

In spring, according to the anomalous behavior of the temperature dependence of the water density, the warming-up of upper layers is accompanied by the density increase and the development of the temperature convection. In contrast to many other lakes, this period for Lake Baikal lasts more then one month because of its great depths. The convection and dynamic mixing result in sequential transformation of T profile and in increase of the upper mixing layer (H) up to values several times exceeding the value of Z_S. The T dependence of H (m) obtained from observation data is nonlinear and can be described by the expression

$$H = 29.7T^2 - 84T + 107.3 \ (r = 0.96).$$

Vertical mixing intensity reaches its seasonal peak in the period under study.[6] The intensity can be characterized by the vertical mixing coefficient K_z and the vertical diffusion rate U (see Table 2). The calculations show that K_z and U increase with the temperature rise, especially in the range T from 2.5 to 3.5–3.6°C (the temperature of mesothermal maximum at a depth of 200–250 m).

Table 2. Mixing layer depth H and vertical exchange characteristics in spring according to observations in 1970–1978

T, °C	1.0	1.5	2.0	2.5	3.0	3.5	4.0
H, m	52	54	61	68	104	222	226
K_z, cm^2/s	4	6	8	12	150	330	70
U, m/day	0.7	1.0	1.1	1.5	12.5	13.0	2.7

N o t e. K_z was calculated by the procedure described in Ref. 7; diffusion rate was determined by data on K_z supposing equality of the scale of mixing and H-layer.

The active mixing provides for conditions for suspension drifting into deep layers of the lake and decreasing its concentration in Z_S-layer, that is confirmed by observations of the phytoplankton distribution. Thus, according to Fig. 1 from Ref. 8, in May, 1972, high and uniform phytoplankton concentrations were registered in Southern Baikal to a depth of about 50 m. In June, this layer increased up to 200 m and the concentration values in the upper

50 m sub-layer decreased several times in comparison with values in May. Hence, in the period of spring convection, the temperature rise is accompanied by decreasing of the organic suspension concentration in upper layer of the lake through suspension redistribution in deeper water layers. Therefore, as the temperature rises, the transparency by Secchi disk increases (on the average, 4 m per 1°C). Observations for the trench show that the transparency by Secchi disk reaches its peak (35–39 m) at Ò ~ 3.5–3.6°Ñ, when the intensity of vertical exchange is maximal for the season under study and *H*-layer dimensions correspond to maximal depth of the temperature convection development.[3] After that, the high transparency holds till the end of the season.

In summer, at $T > 3.96$°C, the convection stops, and the epilimnion (up to 5–10 m) is forming with a thermocline under it. The transparency in this season is connected with changing content of the organic suspension with the predominance of phytoplankton, which growth is directly stipulated by the water temperature. There is an inverse relation between Z_S and T with decreasing Z_S by 0.6–0.9 m per 1°C. At the same time, further increase of $T > 10$–12°Ñ does not decrease the transparency. Probably, the causes are in intensification of the stratification in the thermocline, weakening of vertical exchange and inflow of biogenic elements, necessary to water plants, from lower layers to the trophogenic one.

In autumn (September–November), the temperature convection and wind mixing lead to progressive increase of the depth of the layer of the temperature (density) jump, which holds, nevertheless, to the end of the season. Together with lowering T, this causes a worsening of conditions for phytoplankton growth, a decrease of organic suspension content in the Z_S-layer and increase of the transparency (~ by 0.8–1 m per 1°C). The T dependence of Z_S is practically "symmetric" to the dependence obtained for summer, the analytical expressions also differ insignificantly (see Table 1). This demonstrates the leading role of the same factors for summer and autumn change of suspension content.

Discussion

Thus, the connection between the transparency by Secchi disk and the water temperature in Lake Baikal is established for hydrological seasons of spring convection, summer warming-up and autumn cooling. Two factors cause the connection: 1) the direct temperature effect on the content of organic suspension in upper layers of the lake in summer and autumn; 2) the temperature effect on the vertical mixing responsible for suspension redistribution in the water layer exceeding the transparency by Secchi disk. The sign of the connection differs in different hydrological seasons depending on the relationship between the above-mentioned factors.

In spring, the mixing caused by anomalous increase of the water density with elevation of T from 0 to 3.96°C plays a leading part in changing the transparency. The dramatic enhancement of activity of vertical mixing with warming-up causes the decrease of suspension density in the upper layer due to suspension drifting into deeper layers (no less than 200–250 m in the end of the season). This determines a positive connection between T and Z_S.

In summer and autumn, the effect of the temperature rise on the phytoplankton growth is the determining factor under the conditions of stable stratification of upper water layers, therefore, the connection between the transparency and the temperature is reverse. However, the connection practically vanishes at $T > 10$–12°Ñ, apparently, due to limited growth of water plants caused by weakening of inflow of biogenic elements from lower layers through the enhanced thermocline.

Consider the possibility of using the relations in the analysis of the long-term changes in the lake ecosystem.

The long-term observations (1950–1987) of the transparency were carried out only near Bol'shie Koty[9] as opposed to the continuous temperature measurements conducted at the meteorological stations of Southern Baikal for no less than 40–60 years. The possibility to reconstruct the values of Z_S by the T data for a long period is evident. The data on T measured in Listvenichnoye were used to reconstruct the transparency for 1940–2000. They were reduced to the conditions of the open lake by the procedure from Ref. 6 and then averaged by 8-year moving filter. In averaging, it was taken into account that the relationship between phytoplankton characteristics and the temperature manifests itself in a period no shorter than 5 years.[4] The reconstructed in such a way Z_S-values give us an idea of the trend in long-term transparency changes rather than of its particular values in individual years.

Unexpectedly, the results of reconstruction have revealed different signs in the trend of the transparency change by the Secchi disk in 1940–2000 for spring (positive) and for summer and autumn (negative) (Fig. 2), which can be explained by the increased warming in this period nearby Lake Baikal, accompanied by the temperature rise in upper water layers during the iceless period.[10] The decrease of Z_S in summer and autumn reflects the increase of biologic suspension content in upper water layers as their temperature rises. The increase of Z_S in spring at $T < 4$° is connected with the fact that the water temperature rise corresponded to the phases of more active vertical mixing and, correspondingly, a decrease of suspension quantity in the upper layer of the lake in that season. The comparison of these results with observation data of 1950–1987 near Bol'shie Koty (see Fig. 1.54 from Ref. 9) shows that the computing method simulates the realistic long-term trends in the change of the transparency by Secchi disk in spring and summer, that can be considered as a verification of the accepted interpretation of relations between the temperature and transparency.

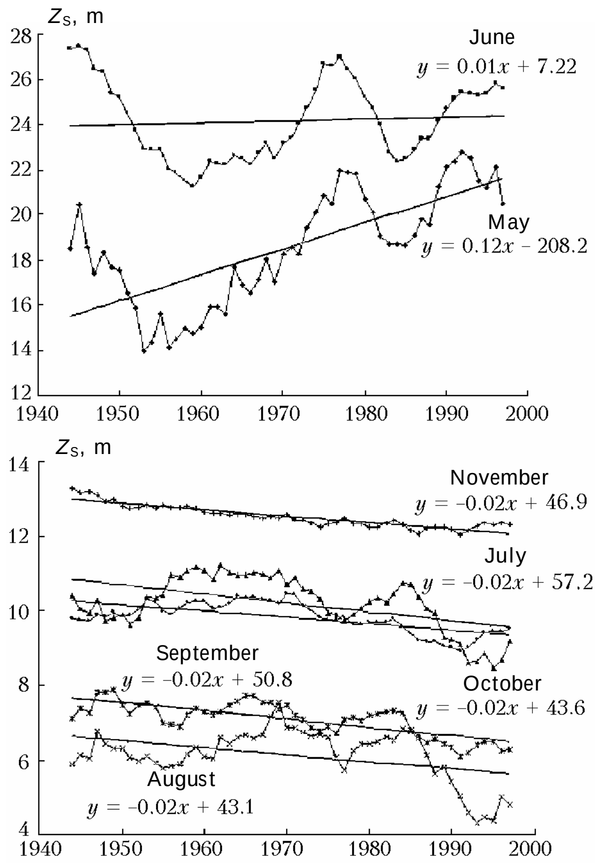

Fig. 2. The reconstructed values of the transparency by Secchi disk.

Conclusion

The obtained dependences testify a possibility, in principle, to use them in the qualitative analysis of trends in long-term changes in the ecosystem of Lake Baikal under the climate impacts. It is also true for biologic characteristics of upper water layers, whose reliable correlation with the transparency by Secchi disk is established both for seas[11,12] and for inland water reservoirs including Lake Baikal.[13,14]

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