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New data on Lake Mogilnoe (Kildin Island, Barents Sea): the results of the 2018 expeditions

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Abstract. Lake Mogilnoe (Kildin Island, the Barents Sea) is a meromictic lake located in the high latitudes of the Arctic. It was formed by separation from the Barents Sea and retained an underground connection with it through a rocky barrier. The first researchers of the lake mentioned the upper fresh-water layer, the middle salty layer, lower anaerobic layer containing hydrogen sulfide, and noted the existence of a layer with rose water in the redoxcline. Observations carried out during the 20th century pointed to a gradual change in the vertical structure of the lake: mineralization increase of the surface layer and the rise of the hydrogen sulfide distribution boundary. In the past 10 years, there have been signals about acceleration of these changes. This is a big concern about an isolated population of Kildin cod (G. morhua kildinensis) listed in the Red Book of the Russian Federation, an endemic to this lake subspecies of Atlantic cod. In July, August and October 2018, three expeditions were organized to Lake Mogilnoe to study the current hydrological state of the lake, seasonal variability of hydrological characteristics, and outline possible causes of the registered changes and the threat to the Kildin cod population.

1. Introduction

Lake Mogilnoe (Island Kildin, Barents Sea) is a coastal meromictic lake located in the high-latitude Arctic (69°19′11″ N, 34°20′55″ E). It was formed as a result of separation from the Barents Sea about 1000–1500 years ago. According to the classification of [1] this lake belongs to water bodies of ectogenic origin. Its uniqueness lies in the fact that its connection with the sea is carried out not by the flow of seawater above separating threshold, but by filtration through a rocky barrier. Water exchange with the sea is enough to cause tidal oscillations with an amplitude of several centimeters, while in the Barents Sea tidal fluctuations are several meters. Due to the underground connection with the sea, the Mogilnoe lake can also be considered as an anchialine lake, the only representative in Arctic region [2].

Among the meromictic lakes of Russia, Mogilnoe has the largest history of study. It dates back to 1887, when during the zoological expedition to the Barents Sea S.M. Herzenstein caught a cod in freshwater, as it was then thought, lake. Analysis of the water showed that "the lake water was a mixture of one part of the ocean water and about 13 parts of snow, rain and spring water," that is, slightly more than 2‰. Later it turned out that under the fresh layer there is a salt one, where the cod lives, and the lake was recognized as relict. The bottom layer of water is stagnant, with a large amount of hydrogen sulfide. Between the aerobic and anaerobic layers there is an interlayer of pink water caused by the massive propagation of anoxygenic phototrophic bacteria.

In 1893–1899 Russian geologist B.A. Rippas and hydrobiologist N.M.Knipovich continued to explore the lake Mogilnoe, in 1899, 1909 and 1921 it was studied in detail by the expedition of K.M. Derjugin, which ended with the first monograph on this lake [3]. This work set the starting point for subsequent monitoring of the lake. Following detailed studies were performed in the second half of the 20th century by the Murmansk Marine Biological Institute (MMBI) and the N. M. Knipovich Polar Research Institute of Marine Fisheries and Oceanography (PINRO), which provided material for two more monographs published in 1975 and 2002 under the same name "Relict Lake Mogilnoe" [4, 5]. Because of its unique structure, in 1985 the lake was recognized as a hydrological special protected area.

Observations carried out in the 20th century pointed to a gradual change in the vertical structure of the lake expressed in increasing mineralization of the surface layer and raising the border of the hydrogen sulfide layer (Strelkov et al., 2014). In the past 10 years, there have been reports that these changes have accelerated. The main concern is about the isolated population of Kildin cod – a subspecies of Atlantic cod, listed in the Red Book of the Russian Federation, endemic of this lake.

An increase in the mineralization of the mixolimnion can lead to density gradient weakening, and loss of meromixis, as it just happened to the lake Shira in Khakassia [6]. In that case this was preceded by a snowless winter resulted in insufficient freshwater inflow in the spring. By next autumn, the density stratification was so weak that after winter cooling of the surface layer convection penetrated to the bottom anaerobic layer and destroyed it.

To clarify the reasons for the observed changes, the Russian Geographical Society allocated a grant for the project "Cod Lake Lullaby. Documentation of the ecosystem of Lake Mogilnoe (Kildin Island, Barents Sea)", which was attended by representatives of three universities: the Lomonosov Moscow State University, the St. Petersburg University and the Murmansk Arctic State University.

In July, August and at the end of October 2018, three expeditions were organized to Lake Mogilnoe. Their main tasks were the examination of the current state of the lake hydrological structure, tracking of seasonal changes in hydrological characteristics, identification of possible causes of perennial changes and estimation of the threat to the Kildin cod population.

2. Materials and methods

Hydrological parameters were measured at different depths of the lake in two ways: 1) in situ using immersion probes and 2) immediately after sampling by Whale Premium Submersible Pump GP1352. The measurements and sampling step was 0.1–0.5 m in depth. The probes determined the temperature and electrical conductivity (by conductivity meter YSI Pro30), the concentration of dissolved oxygen (by YSI ProODO Optical Dissolved Oxygen Instrument), and the illuminance (with regular digital luxmeter AR813A, modified to immerse its measuring unit under water). In the samples we measured acidity (pH) and ORP (Eh) (with WaterLiner WMM-73), and re-measured temperature and salinity by conductometer WTW Cond 315i that we use in our research of other saline lakes, to ensure comparability of results.

The concentration of sulfide ions was determined by photometry with N,N-dimethyl-p-phenylenediamine and iodometric method after pre-fixation by zinc acetate and cadmium acetate.
To study dominant phototrophs spectrophotometry and spectrofluorimetry were used. Fluorescence spectra were recorded using luminescence spectrometer Solar CM2203. Absorption spectra were measured with the use of spectrophotometer Solar PB2201 and quartz cuvettes with optical path length of 1 cm in the optical range 200–1100 nm.

3. Results

As in previous studies, the same layers were presented in the lake in 2018. Thickness of the surface layer mixed by the wind was of 2 m in July – August, and 3 m in October. It went down because of storm winds mixed it to greater depth. The salinity of the surface layer increased from July to October 2018 by 5 units: it was 5.4‰ in July, 7.1‰ in August, and 10.7‰ in October (figure 1). Below 4 m depth there were no seasonal salinity variations. In salinity profiles, two jumps were present: one between 3 m and 7 m, where salinity increases by more than 20 units, and the second one between 10 m and 12 m with an increase in salinity by 1.5 units. The second jump allows us to distinguish one more water mass near the bottom, with a maximum salinity of 29.9‰. It's important that throughout the water column, including the bottom layer, the salinity was less than at the sea (33‰). In similar coastal meromictic lakes and lagoons partially isolated from the White Sea, the salinity of the bottom layer often equals or even exceeds the salinity of the adjacent sea area [7, 8].

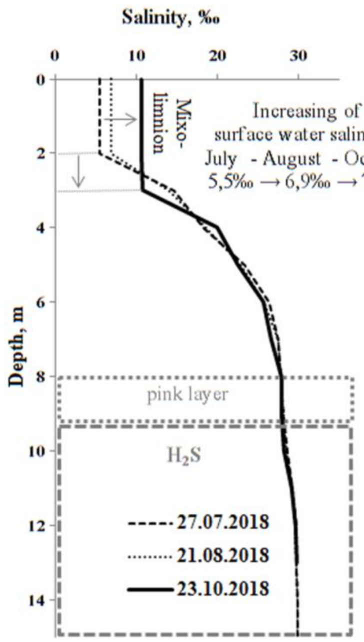

Figure 1. Seasonal variations of salinity in the lake Mogilnoe in 2018.

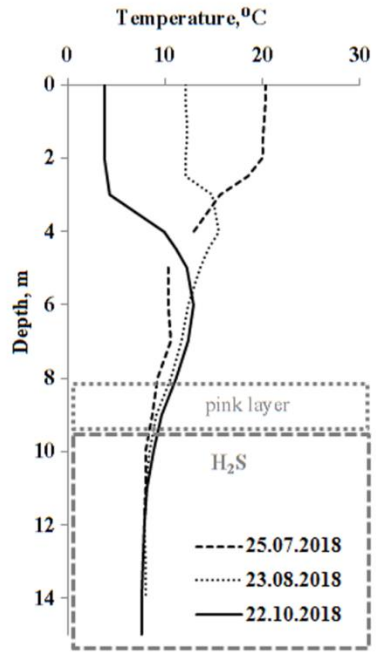

Figure 2. Seasonal variations of temperature in the lake Mogilnoe in 2018.

Difference between Mogilnoe and the White Sea coastal lakes is in the way the sea water enter the lake. In the White Sea coastal lakes, the water from the sea flows above the barrier and enters the lake unchanged, while in Mogilnoe sea water passes through the filter rocky dam, which serves as a kind of mixer. Entering seawater is mixed there with water stored in the dam, and it is squeezed out of it, already diluted. This was confirmed by measurements of the salinity in the underwater streams entering the lake at high tide using the diving method. In the stream salinity was 14.4-19‰, instead of the expected 33‰. At the low tide, water flows out of the outer side of the dam with a salinity of 16–28.5‰. This indicates both the existence of a salinity gradient inside the dam and the mixing here of water with different salinity.

Seasonal temperature fluctuations covered only 6 m from the surface. The most variable is the surface layer by the depth of 4 m (figure 2). In July, the surface of the lake warmed up to 20°, extremely unusually for arctic water bodies. This was caused by abnormally hot weather in the summer 2018. Summer warming was noticeable even in October at the depth of 5–8 m (14.4° C), when its temperature was 10° higher than in the surface layer (3–4° C). Starting from 9 m in the hydrogen sulfide zone the temperature is the same in time and in depth.

At the profile of dissolved oxygen (figure 3) four different layers can be distinguished: 1) homogeneous surface layer by the depth of 2 m saturated with oxygen due to waves and wind mixing, 2) middle salty layer (3–5 m) where in summer the oxygen content exceeds the saturation level up to 133%, this is due to phytoplankton photosynthesis and O2 accumulation in absence of convective mixing, 3) chemocline (6–8 m), in which the oxygen content quickly drops to zero over 2 m, 4) anaerobic zone.

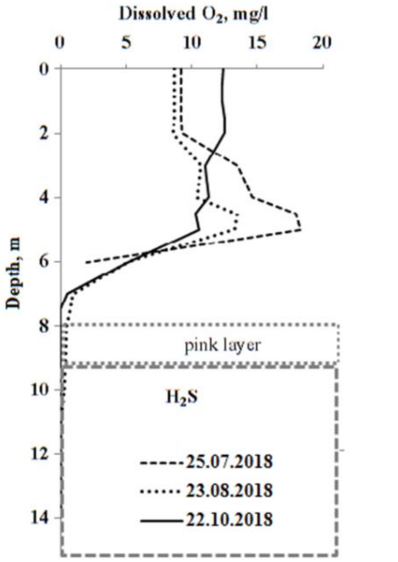

Figure 3. Vertical distribution of dissolved oxygen.

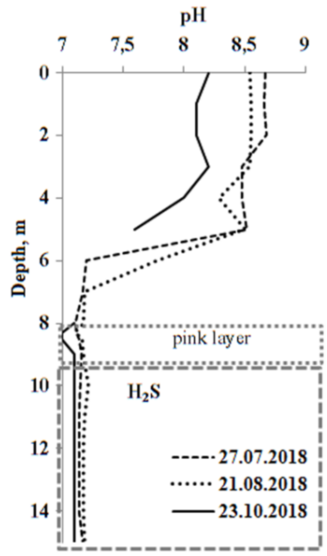

Figure 4. Seasonal variations of pH in the lake Mogilnoe in 2018.

In all seasons, we observed a sharp change in pH at a depth of 5–6 m (figure 4). Unexpectedly, it did not coincide with the redox boundary located 2 m below. In a layer with high oxygen content, a local increase in pH to 8.5 was observed, which indicates a use of carbonate by photosynthesis.

The boundary between water with positive and negative redox potential (i.e. aerobic and anaerobic zones) was situated at the depth of 8–8.5 m (figure 5). During the observation period, the boundary of hydrogen sulfide gradually sank: in July it was located at a depth of 8 m, in August 8.3 m, and at the end of October 8.5 m, and a pink bacterial layer sank too. It is likely that the lowering of the sulfide zone boundary is related to microbial activity, since these bacteria oxidize hydrogen sulfide (and realize sulfur) due to anoxygenic photosynthesis.

Measurements of illumination at different depths showed that the water in the lake is very transparent to the depth of the pink layer (figure 6). Bacterial suspension completely absorbs light, resulted in aphotic conditions below it. In August pink layer sank and light penetrated to a greater depth despite the sun was low, and total illumination decreased. In October, due to difficult weather conditions, light measurements were not provided.

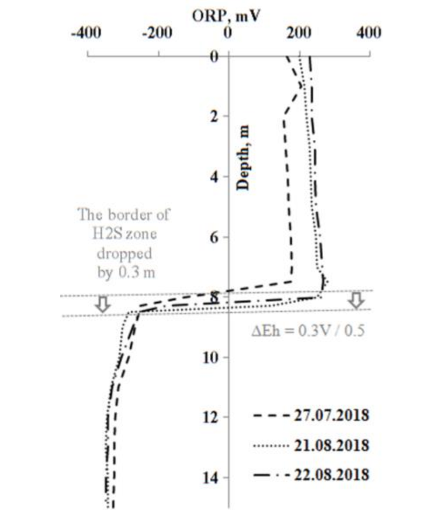

Figure 5. Vertical profiles of ORP (Eh) in summer 2018.

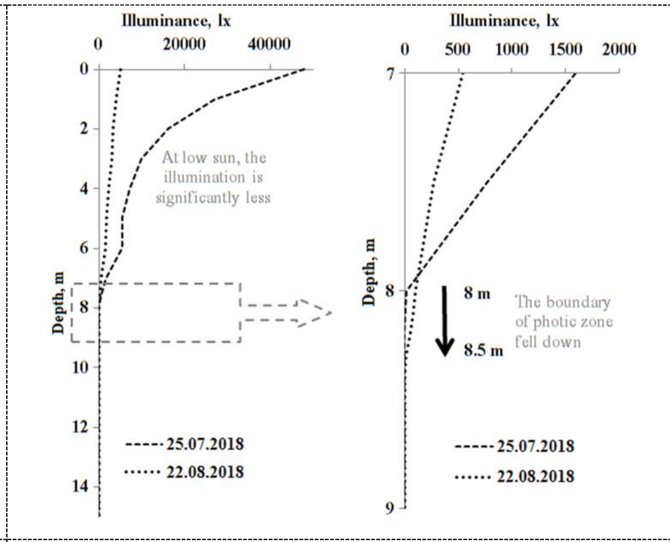

Figure 6. Illuminance at different depths of the lake Mogilnoe in summer 2018.

Chemical analysis of water samples from different depths showed that hydrogen sulfide appeared in small quantities about 1 m above the redox interface, and its concentration gradually increased (table 1). The highest values of sulfide ion concentration were 104–136 mg/l registered near the bottom (11–15 m) at the highest salinity. Compared to 1999–2001 [5] its level has remained the same.

Our studies have confirmed the existence of a negative trend. During previous studies in the summer 2003–2007, the salinity in the surface layer was 3–5‰, our summer data are 5.5–6.9‰, and therefore, over the past 14 years it has increased by two units. Desalinated mixolimnion shrank by 1 m in comparison with the summer of 2004, when the halocline began at the depth of 3 m.

We also faced a question what kind of bacteria color the pink layer. The first microbiologist who studied the bacterial community of the lake Mogilnoe was B.L. Isachenko who discovered in this layer motile purple sulfur bacteria [9]. That time pink layer was at the depth of 13 m. Further researchers from S.N. Vinogradsky Institute of Microbiology discovered the development of large quantities of the brown–colored green sulfur bacteria dominated by Chlorobium phaeovibrioides in the lake chemocline. Maximum number was 106 cells/ml at a depth of 8.75 m [10]. Purple sulfur bacteria were two orders less abundant. Next research in 1999 and 2001 confirmed that the brown-colored green sulfur bacteria dominate in the Mogilnoe Lake chemocline, and the purple ones were found only in single cells [11]. Thus, over the past hundred years, there has been a change of dominants. Both purple and green sulfur bacteria play the same role in a reservoir: they use hydrogen sulfide for photosynthesis, oxidize it, and thus protect the overlying aerobic ecosystem from the diffusion of this toxic substance. Important ecological differences between these bacteria are that: 1) purple bacteria need more light (50м300 lux), whereas for green ones few luxes are enough; 2) purple sulfur bacteria can withstand the presence of oxygen in small quantities, while green ones are strict anaerobes. The question of which bacteria color the pink layer now is not only taxonomic, but also ecological because bacteria serve as indicators of specific abiotic conditions.

We have analyzed the samples from various depths using the fluorimetric method, previously developed for the White Sea meromictic reservoirs [12, 13] (figure 7). When fluorescence is excited by the light with a wavelength of 440 or 525 nm, the first maximum of the fluorescence emission band of the bacteriochlorophyll (BChl) falls in the range of 740–750 nm, which clearly indicates the presence of brown-colored green sulfur bacteria. In the absorption spectra of water samples, an absorption peak was observed with a maximum of 726 nm, which is typical for the chlorosomal BChls c,d,e of green sulfur bacteria. At the same time, we did not register the absorption bands of BChl a with wavelengths 830–890 nm, characteristic of purple bacteria. The concentrations of phototrophic bacteria in the sample above and below the chemocline (depth 7.8 and 8.0 m) differ by an order of magnitude: the number of bacteria above the chemocline decreases significantly.

Table 1. The concentration of sulfide in the lake Mogilnoe at different depths (mg/l).

22.07.2018			27.07.2018			21.08.2018			22.10.2018	
	Fixation by:			Fixation by:			Fixation by:			Fixati-on by:
Depth, m	Zn $(CH_3COO)_2$	$Cd(CH_3COO)$	Depth, m	Zn $(CH_3COO)_2$	$Cd(CH_3COO)$	Depth, m	Zn $(CH_3COO)_2$	$Cd(CH_3COO)$	Depth, m	Zn $(CH_3COO)_2$
1	0	–	**1**	0	-	**1**	0	-	1	–
3	–	–	**3**	–	–	**3**	0	–	2	0
5	–	–	**5**	–	–	**5**	0	–	6	0.02
7	0	–	**7**	0	–	**7.5**	0.05	–	7	–
7.7	0,18	–	**7.7**	0.21	–	**7.7**	–	–	7.7	–
7.9	1,03	–	**7.9**	–	–	**7.9**	–	–	7.9	
8	–	–	**8**	12.87	2.43	**8**	0.69	–	8	0.1
8.3	–	–	**8.3**	–	–	**8.3**	3.09	–	8.3	–
8.5	–	–	**8.5**	6.24	6.58	**8.5**	14.4	–	8.,5	1.64
9	15.25	87.33	**9**	20.1	–	**9**	20.6	–	9	13.3
10	–	–	**10**	64.11	–	**10**	52.2	–	10	27
11	85.9	114.7	**11**	103.6	83.86	**12**	125.6	–	11	73.9
13	–	111.9	**13**	–	–	**13**	–	111.9	13	–
14	141	–	**14**	–	–	**14**	–	121.5	14	127.2
			14.5	135.5	123	**14.5**	138	119.4	–	–
			15	149.7	–				15	139.2
			15.5	138.3	–					

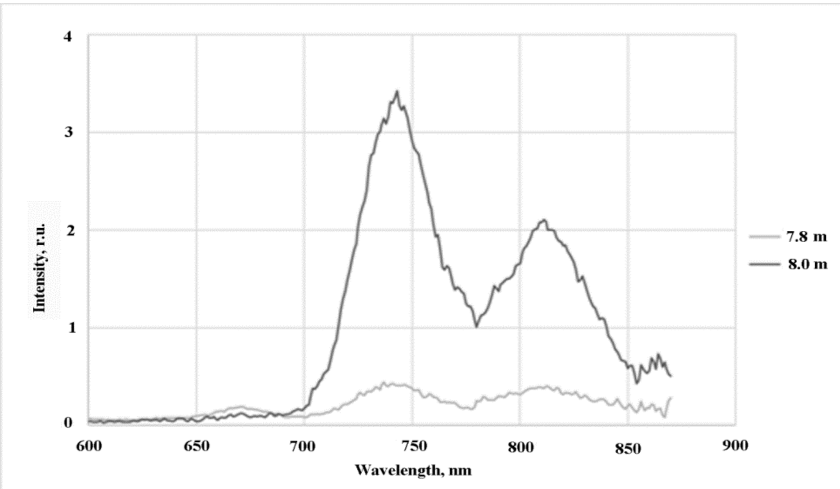

Figure 7. Bacteriochlorophyll fluorescence spectra excited at 525 nm for the samples from the lake Mogilnoe taken at the depth of 7.8 m and 8.0 m.

4. Discussion

Unfortunately, negative changes in the lake Mogilnoe are confirmed. Mixolimnion has become thinner, the salinity in it has increased by several units, the hydrogen sulfide boundary has risen by another 1 m compared to studies of the 2000s (figure 8).

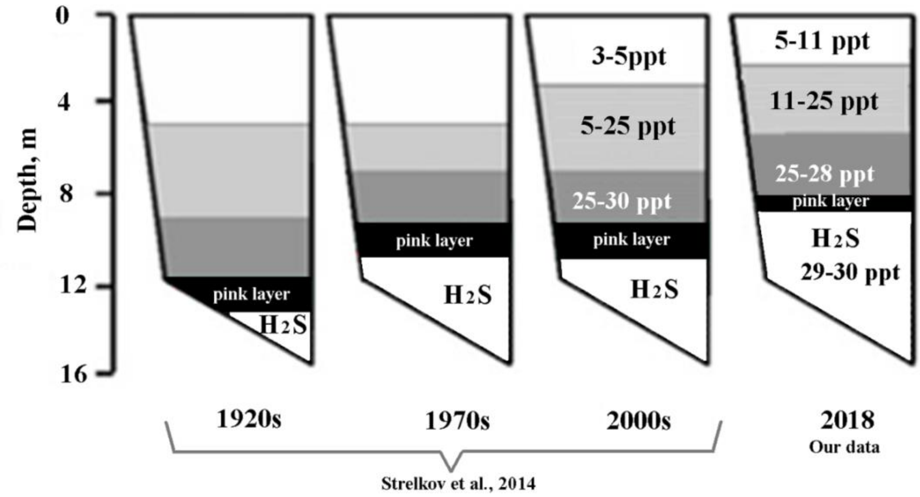

Figure 8. Centenary changes in the vertical hydrological structure of the lake Mogilnoe.

The stability of the multi-layer structure of coastal meromictic lakes is ensured by the balance between freshwater flow from the catchment area and the salt water flow from the sea. Desalination of the upper layer is mainly confined to the spring season due to snow and ice melting. The lake Mogilnoe is covered with a thick layer of ice in winter, while the Barents Sea does not freeze in this area. During the summer, the salinity of the surface water layer gradually increases [4]. The summer of 2018 was particularly hot and dry, the streams and springs dried out, so the salinity of the surface layer could increase more than in other years. We could not find a single watercourse that would feed the lake with fresh water. In such a situation, the lake is clearly experiencing a shortage of fresh water. Taking into account the general warming of the climate, this trend may continue.

Wind can also play a significant role: increased wind activity may lead to deepening of the mixing zone. And, finally, the storm activity of the sea, the reinforcement of which is recently recorded in all seas, including the Arctic, can affect the permeability of the rocky barrier which separates the lake from the sea.

The registered changes are not related to the pollution of the lake, because in the last 10 years (at least) there is no economic activity around the lake.

As for cod, there is no reason for alarm, yet. According to our information, poaching poses a much greater danger. With an increase in salinity, the surface layer should become more comfortable for this fish, marine by origin.

However, in the case of continued salinization, the difference in water density may become insufficient to maintain meromixis. In this case the lake may be completely mixed, for a short time the hydrogen sulfide will spread to the entire lake. Die-off of aquatic organisms is possible, including Kildin cod listed in the Red Book, which is not found anywhere else in the world. The lake can lose its hydrological uniqueness, hydrological special protected area will lose value.

Later the lake will turn salty holomictic, with favorable conditions for marine hydrobionts. But the unique gene pools, formed in the specific conditions of the lake for thousand years of isolation, will be irretrievably lost. It will take centuries to restore them.

To prevent a catastrophe, it is necessary to continue observations in different seasons. Only then will it be possible to make predictions about the stability of meromixis in the lake Mogilnoe and future of Kildin cod.

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