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Annual temperature regime of the shallow zone of Lake Baikal inferred from high-resolution data from temperature loggers

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ABSTRACT. Annual changes in temperature characteristic of the shallow zone during 2017-2022 have been studied in this work. Dataset was contrasted based on 8 transects located in South, Central and Northern Baikal at depths of 3, 4, 6, 12, 15 and 26 m. Temperatures were measured every 1.5-3 hour. It was determined that modal values of maximal heating of the shallow zone at all stations and depths were 15-16°C, however, distribution of maximal temperatures of South Baikal shifted toward the low temperatures, and these maximums could be only 9-10°C. Temperature regime of the shallow zone during warm seasons is characterized by sharp changes due to wind mixing and upwelling, when temperature drops dramatically from 16-18°C to 4°C for the 1-1.5 day. In most cases, the duration of stabile temperature condition without wind mixing was 4 days. On average, upwelling events occurred 5 times (maximum - 13 events) from July to November. As a result of wind mixing, the shallow zone is characterized as moderately warm with average temperatures of 6-7°C from June to November. A temperature effect on the shallow zone of Lake Baikal due to the Global warming is smoothed by cooling of the zone by deep waters during upwellings.

Keywords: Lake Baikal, shallow zone, temperature regime, upwelling, renewal

1. Introduction

Seasonal changes in temperature characteristics of Lake Baikal are well studied, and it is found that main temperature changes under force of wind and air temperatures occur in the uppermost 250-300 m layer. There are three temperature stratification of Lake Baikal: i) direct stratification – temperature decreased toward the depth (July-September); ii) inverted stratification-temperature increased toward the depth (November-May); iii) homothermy – temperature along 250-300 m depth is equally distributed (the end of May-June, and the middle of October-November). However, details of studies of temperature regime of the shallow zone (0-20 m) are still rare. In most cases, temperature regime of the shallow zone and the upper layer of the pelagic zone are characterized based on single measurements from research vessels during June-October, because, navigation on Lake Baikal begins from the end of May and ends in November.

Although the shallow zone occupied only *ca.* 5% from the entire Lake Baikal, this area is very important for benthic aquatic biota. For example, four vegetated benthic belts with approximately 88 endemic species occurred along 0-20 m depths (Izhboldina, 2007). Thus, endemic sponge *Lubomirskia baikalensis* is most abounded and may form “forests” at depths of 5–15 m. In addition, species diversity and numbers of mollusks are maximal at depth of 4-20 m (Sitnikova, 2006; Maximova et al., 2012).

In the last decade, expansion of benthic green alga *Spirogyra* into the shallow zone of Lake Baikal from coastal bays and streams is registered, which is an anomaly for Lake Baikal (Timoshkin et al., 2016, Ozersky et al. 2018). The endemic species have tended to reduce their contribution to the formation of the total biomass of plankton and benthos in Lake Baikal (Kravtsova et al., 2021). One of the hypotheses is intensive heating of the shallow zone as a result of the Global warming as a key cause for the formation of conditions of expansion of *Spirogyra* and changes in the Baikal phytoplankton assemblages.

In the Northern Hemisphere, the temperature rise has been recorded since the mid–1970s, thus, average annual temperature anomalies were +0.81°C for Globe, +1.48°C for the Northern Hemisphere, +2.02°C for Russia, and +1.28°C for the Baikal region (Potemkina et al., 2018). However, there is no union temperature trend for surface water of the entire Baikal. For example, the trend was 0.28, 0.38 and 0.32°C/10yr

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for western, eastern coast and all Baikal, respectively (Shimaraev and Troitskaya 2018). In addition, there is a strong spatial difference of trends from 0.11 (Lystvyanka, South Baikal) to 0.68 (Nizhneangarsk, Northern Baikal) °C/10yr (Shimaraev and Troitskaya, 2018).

In this study, we attempted to determine the features of temperature regimes of the shallow zone (3-15 m depth) from 2017-2022 based on high-resolution records using temperature loggers.

2. Method and setting

Temperature logger - model DS1921Z-F5 with the range from -5.5 to +26.25°C and accurate to 0.125 °C was used in this study. Loggers were installed along 8 standard transects from 3 to 15 m depth from 2017 to the present (Fig.1) These transects are located in South Baikal – Ulanovo station, Listvyanka, Bolshie Koty, Central Baikal – Aya Bay station, Ukhan, Svyatoy Nos station and Northern Baikal – Capes Elokin and Turaly (Fig.1). On Listvynka station was installed additional logger at 26 m depth. Temperatures were measured every 1.5 hour during June-September and every 3 hour during September-June.

Daily Data about air temperatures and wind parameters from weather stations were used: Kultuk station – South Baikal, Uzure station - Central Baikal and Solnechnaya station – Northern Baikal. The datasets were taken from www.rp5.ru.

3. Results and Discussion

3.1. Maximal heating of the shallow zone

Maximal heating occur almost at the same time on all Baikal area in the second half of August-early September, and there is no significant time lag between heating of 3 and 15 m depth. This annual heating is synchronous with maximal annual air temperatures (Fig. 2).

There is no drastic offset in maximal air temperatures between years, however, the offsets are observed in maximal water temperatures (Fig.2). Modal values of maximal temperatures for all stations and depths are 15-16°C (Fig. 3), but Elokhin station showed the height heating up to 19°C at depth of 3m. On the other side, distribution of maximal temperatures of South Baikal shifted toward the low temperatures, when these maximums could be only 9-10°C (Fig. 3). It can be evidence of intensive mixing between surface and deep layers in South Baikal due to high wind activity. Low heating of water and high wind activity in 2022 confirms this assumption (Fig.2).

It should be noted that heating of the shallow zone sharply accelerates when the water temperature reaches 4°C, and this accelerate is synchronic with the highest air temperatures (Fig. 2).

Temperature difference between 3 and 15 m depths is more pronounced during July. These offsets are *ca.* 2-3°C in South and Central Baikal, and can increase up to 10°C in Northern Baikal. However, temperature

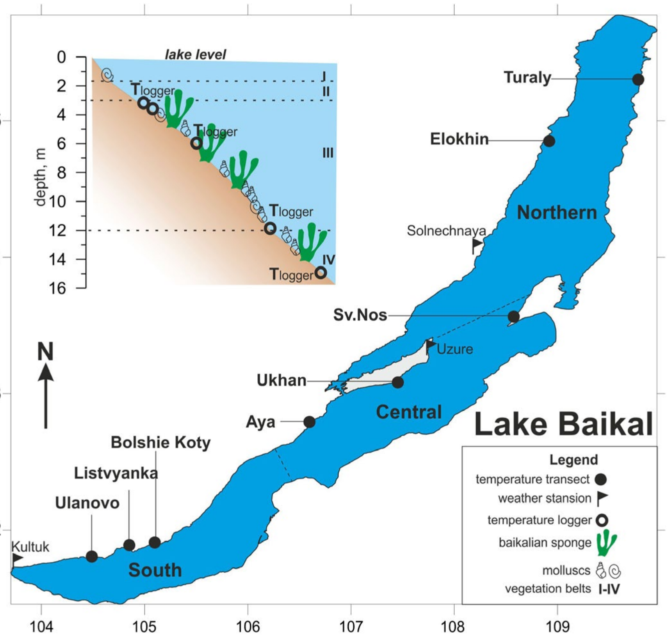

Fig.1. Sketch of location of temperature transects. *The left-upper panel* – distribution of temperature loggers along zones of benthic flora and fauna (see text).

difference between these layers is negligible during August-November (Fig. 4).

Based on single and not regular temperature measurements, it was early found that the mean thickness of epilimnion zone was 7-10 and around 2 m in South, Central and Northern Baikal, respectively (Verbolov et al., 1986; Shimaraev et al., 1994). However, our continuous data show that epilimnion zone forming on depth of 15-26 m along all Baikal from the middle of August to November (Fig.4).

3.2. Rate of heating and cooling

We calculated rates of heating of water layers from 1°C to maximal annual temperature, and following cooling to 1°C. Stations of Northern Baikal show the height rate of heating in 0.16-0.2°C/day. For example, heating in Elokhin station was 0.2°C/day (Fig.5). In contrast, the rate in 0.12-0.14°C/day was typical for South and Central Baikal.

Northern Baikal is often 15-25 days later freed from ice cover than South Baikal, however, the temperature difference between these basins is only *ca.* 1.5°C in the end of May when all Baikal is free from ice cover (Fig.6). It should be noted that temperature of the shallow zone, at which Lake Baikal is opened from ice cover, are different from year to year, but these annual temperatures are similar for South and Northern Baikal (Fig.6).

The opening of Lake Baikal from ice cover often occur at water temperature of 1°C. In the other side, air temperatures were similar (3-5°C) in South and Northern Baikal in the early of May, however, temperatures of the upper water layers (3-6 m) were 0.7-1.5 and around 0°C in South and Northern Baikal,

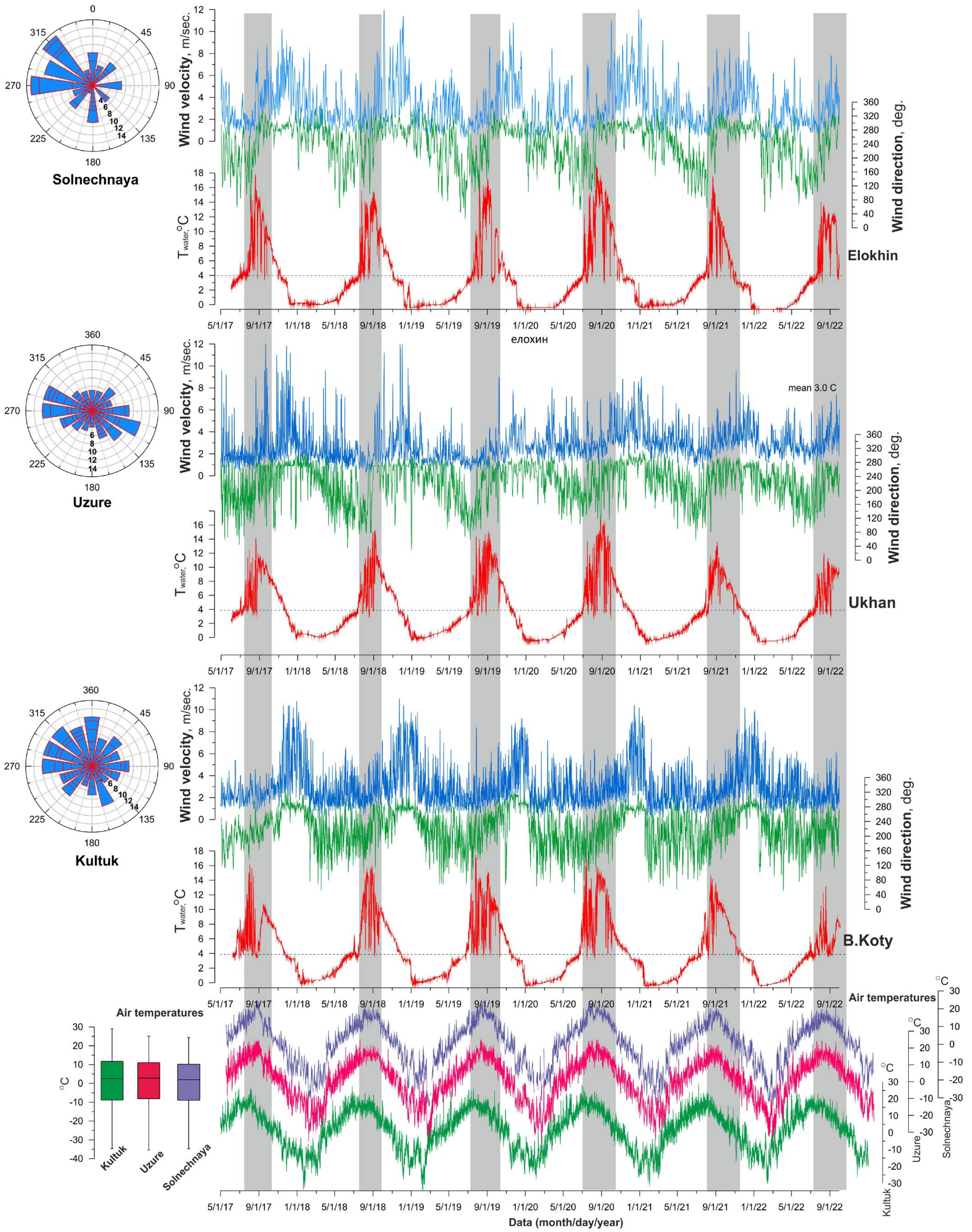

Fig.2. *The bottom panel* –air temperatures (Kultuk-*green*, Uzure-*red*, Solnechnay- *blue*), the upper panels – water temperature at depth of 15m (*red*), wind direction (*green*) and wind velocity (*blue*). *Circle diagrams* – total distribution of wind direction and velocity. *Vertical gray boxes* – maximal of air and water temperatures. *Dashed horizontal line* - after 4°C sharply increased heating or cooling.

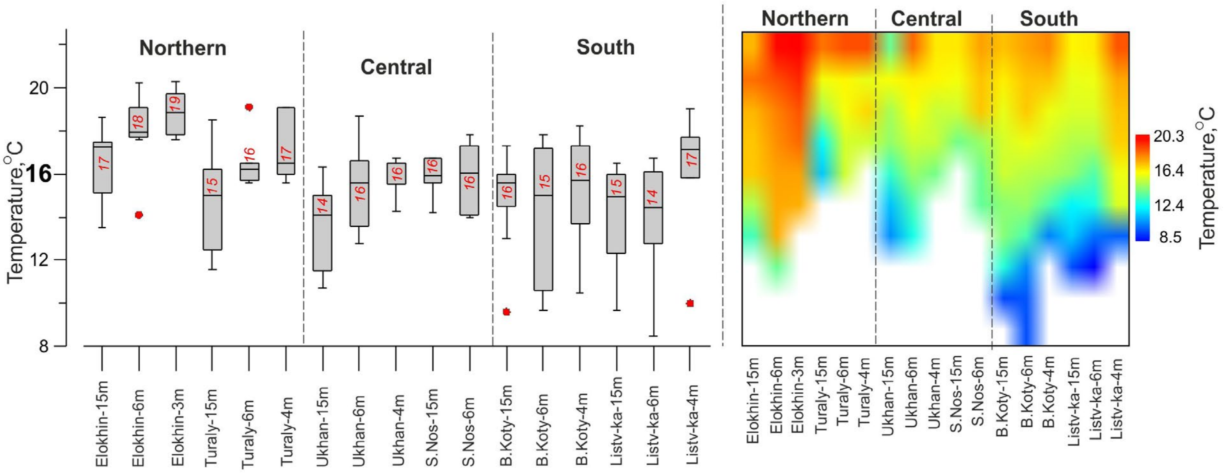

Fig.3. Distribution of maximal water temperatures in June-September 2017-2022. *Red digits*- mean values of temperature.

respectively. It likely evidences that South Baikal is more heated than Northern Baikal in a final time of ice cover by deep water due to more intensive mixing surface water by undercurrents. In addition, daily temperature changes under ice-covered condition of Northern Baikal from the middle of May can be up to 0.4-0.7°C, which is similar to those ones of South Baikal at open-water condition (Fig. 6).

In contrast to heating, the rate of cooling - 0.1°C/day is similar to all Baikal and slightly changes from year to year. The shallow zone cools down to 1°C by the end of December or beginning of January.

3.3. Renewal of the shallow zone

Temperature regime of the shallow zone is characterized by sharp changes in temperatures during warm seasons, when temperature can drop to 6-4°C (Fig.7). It happens when cold water from deep zone is upwelled to the uppermost zone. For Lake Baikal, the water surface temperature decreased to 4–7°C in 66% of upwelling events, and these values corresponded to water temperatures at depths of 75-100 m (Troitskaya et al., 2015). Shoreline upwelling frequency is 11-17 and 28% in July, September and August, respectively, with the average duration of 8-11 days (Shimaraev et al., 2012).

In most cases, we found duration of stabile temperature condition without upwelling was 4 days (Fig.7). However, this duration was reduced to 2 days on stations of South Baikal and Ukhan. The longest stabile conditions of 52 days were observed on Turaly station in 2022.

On average, upwelling events occur 5 times (maximum 13 events) from July to November, however, they are more frequent in South Baikal compare to Northern Baikal (Fig.7). In addition, upwelling is active from July to mid-August (Fig. 2, 7).

According to NOAA/AVHRR satellite data, the average length of upwelling zones in all basins of Lake Baikal was similar and varied from 44 to 46 km (Troitskaya et al., 2015). However, we found that

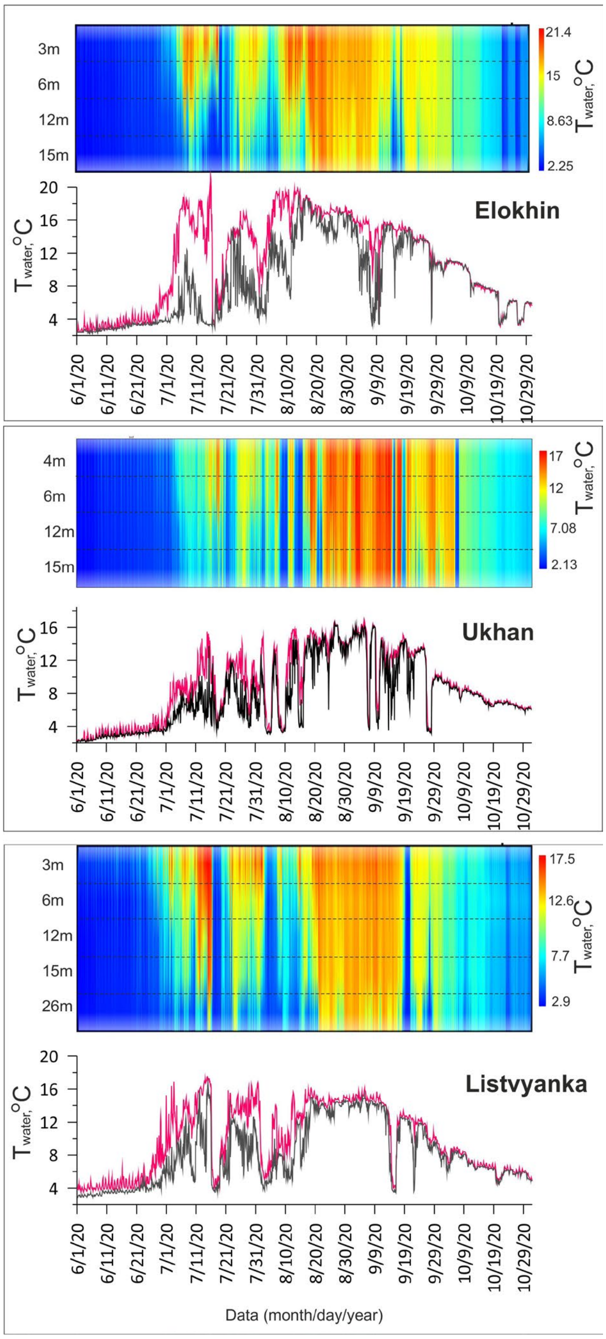

Fig.4. *The upper hot-map panels* are examples of difference temperatures from 3 to 15 m. *The down plots* - distribution of temperatures at depths of 3 m (*red line*) and 15 m (*gray line*).

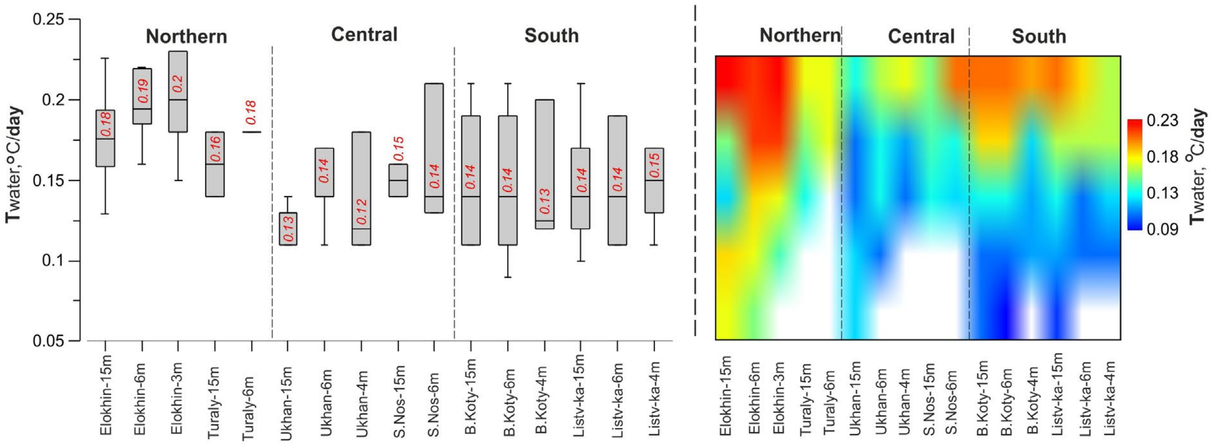

Fig.5. Rates of heating from 1°C to maximal annual temperature. *Red digits*- mean values of rate of heating.

there were upwellings that synchronically appear in South and Central Baikal (distance between the stations Ulanovo and Ukhan is 280 km), and even in Northern Baikal (Fig.7). In addition, all depressions of Baikal are interconnected from the wind activity of neighboring depression. In the case of such "response" upwelling can be from shallow depths of 30-75 m, when water temperature is 6-10°C.

It should be noted that upwelling in South and Central Baikal is very sharp, thus, temperature drops dramatically from 16-18°C to 4°C for the 1-1.5 day, and following temperature also rises rapidly (2-3 day) to 16-18°C (Fig.7). The water body with depth of 15 m cannot be rapidly heated with solar radiation. Thus, it most likely occurs when heated surface water is replaced from the axial zone in the coastal zone.

It is well known that concentration of nutrient components in Lake Baikal is minimal in summer months due to high bio-productivity (Votintsev, 1961). The shallow zone can be contaminated by anthropogenic factors caused by high tourist activity in summer (Ozersky et al., 2018, Timoshkin et al., 2016). Hence, replacement of depleted nutrient components or polluted water by clear water from deep or axial zone during upwelling circulation is an important mechanism for renewal of the shallow zone. The result of measurements of nutrient components and chlorophyll-*a* during June-October with frequency of 1 day showed that the inflow of water from the pelagic zone of the lake to the shallow zone during strong waves has a short-term effect (no more than 1–2 days) on increase of concentration of oxygen and nutrients (Domysheva et al., 2023).

It shows that the shallow zone of South and Central Baikal is intensively ventilated and renewed by pelagic water. However, in Northern Baikal, this upwelling cycle (cooling and heating) is longer - 8-16 days. It seems that the shallow zone of Northern Baikal is slowly renewed because upwelling occurs rarely and its cycle is continuous.

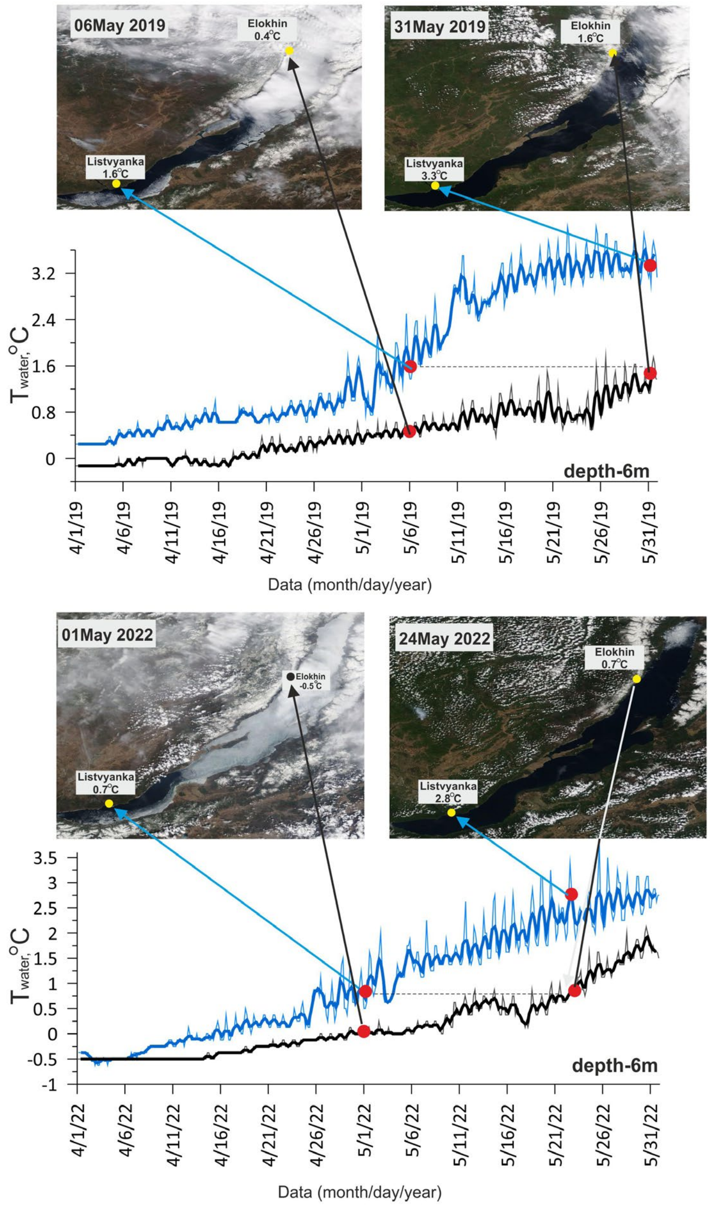

Fig.6. Examples of different temperature regime between South and Northern Baikal (depth in 6m) after opening from ice cover. *Blue line* – Lystvaynka, *black line*- Elokhin, *red circles* – condition of ice cover, *dashed horizontal line* – temperatures at opening from ice cover. Satellite images were taken from https://worldview.earthdata.nasa.gov.

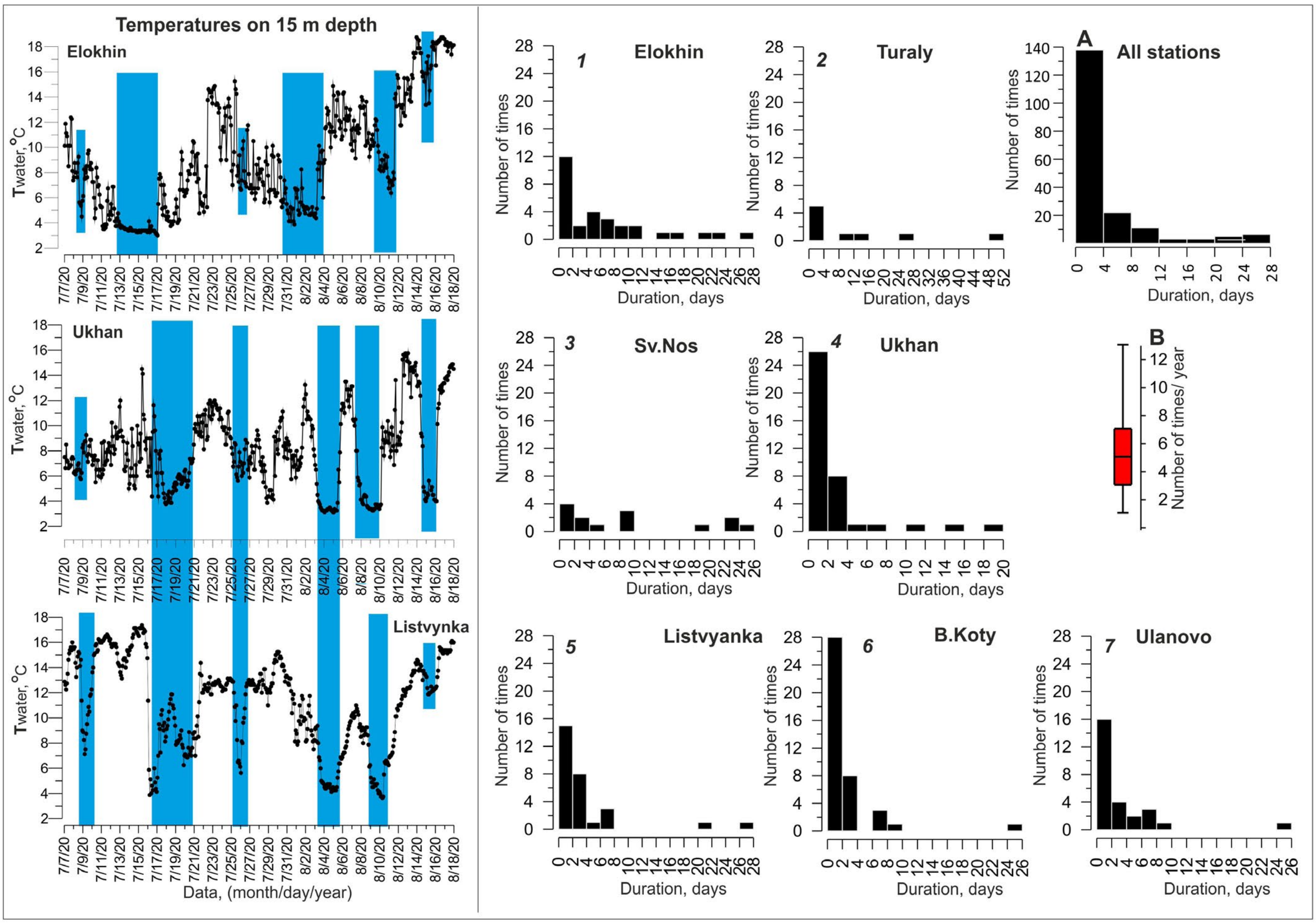

Fig.7. *Left panel*- distribution of temperatures at 15 m depth as an illustration of upwelling events (*blue boxes, short blue boxes*- response upwelling), *Right panel – 1-6* duration of days without upwelling during July-October 2017-2022, *incut A* - total duration for all stations, *incut B*- number of times/year when occurred upwelling.

As a result of wind mixing, the shallow zone is moderately warm with mean temperatures of 6-7°C from June to November (Fig.8). Hence, the temperature effect of the Global warming on the shallow zone of Lake Baikal should be smoothed by cooling of the zone by deep waters during upwellings. As a result, there was no clear evidence that expansion of *Spirogyra* was related to the anomalous warming of the shallow zone.

4. Conclusion

Temperature characteristic of the shallow zone of Lake Baikal during 2017-2022 was studied in this work. The difference of this study from previous investigation of the shallow zone is in obtaining of continuous and synchronic temperature records from 8 transects situated in South, Central and Northern Baikal at depths of 3,4, 6, 12,15 and 26 m using temperature data loggers. Based on obtained data we found that:

i. Maximal heating occurred almost at the same time in all Baikal areas in the second half of August-early September.

ii. Heating of the shallow zone is very sanative to wind activity, and there is a negative correlation between these factors. Modal values of maximal heating for all stations and depths of the shallow zone are 15-16°C.

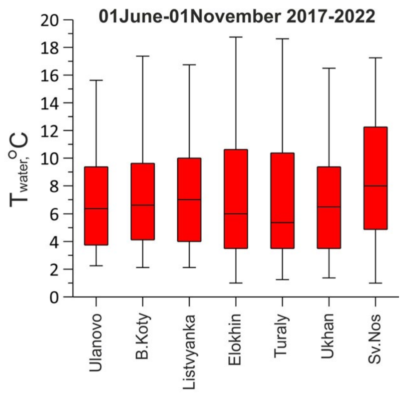

Fig.8. Total distribution of temperatures at depth of 15 m during June-October of 2017-2022.

iii. Temperature difference between depths of 3 and 15 m is more pronounced during July. However, temperature difference between these layers is negligible during August-November.

iv. Mean rates of heating were 0.16-0.2 and 0.12-0.14°C/day for stations of Northern Baikal and South and Central Baikal, respectively. The rate of cooling - 0.1°C/day- is similar for the entire Baikal and changes slightly from year to year.

v. On average, upwelling events occurred 5 times (maximum -13 events) from July to October. Upwellings abundantly are from July to mid-August, and occur often in South Baikal compare to Northern Baikal.

vi. As a result of wind mixing, the shallow zone is moderately warm with mean temperatures of 6-7°C from June to November

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Conflict of interest

The authors declare that they have no competing interests.

References

Domysheva V., Vorobyeva S., Golobokova L. et al. 2023. Assessment of the current trophic status of the Southern Baikal littoral zone. Water 15: 1-14. DOI: 10.3390/w15061139

Izhboldina L.A. 2007. Guide and key to benthonic and periphyton algae of lake Baikal (meio- and macrophytes) with short notes of their ecology. Novosibirsk: NAUKA. (in Russian)

Kravtsova L., Vorobyeva S., Naumova E. et al. 2021. Response of aquatic organisms communities to global climate changes and anthropogenic impact: evidence from Listvennichny Bay of Lake Baikal. Biology 10: 1-22. DOI: 10.3390/biology10090904

Maximova N.V., Melnikova E.N., Shirokaya A.A. et al. 2012. Seasonal and inter-annual distribution of Gastropoda in three hydrodynamic stony littoral zones of Lake Baikal. Ruthenica 22: 1-14.

Ozersky T., Volkova E.A., Bondarenko N.A. et al. 2018. Nutrient limitation of benthic algae in Lake Baikal, Russia. Freshwater Science 37: 472-482. DOI: 10.1086/699408

Potemkina T.G., Potemkin V.L., Kotsar O.V., Fedotov A.P. 2018. Climate factors as a possible trigger of modern ecological changes in shallow zone of Lake Baikal (Russia). International Journal of Environmental Studies. 75: 86-98. DOI: 10.1080/00207233.2017.1406727

Shimaraev M.N., Troitskaya E.S. 2018. Current trends in upper water layer temperature in coastal zones of Baikal. Geography and Natural Resources. 39: 349-357. DOI: 10.1134/S187537281804008X

Shimaraev M.N., Troitskaya E.S., Blinov V.V. et al. 2012. On upwellings in Lake Baikal. Doklady Earth Sciences 442: 272–276.

Shimaraev M.N., Verbolov V.I., Granin N.G. et al. 1994. Physical limnology of Lake Baikal: a review. Irkutsk-Okayama: Baikal International Center for Ecological Research.

Sitnikova T.Ya. 2006. Endemic gastropod distribution in Baikal. Hydrobiologia 568: 207-211.

Timoshkin O.A., Samsonov D.P., Yamamuro M. et al. 2016. Rapid ecological change in the coastal zone of Lake Baikal (East Siberia): Is the site of the world’s greatest freshwater biodiversity in danger? Journal of Great Lakes Research 42: 487-497. DOI: 10.1016/j.jglr.2016.02.011

Troitskaya E., Blinov V., Ivanov V. et al. 2015. Cyclonic circulation and upwelling in Lake Baikal. Aquatic Sciences 77: 171-182. DOI: 10.1007/s00027-014-0361-8

Verbolov V.I., Pokatilova T.N., Shimaraev M.N. et al.1986. Formation and dynamics of Baikal waters. Novosibirsk: Nauka. (in Russian)

Votintsev K.K. 1961. Hydrochemistry of Lake Baikal. In: Galaziy G.I. (Ed). Moscow: Publishing House of the Academy of Sciences of the USSR. (In Russian)