Limnology and Freshwater Biology 2018 (1): 10-14 DOI:10.31951/2658-3518-2018-A-1-10

Original Article

ISSN 2658-3518

LIMNOLOGY FRESHWATER BIOLOGY

www.limnolfwbiol.com

Heat balance of Lake Baikal and the relationship of its ice-thermal and water regime with global atmospheric circulation in the Northern Hemisphere during the modern period

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ABSTRACT. The article presents a summary of the most important results obtained during the studies of the heat balance at Lake Baikal since the 1930s. The systematic regime measurements of water temperature initiated in Limnological Institute since 1970 indicated the features of the spatial structure and temporal changes in the elements of the Baikal heat balance. We have determined the magnitude of the annual evaporation from the surface of Lake Baikal by the independent method considering the data on temperature of the water column. We have investigated one of the main renewal processes of deep and near-bottom Baikal waters associated with thermobaric effect. As a result of this effect, the water renewal and aeration in the near-bottom layer annually occurs under certain hydrological conditions. We have determined the vertical flows of mass, heat and gas exchange of the upper and deep layers in Lake Baikal.

We have studied the effect of changes in the characteristics (indices) of the atmospheric circulation in the Northern Hemisphere on the variability of the characteristics of climate and ice-thermal regime at Baikal, i.e. air temperature and water surface temperature, ice thickness, as well as dates of ice phenomena during the modern period. Anomalies of the atmospheric circulation are most obvious in the ice processes. We have found the relationship between the water temperature of the warm (May-September) period and the indicators of the zonal circulation (positive relationship), as well as indices of the formations blocking the western transfer (negative relationship). There is an obvious effect on the water surface temperature of the winter circulation indices. We have shown that these changes are associated with the fluctuations in the intensity of the zonal circulation and the baric formations blocking them. There is the effect of circulation on the moisture characteristics (precipitation and runoff), but it is complicated by large differences in climate within the Baikal catchment area.

Keywords: Baikal, water-atmosphere heat fluxes, evaporation, intrusions and renewal of nearbottom waters, atmosphere circulation, hydrological processes

1. Introduction

In 1934, Russian Academy of Sciences convened the first meeting on limnology. G.Yu. Vereshchagin and L.L. Rossolimo much contributed to its organization. The meeting dealt with the problems and objectives of limnological research, as well as methodology issues. G.Yu. Vereshchagin identified the research areas concerning Baikal (Vereshchagin, 1937) and headed their development at the Baikal Limnological Station (BLS):

1) the origin and history of Baikal, as well as of its flora and fauna;
2) specific lacustrine processes characteristic of deep lakes;
3) the relationship of the lake water masses with the environment;
4) limnological forecasts.

Work in areas 1) and 2), had not only theoretical, but also practical importance, since their results could be used to explain the rational development of natural (water, biological, recreational, etc.) resources of Baikal and Siberia. Such work required a significant expansion of the material and human potential of the research team, which could not be implemented in the prewar period. This became possible only in the 60-70s of the past century, when the demand for the rapid development of the natural Baikal resources, primarily the hydropower resources of the Angara River, increased significantly. During this period, the Baikal

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Limnological Station (which has become Limnological Institute since 1961) significantly boosted the personnel and technology. The Institute received almost all-weather vessel with modern navigation and scientific equipment for physicochemical and biological investigations throughout the water column.

2. Heat balance of Lake Baikal

The first stage in this research area was a comprehensive study of the heat balance in Baikal (Verbolov et al., 1965). Data were obtained on the average thermal interaction of the lake with the atmosphere for the long-term period and in certain years (Verbolov et al., 1965). For the complete closure of the heat balance equation, one of the main components, the annual heat budget of the entire water mass of Baikal, was determined experimentally (Shimaraev, 1996). It was based on the long-term systematic observations of the water temperature in the pelagic zone of the lake in 1950-1996. Considering these data, the average value of annual evaporation from the surface of Lake Baikal (400 mm), was first determined by the independent heat balance method.

Temperature monitoring in all parts of the lake identified the main processes of vertical heat exchange, as well as patterns of structure and dynamics of the temperature field at different depths (Shimaraev, 1977; 1996; Shimaraev and Granin, 1991; Shimaraev et al., 1994).

The analysis of the stratification conditions and the mechanism of free convection has implied the division of the Baikal water column into two main zones by the processes of heat transfer. In the upper zone, the water temperature (T) twice a year passes the value T_{md} (3.96 °C), which is accompanied by the change in T stratification (in spring – from reverse to direct, and in autumn – from direct to reverse) and development of free temperature convection (Shimaraev et al., 1994). Convection in combination with wind mixing in the spring provides active heating, and in the autumn – cooling of the waters in the upper zone. In the spring, convective-wind mixing is limited to the position of the mesothermal maximum temperature (T_{mm}), average 220-250 m, with a temperature $T_{mm} = T_{md}$, that was formed by convective-wind mixing at the end of the previous year. Such depth determines the dimensions of the upper zone of Baikal, which normally exceeds average and maximum depths of most deep freshwater dimictic lakes in the world.

3. Intrusions

Deep zone of Lake Baikal is close to warm tropic lakes or seas by the constancy of direct temperature stratification ($T > T_{md}$), positive or negative coefficient of thermal expansion and weak stability. Thermal convection in this zone can occur as a forced convection, when cold water with $T < T_{md}$ ascends from the upper zone (Shimaraev and Granin, 1991; Weiss et al., 1991). This ascending is possible with vertical circulations in the field of currents (upwelling), with water compac-

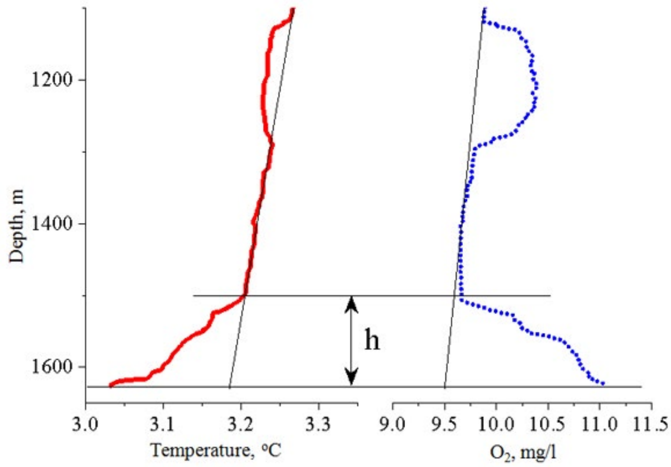

Fig. 1. Vertical distribution of temperature T and concentration of dissolved oxygen O_2 in near-bottom cold layer h (1500-1626 m) in 7 km from Izhimey Cape of Central Baikal on June 6, 2012; secondary intrusion is recorded by decrease in T and increase in O_2 in a layer of 1130-1300 m.

tion at the front of the spring thermal bar and strong wind forcing. The ascending leads to violation of the stratification stability (thermobaric instability) at the upper boundary of the zone as well as occurrence of intrusions of cold water lowering to the horizon with the equal temperature (density) and cooling the waters in deep and near-bottom zones of Lake Baikal. Deep intrusions are associated with the renewal of deep waters and formation of a cold near-bottom layer with a thickness of up to 100-222 m or more (Fig. 1).

The actual data on annual heat budget of the entire water mass of Lake Baikal allowed applying the method of heat balance to independently determine the annual evaporation rate from the surface of Baikal. It was equal to 400 mm, which corresponds to calculations using semi-empirical formulas that consider the stratification character of the atmosphere in the near-bottom layer.

4. Ice-thermal and water regime of Baikal and the atmospheric circulation in the Northern Hemisphere in 1950-2017.

The problem of the effect of climate on lakes is one of the pressing problems in limnology. For Baikal, this effect is revealed as a change in the abiotic components of the ecosystem, which can affect the biota of the lake (Shimaraev, 1977; Afanasyeva, Shimaraev, 2006; Izmest'eva et al., 2015). Structure of modern climate changes includes a 'secular' trend of warming and intrasecular fluctuations exceeding this trend in scale that are caused by the atmospheric circulation. We have studied the effect of changes in the global atmospheric circulation in the Northern Hemisphere on the ice-thermal and water regime of Baikal from the middle of the 20th century to the present.

Regression equations of air temperature (T_a) with circulation indices describe 38-66 % of the changes in annual T_a, and only 17 % – in winter, spring, summer, and autumn T_a (Sizova, 2017). The main role in chang-

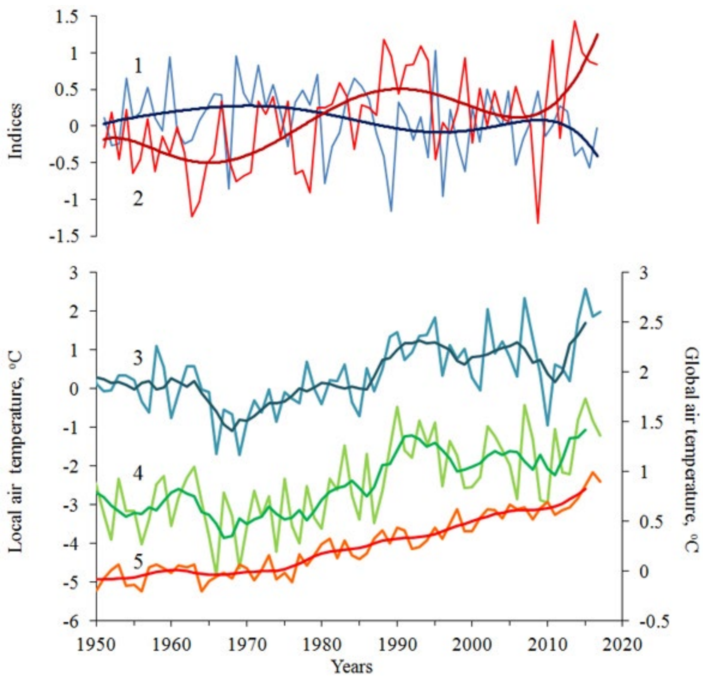

Fig. 2. Changes in SCAND (1) and NAO (2) indices in 1950-2017, as well as their polynomials and air temperatures at weather stations Babushkin (3) and Nizhneangarsk (4), as well as in the Northern Hemisphere (5), and their smoothed values for 5 years.

ing T_a belongs to the zonal transfer indices (AO and NAO), as well as the transfer blocking indices (SCAND, Sh). The effect of other circulation indicators, as a rule, is secondary in importance. The nature of the change in circulation indices and T_a indicates the end of the intasecular T_a cycle in 2010-2011, which has begun as early as in 1970 (Fig. 2).

The effect of circulation on T_a during the cold season determines its leading role in changing the characteristics of the ice regime (Livingstone, 1999; Todd and Mackay, 2003). During the intensification of the zonal transfer and increase in its indices (1970-1995), the T_a values increase, freezing dates gradually delay, the ice breaks up earlier, and the maximum ice thickness decreases (Fig. 3). Reverse trends in the changes in characteristics of the ice regime occur during weakening of the zonal transfer and strengthening of the blocking mechanisms of SCAND and Sh circulation, in 1950-1970 and 1995-2009 (Sizova, 2017).

The relationship between the date of the ice-breaking at Lake Baikal and the surface water temperature (T_w) explains the effect of the mean values of the circulation indices in December-March to the mean value of the Baikal water temperature in May-September (Shimaraev, 2007). The relationship of T_w with the zonal transfer indices NAO, AO, EA, and EAWR is positive (r = 0.26÷0.54), and with the indices SCAND and Sh is negative (r = -0.27÷-0.39) in all parts of the lake. The multiple regression equations describe 31 % of the T_w variability in Southern Baikal, 48 % – in Central Baikal, and 22 % in Northern Baikal, with S±0.7-0.9°C. AO (62 %,) make the predominant contribution in the southern part, NAO (61 %) – in the central part, and SCAND (70 %) – in the northern part of the lake.

Precipitation is associated with SCAND (r = -0.32) in the spring, with POL and PNA (r = -0.27÷-0.31) – in the autumn, with AO – from May to October (r = 0.26), as well as with AO (r = 0.30) and SCAND (r = -0.29) – in general, during a year. The regression equations for these periods describe 14-22 % of the precipitation variability.

The circulation processes predominantly influence on the total water flow in Lake Baikal and runoff of the main tributaries from June to October (R^2 = 0.32, S ± 8.7 km^3). The EAWR indices influence the changes in the total annual inflow of rivers and the annual runoff of the Selenga River, WP indices – the annual runoff of the Barguzin River, and EA indices – the annual runoff of the Upper Angara River. Atmospheric circulation processes describe approximately 28 % of the annual runoff of the Selenga River, 41 % of the annual runoff of the Barguzin River, and 16 % of the

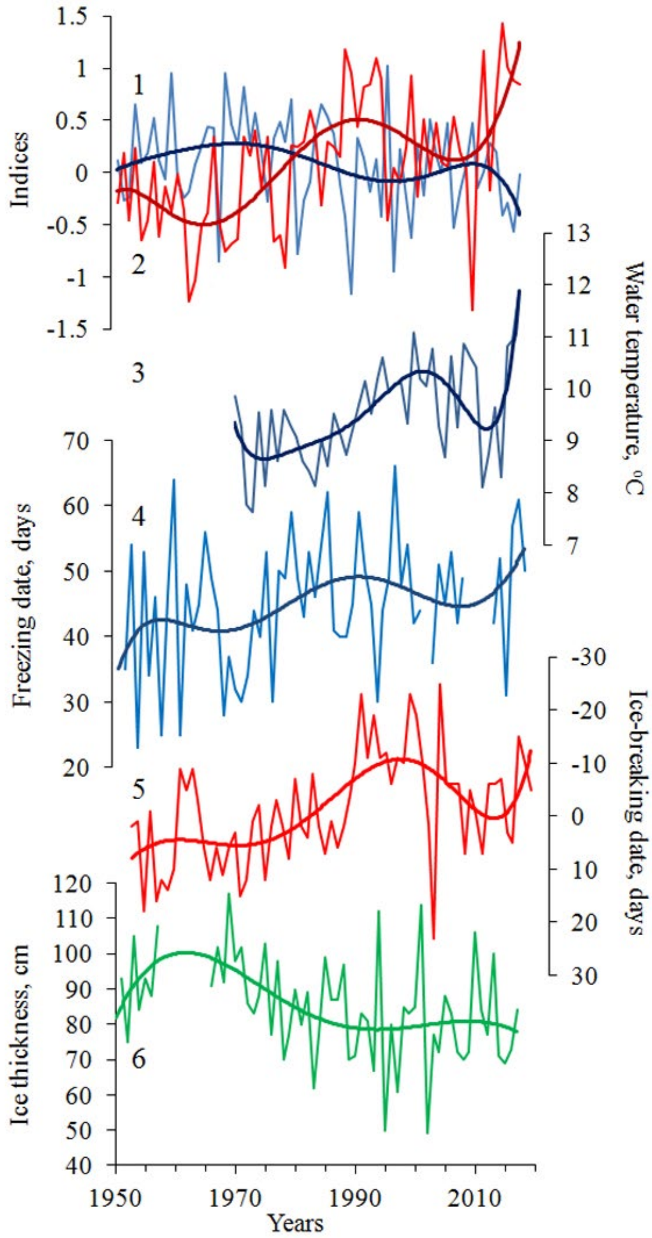

Fig. 3. Changes in SCAND (1) and NAO (2) indices in 1950-2017, as well as water surface temperature (3), dates of freezing (4) and ice-breaking (5), ice thickness (6), and their polynomials.

annual runoff of the Upper Angara River.

The role of meteorological factors for the rivers of the basin is ambiguous. Change in precipitation explains 51 % of the fluctuations in the total annual inflow into the lake, 12 % of the annual runoff of the Upper Angara River and 34 % – of the Selenga River, as well as 62 % of the fluctuations of the inflow of the Barguzin River. The effect of the air temperature on the total inflow from the entire basin and the runoff of the Barguzin River is very small, and its contribution in the variability of the inflow is statistically insignificant. In case of the Selenga River, this contribution increases up to 8 %, and in case of the Upper Angara River, it reaches 87 % (Sizova, 2017).

The reason for the differences in trends of the change in the inflow of the main Baikal tributaries is the different reaction of their water content to the warming due to differences of natural conditions in their basins.

The heterogeneity of heat-transfer properties of the underlying surface (represented by water or soils) causes a different reaction of the ice-thermal and water regime in separate parts of Lake Baikal and its basin to the climate change (Sinyukovich et al., 2013; Sinyukovich and Chernyshov, 2017; Shimaraev et al., 2018). The differences in the water regime on the territories of the Baikal watershed most clearly indicate it. Thus, in the basin of the Selenga River predominated by the territories with moisture deficit (more than 80% of the area) the warming leads to the increase in the deficit due to the high loss of moisture by evaporation, which causes a decrease in the Selenga water runoff. On the contrary, the warming of the Upper Angara and the Barguzin rivers, which basins are located within the mountain frame of the Baikal Basin having a moderate moistening, with permafrost can involve the additional moisture to the nourishment of the rivers. This is especially obvious for the Upper Angara River.

Less obvious effects include poor relationship between the thickness of the ice cover and the atmospheric circulation in Northern Baikal due to the increase in the thickness of snow on ice, which reduces the thermal conductivity of the ice-snow cover.

During the summer heating of the lake, a more active vertical exchange due to upwelling (Troitskaya et al., 2015) in Southern Baikal results from the relatively weak heating of the upper water layers compared to Central and Northern Baikal.

Intracellular fluctuations of the elements of the ice-thermal and water regime caused by the atmospheric circulation should be taken into account in the long-term prognostic estimates of the changes in the ecosystem of Lake Baikal.

Acknowledgments

The study was performed within the framework of the State Task No. 0345-2016-0008 (AAAA-A16-116122110065-4) “Assessment and Forecast of the Ecological State of Lake Baikal and Adjacent Territories under Conditions of Anthropogenic Impact and Climate Change”.

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