Specific Features of Cold Bottom Intrusion in Baikal According to Observations in 1993—2009

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Abstract—The specific features of cold bottom intrusion in Baikal are considered based on the results of observations of 1993–2009. It is shown that the intrusion-related renewal of bottom water takes place not regularly and not simultaneously in different hollows. Its maximums were recorded in Southern Baikal in 1997 and 2007, in Middle Baikal in 1995, 2006, and 2009, and in Northern Baikal in 1997 and 2009. In these years, the volume of cold bottom layer in some hollows reached 200–470 km$^3$ and its total cooling reached $-20$ to $-60$ MJ $10^9$. Cold intrusions were more frequent and had greater effect on the bottom layer in Southern Baikal than in other parts of the lake. The intrusions, especially in the years of their active development, are shown to cause water cooling in both the bottom layer and the major part of the deep-water zone of all hollows.

Keywords: Baikal, deep convection, bottom layer, thermal effect of intrusions, space and time features.

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INTRODUCTION

Studying the stratification and the development of convection in Baikal has shown that under the conditions of decreasing temperature, maximal water density (pressure), with increase in the depth in the spring and before freezing, a thermobaric instability appears in the layers of the upper zone, leading to cold-water intrusion into deep and bottom layers [4, 14]. This instability can be caused by atmospheric impact [14], compression during mixing at the front of thermobars [12, 13], salinity variations [6], chimney-type phenomena [15], and upwelling. The cooling of deep layers in spring and summer, noted earlier [3, 13], can be explained by intrusions—a major mechanism of renewal of deep Baikal water and its aeration with oxygen. Intrusions, penetrating to the depth, lead to the formation of a cold bottom layer, whose characteristics contain information about the intrusions.

Studying cold intrusions as a renewal mechanism deep water is mostly based on the records of bottom temperature in two measurement points in Southern Baikal—in its center (1461 m) in 1995–1997, and since 2000, in the western part in the mounting site of a neutrino telescope (NT) (depth of 1352 m) [11, 15]. In the work period, cold-water intrusion was recorded in June 1997 and 2000, in December-January 2002–2003, 2003–2004, January 2005, February 2006, and early January 2007. No such data are available on other parts of Baikal. The limited number of measurement horizons (at the NT site, at 2 and 50 m from the bed) and the local character of observation sites do not allow one to gain a comprehensive idea of the size of the cold bottom layer, and the issue of the spatial extent of the process remains open. In this study, data of many-year temperature surveys of the entire Baikal are for the first time used to study cold intrusions.

MATERIALS AND METHODS OF OBSERVATIONS

Materials of one-time surveys of Baikal in May—September 1993, 1995, and 1997–2009 were used. The surveys were commonly carried out within short periods (6–12 days) and included temperature $T$ sounding down to the bed at stations on a longitudinal section and five transverse sections with a total number of stations up to 18–30 in Southern, 10–11 in Middle, and 13–17 in Northern Baikal. Measurement results provide detail information about $T$ distribution in the deep part of the lake and allow all cases of intrusions penetrating to the bed to be identified. Their sign was assumed to be the presence of a cold bottom layer (CBL), identified by an abrupt (up to 8 times) increase in the vertical temperature gradient $\partial T/\partial z$ relative to its values in the overlying layers of the deep zone (Fig. 1). The evaluated characteristics were the height of CBL $h$, the differential of $T$ from the upper to the lower boundary of the layer $\Delta T$, and the vertical gradient $\partial T/\partial z$, background gradient $\partial T/\partial z_b$ in the 200–400-m water bed above the bottom layer, which was taken as typical for $T$ distribution in the bottom zone not disturbed by intrusions. The thermal effect of cold intrusions is evaluated by the heat “deficit” $\Delta Q_{\text{def}}$ in CBL [7]. It is evaluated as the difference between the actual heat reserve of this layer and its reserve corresponding
to the background $T$ distribution. The final expression for calculating $\Delta Q_{(–)}$ has the form

$$\Delta Q_{(–)} = \rho c_p \times 0.5h(T_{\text{act}} - T_{\text{hyp}}),$$

where $\rho$ and $c_p$ are the density and specific heat of water, $T_{\text{act}}$ is the actual, and $T_{\text{hyp}}$ is hypothetical temperature at the bed, obtained by linear approximation of the background temperature profile (Fig. 1). Data of all observations were used to determine CBL characteristics averaged for each survey (Table 1), allowing one to analyze the spatial and temporal features of bottom intrusions in Baikal. In the analysis of CBL, it was taken into account that their values can be underestimated, since the formation of this layer under the effect of intrusions could take place before the temperature surveys.

**DISCUSSION OF RESULTS**

The large number of cases with CBL (70% of the total number of surveys) suggests a frequent (once in 1–3 years) formation of cold intrusions in all parts of the lake the persistence of CBL from May to August. Averaged data (Table 2) demonstrate a tendency toward an enhancement of CBL by July, which is possible at the development of intrusions during the major portion of June because of the late (in the pelagial zone of the lake—in late June—early July [3]) passage to summer stratification. By August, $\Delta Q_{(–)}$ decreases on the average by 5 times, whereas the layer size $h$ decreases by only 70%. In early autumn (September 1998–2001, except for 2000 in Southern Baikal) CBL practically disappears under the effect of exchange processes.

Observations demonstrate both mass and local character of intrusions in individual years. In Southern Baikal, in years of mass intrusions (1997, 2000, 2003–2005, 2007, 2008), CBL occupied the major portion of the hollow with depths >1100–1200 m. Its height was above 100 m (with a mean of 131 and maximal of 270 m in 1997, 2007), and the distribution in the hollow was relatively uniform. The values of $\Delta T$ were large (mean of $-0.025^\circ C$, up to $-0.12^\circ C$ in July), as well as heat deficit $\Delta Q_{(–)}$ (mean of $-7.2$ MJ m$^{-2}$, maximums of $-11.9$ in July 1997, $-23.7$ MJ m$^{-2}$ in July 2007). Note that almost all cases mentioned above fell in years with an appreciable drop in $T$ in its registration points near bed [11, 15]. In June 1993, 2002, CBL was detected only in the center of the hollow below 1400 m, and in May 2006 and 2009, only south of Selenga R. delta at depth of 1000 m (Table 1). The small mean values of $h$ (51 m) and $\Delta Q_{(–)}$ ($-1.8$ MJ m$^{-2}$) in those years indicate to a low activity of intrusions, which were most likely of a local character.

In Middle Baikal, almost all cases of intrusion were recorded in the area with depths >1500 m and in some years, >1300 m. As compared with Southern Baikal, CBL height is less (with a mean of 85 m and the maximum of 200 m in July 2007), $\Delta T$ differential is greater (mean of $-0.045^\circ C$, maximum of $-0.128^\circ C$ in June 2006), and the value of $\Delta Q_{(–)}$ ($-7.2$ MJ m$^{-2}$) is the same. Maximums of $\Delta Q_{(–)}$ ($-12.2$ to $-12.7$ MJ m$^{-2}$) fell in May 1995, June 2006, and May 2009.

Intrusions in Northern Baikal commonly occurred in the area with depths >850 m, though in some years (2004, 2006, 2009), in the entire central part below 750 m. The mean value $h = 84$ m (with a maximum of 289 m in June 1997), $\Delta T = -0.038^\circ C$ ($-0.1^\circ C$ in June 1993). The mean value of $\Delta Q_{(–)} = -4.2$ (in July 1997, $-11.4$ MJ m$^{-2}$) was less than in other parts of the lake. During local intrusions in 1993 and 2007, the layer $h$ (~40 m) was much less, while the value of $\Delta Q_{(–)}$ was near the mean level.

The comparison of mean and maximal values of $\Delta Q_{(–)}$ in different hollows suggests that overall for the period, the cooling of bottom layer by intrusion was stronger in Southern Baikal.

Time variations. In each hollow, intrusions were irregular and featured different intensity in individual years. Years with CBL alternated with years when this layer occurred in isolated sites or was absent. Water renewal in different hollows was not synchronous, as can be seen from different values of $\Delta Q_{(–)}$ and $h$ in the survey years, as well as from the absence of coincidence of years without intrusions (Table 1). Thus, in 1993 and 1995, in the presence of distinct signs of bottom water reneal in Middle and Northern Baikal, no such process took place in Southern Baikal, the fact that was confirmed by the analysis of mass balance of $^3$He isotope [9]. In July 1997, active renewal of bottom waters was recorded only in Southern and Northern Baikal, while in 2000, 2003, 2005, and 2008, it appeared only in Southern Baikal. Simultaneous appearance of CBL at several stations in each hollow, indicating to the activity of intrusion in the entire lake, was recorded only in 2002 and 2004. Earlier, such case