SALT LAKES SEPARATED FROM THE WHITE SEA

Elena Krasnova[1], Dmitry Voronov[2], Natalia Frolova[3], Anatoly Pantyulin[3], and Timofey Samsonov[3]

1. Lomonosov Moscow State University, N. A. Pertsov White Sea Biological Station, Moscow, Russia; e_d_krasnova(at)wsbs-msu.ru
2. A. A. Kharkevich Institute for Information Transmission Problems, Russian Academy of Sciences, and Lomonosov Moscow State University, A.N. Belozersky Institute of Physico-Chemical Biology, Moscow, Russia; da_voronov(at)yahoo.com
3. Lomonosov Moscow State University Faculty of Geography, Moscow, Russia; frolova_nl(at)mail.ru, apantiulin(at)newmail.ru, tsamsonov(at)geogr.msu.ru

ABSTRACT

Many lakes at different stages of separation from the sea were formed along the coast of Kandalakshsky Gulf of the White Sea because of a rapid glacioisostatic lifting. The natural stage of their hydrological evolution is the meromixis. Five stratified lakes at different stages of isolation were studied in 2010-2014. The studies included echo-sounding of bottom topography, measurements of hydrological parameters: temperature, salinity, pH, redox potential, oxygen content, as well as registration of organoleptic properties of water, and *in situ* illumination measurements at different depths. Data from four years of observation are generalized, the vertical structure of the lakes was determined, as well is its seasonal and interannual variations. The lakes are ranked by chronology of their separation from the sea.

Keywords

White Sea, separating bays, stratification, redox zone, meromixis, salinity, temperature, oxygen, pH, illumination, coloured layers, seasonal variations, stages of isolation.

INTRODUCTION

The White Sea coast provides a unique opportunity for studying the ecological transformation of coastal lakes caused by sea transgressions and regressions. In the western part of the White Sea, in particular in the Coast of Kandalakshsky Gulf, the shore undergoes a rapid glacioisostatic lifting. In the vicinity of the White Sea Biological Station of MSU (WSBS), the speed of the uplift is at the rate of about 40 cm per century (1). This, together with meandering shoreline and abundance of islands and cross-country terrain provides favourable conditions for separating the bays from the sea and forms many water bodies at different stages of isolation. As a result of several years of investigation of the coastal lakes we have data concerning 15 water bodies in various stages of isolation from the sea, including three meromictic lakes, flow-through lagoons and the bays with yet unaltered tidal regime, as well as fresh lakes that have completely lost their connection with the sea (2,3,4).

In this paper, we describe the hydrological structure of five reservoirs in the vicinity of the WSBS (Figure 1) investigated during the White Sea International Student Workshop on Optics of Coastal Waters in September 2014, jointly organized by WSBS, Department of Physics of MSU, International Laser Center of MSU and European Association of Remote Sensing Laboratories (EARSeL).

METHODS

In this article, we use data of field research carried out at the WSBS in 2010–2014 at five separating lakes: Kislo-Sladkoe ("Sour-sweet lake"), the lagoon on Cape Zeleny (Green Cape), Nizhnee Ershovskoe ("Lower Ruff's lake"), Elovoe ("Fir lake") and Trekhtzvetnoe ("Tricolor lake"). Characteristics of the studied lakes are presented in table 1. In all of these reservoirs regular monitoring,

DOI: 10.12760/02-2015-1-02

including monthly research at the summer-autumn season (from June to October) and winter annual work, were carried out. The studies included echo-sounding of bottom topography, measurements of standard hydrological indicators – temperature, salinity, pH, redox potential, oxygen content, as well as registration of organoleptic properties of water at different depths (colour, smell, presence of gas bubbles), and *in situ* illumination measurements at different depths.

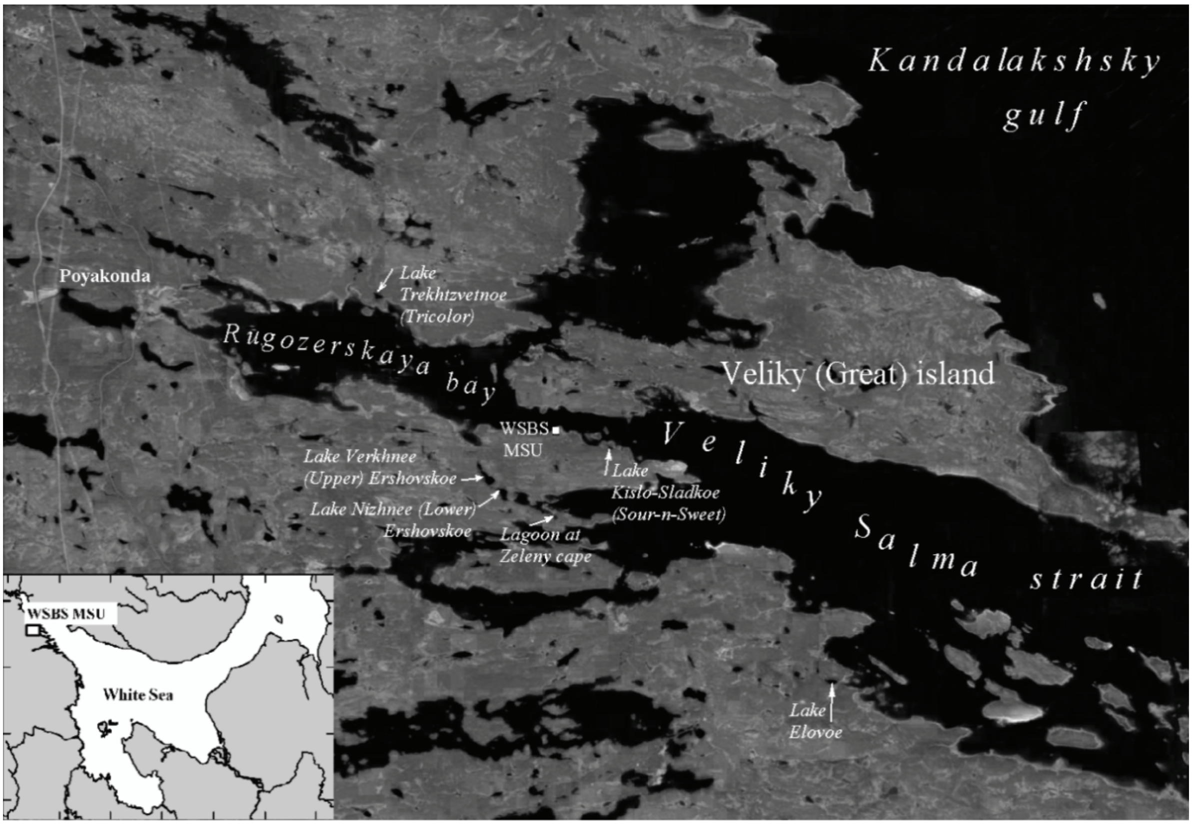


Figure 1: Map of the vicinity of the White Sea Biological Station and location of the studied lakes separated from the sea.

Table 1: Characteristics of the studied lakes.

Name of the lake	Coordinates	Elevation, m (Baltic system)	Lake area, ha	Drainage area, m^2	Depth, m	
					average	max
Kislo-Sladkoe	66°32'54"N 33°08'05"E	0.4	1.6	157,000	1.5	4.5
Lagoon on Cape Zeleny	66°31'49"N 33°05'55"E	-0.05	1.3	92,500	2	6.5
Elovoe	66°28'53"N 33°16'50"E	no data	2.8		1	5.5
Nizhnee Ershovskoe	66°32'16"N 33°03'30"E	1.2	8.1	2,029,000	1	2.5
Trekhtzvetnoe	66°35,53'N 32°59,97'E	1.3	3.3	643,809	2	7.5

In every lake, the deepest position was located with sonar and water samples were collected using a portable Whale Premium Submersible Pump GP1352 with silicone tube attached to a calibrated rope. The samples were collected from surface to bottom at steps of 0.5 m, and in the redox zone at steps of 0.1 m. Temperature and salinity were measured with a conductometer WTW Cond 3110. The oxygen content was measured *in situ* with an oximeter "MARK 302 E" with immersion probe. Illumination was measured with a regular digital luxmeter AR813A, modified to immerse its measuring unit under water to different depths. The water samples were examined using a Leica microscope in bright field and also using the epi-fluorescence with filter set N2.1 (excitation / transmittance 515□560/580 nm). Altitude of the ice surface and water surface altitude were determined early in February 2014 by trigonometric geometric levelling using a high precision electronic level Leica Sprinter.

RESULTS

Lake Kislo-Sladkoe

Lake Kislo-Sladkoe is located 1.5 km east of WSBS. It is connected with the Velikaya Salma Strait between WSBS shore and Veliky ("Great") Island belonging to the Kandalakshsky nature reserve. There are no regular tidal fluctuations; inflow of seawater occurs several times per year during high syzygy tides.

The lake was formed as a result of the separation of a bay, shaded from the sea by an island with two rocky rises on its both sides. One of the rises rose above the sea surface and turned into a dry dam, now covered by terrestrial vegetation. The second rise is a rocky dam that is almost dry with a small stream from the lake to the sea. Seawater flows backward into the lake only during rare high tides. Fresh water filling occurs mainly during snowmelt. The daily debit of the freshwater creek does not exceed 1.5 m^3 in summer.

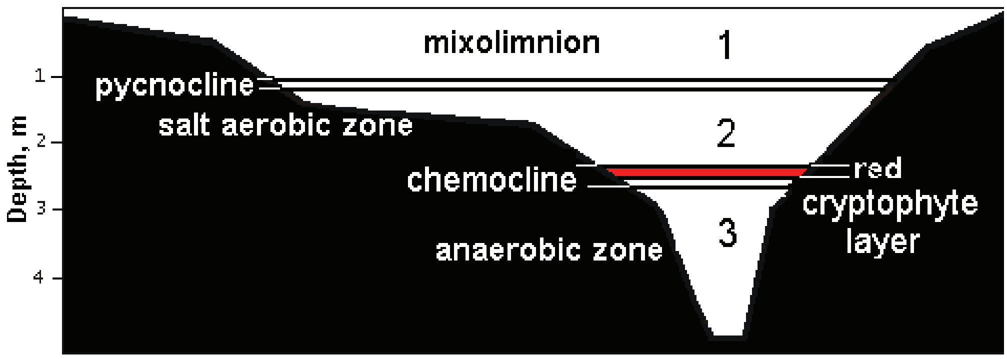


Figure 2: The scheme of vertical stratification in the lake Kislo-Sladkoe. 1 – upper layer (mixolimnion), 2-3 – monimolimnion: 2 – salt aerobic layer, 3 – salt anaerobic layer; in between 1÷2 – pycnocline, 2÷3 – redox zone with sharp vertical redox and chemical gradients, in summer it is coloured in red because of a Rhodomonas sp. bloom.

The vertical structure of Lake Kislo-Sladkoe undergoes seasonal and interannual variations. In summer it consists of three layers (Figure 2):

1. The top 1 m layer is exposed to wind mixing. Salinity in this layer is less compared to the downward part of the lake and to the sea. During a year, it is minimal in spring after the snow melts (7-9 psu), and gradually increases to 27 psu in autumn, when aligned with the seawater.
2. The middle layer from 1 m to the depth of 2.2-2.9 m has a salinity equal to that of the sea; due to photosynthesis of phytoplankton it is saturated with oxygen or even oversaturated. Its temperature differs from the other layers, in summer and autumn this layer is the warmest, compared with the surface and underlying layer.
4. A bottom hollow with a depth of more than 3 m which accounts for about 15% of the lake area is filled with cold salt water without oxygen, and high levels of sulfide and hydrosulfide (5). Between the main three layers there are transitional zones each less than 0.5 m thick with sharp gradients of physical and chemical parameters.

The surface layer plays a crucial role in the hydrological structure of the lake: it insulates the underlying layer of salty water from contact with the atmosphere. As the water in the lake is clear, the sun rays penetrate to the bottom in the shallow part of the lake at a depth of 1.5-2 m, heat the water near the bottom, but the difference in density prevents heat exchange with the upper layers and further with the atmosphere. This creates a solar pond effect and leads to a temperature inversion in the summer. In the same way, the surface layer retains oxygen produced by photosynthesis in the salt water mass. As a result of oxygen accumulation, its concentration may exceed 100% saturation (Figure 3) and even reaches values of 200-300% (6).

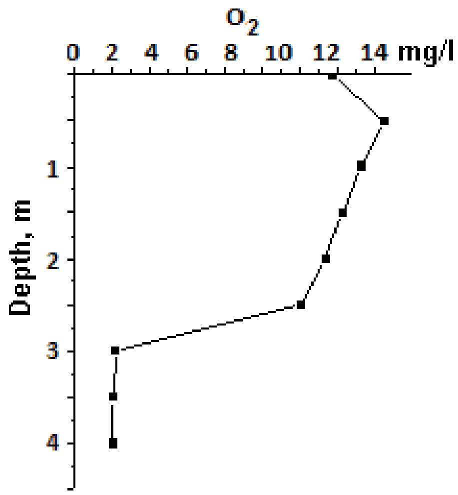


Figure 3: The oxygen concentration in the lake Kislo-Sladkoe in July 26, 2013. The maximal value of dissolved oxygen concentration 14.5 mg/l corresponds to 165% saturation.

In summer, there is a red coloured layer caused by a cryptophyte algae *Rhodomonas* sp. bloom in the redox zone of lake Kislo-Sladkoe (the border of the salt aerobic and anaerobic layers). By genetic peculiarities the strain in this lake is identical with the one isolated from the Beaufort Sea (3,7), but is different from two close species *R. abbreviata* and *R. salina*.

In the lower layer, the temperature does not exceed 11°C even in the summer, when the temperature of the upper layer of the lake and the surface of the sea reaches 18-25°C. Strong density stratification, lack of convection and high abundance of suspended microorganisms in the redox zone intercepting radiant energy prevent its heating. Illumination measurement showed that sun light does not penetrate below the red cryptophytic layer (Figure 4).

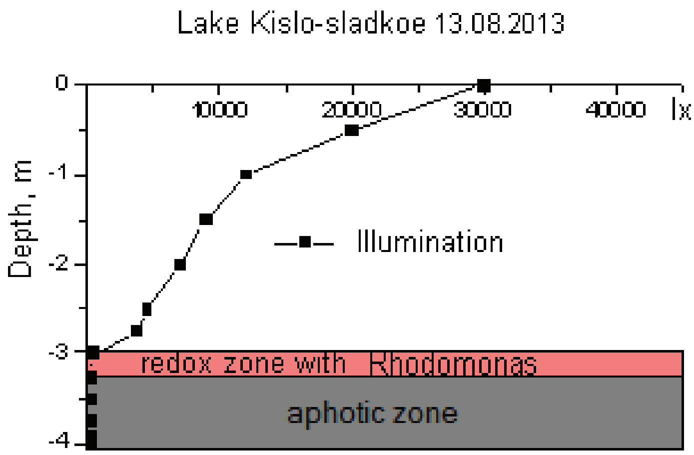


Figure 4: Illumination in the lake Kislo-Sladkoe. Steep decline occurs in the mixolimnion, a less rapid decline is found in the aerobic salt layer; below the layer with the Rhodomonas bloom, conditions are aphotic.

Usually, the salinity of the bottom layer is slightly higher compared with the overlying water and the sea (Figure 5). On the one hand, it may be a result of conservation of water penetrated to the lake in winter, when the salinity of the sea is highest; on the other hand, it can be a result of brine draining from the ice to the bottom during seawater freezing. The same phenomenon occurs in some coastal lakes in the high Arctic (8), as well as in some other lakes separating from the White Sea: the lagoon on Cape Zeleny and the lake at the island Tonisoar (9,10).

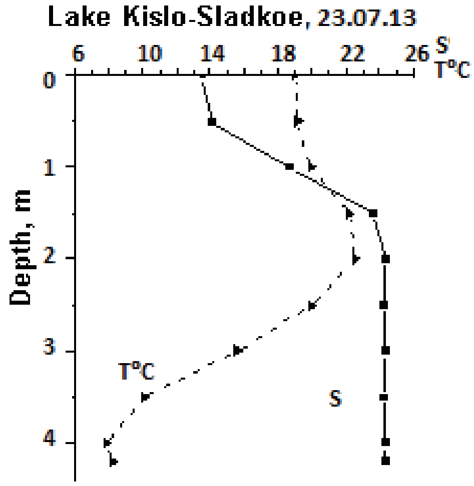


Figure 5: Vertical profiles of temperature and salinity in the lake Kislo-Sladkoe in July 2011.

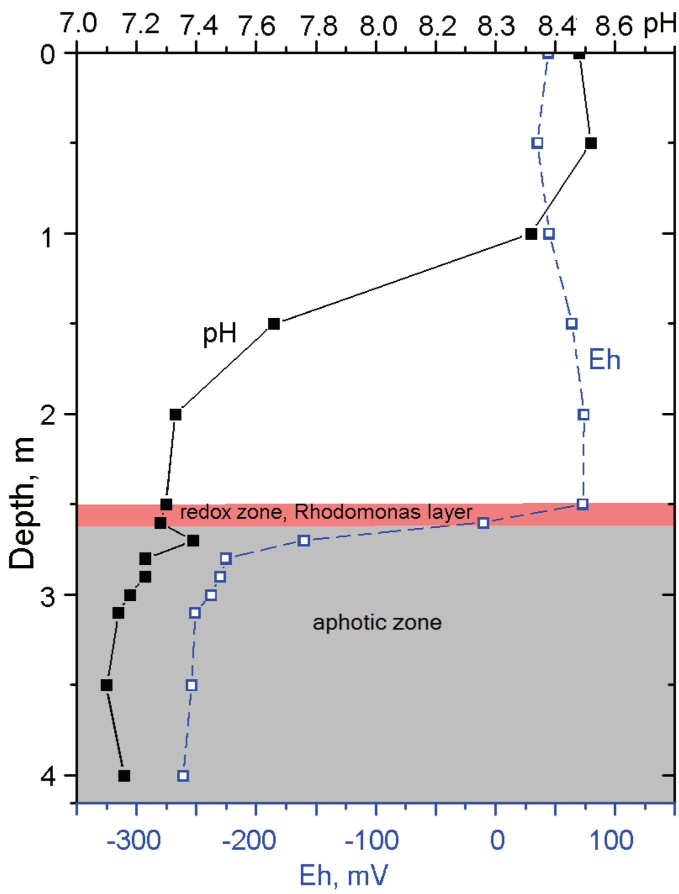


Figure 6: PH and redox potential in the lake Kislo-Sladkoe, 26.07.2014.

Values of pH and redox potential also differ in the layers (Figure 6). In the mixolimnion, the pH is the same as in the sea, declining below and reaching a minimum near the bottom. Sometimes, we registered an increase of the pH inside the oxygenated layer indicating active photosynthesis consuming carbon dioxide. A rapid decline of the redox potential occurs in the narrow redox zone about 20 cm thick marked by a red layer.

The three-layer vertical structure can persist for years, but rarely (not every year) it is broken in the case of especially powerful tides and wind surges, when large amounts of seawater penetrate into the lake mixing the water, after which the water column becomes homogeneous.

Maximum ice cover thickness observed at the end of winter is 40-50 cm, whereas it is 60-70 cm in the sea. Ice cover forms an ice dam that seems to be sufficient to block the lake from tides. It is still questionable, however, whether there is a period of complete lake isolation from the sea in winter.

Lagoon on Cape Zeleny

The lagoon is located at the peninsula isthmus and connected with the tip of the bay Kislaya separated by rocky rise. Twice a day during high tide, seawater flows into the lake over the rise. The amplitude of tidal oscillations in the lake is about 10 cm, while it is about 2 m high in the sea. The tidal cycle in the lake is asymmetric: the duration of inflow is shorter than the ebb-tide, so most of the time the current over the rise is directed out of the lake to the sea.

Similarly to the Kislo-Sladkoe Lake, the lagoon on Cape Zeleny has a three-layered hydrological structure first described in (6). Since the lake is deeper, its layers are thicker. At the same time, the hydrological structure has individual features (Figures 7, 8), in particular, sharper gradients. Bottom water in the lagoon is colder and more salty than in the lower layer of the lake Kislo-Sladkoe. This distinguishes it from most of the other studied separating lakes. Moreover, its salinity is higher than in the adjacent sea. This is due to the relatively small watershed, small fresh water income, and accumulation of brine formed by the freezing of seawater in winter (9,10).

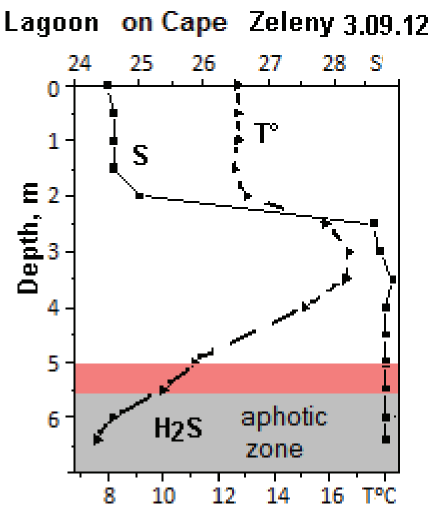


Figure 7: Temperature (T°C) and salinity (S, psu) in the lagoon on Cape Zeleny in September 2012. Upper layer (mixolimnion) from the surface to 1.5 m, middle oxygenated layer from 2 m to 5 m, red cryptophyte layer at 5□5.5 m, further below, the water is anoxic. The middle layer is the most heated one. Below 2 m, the salinity is higher than in the sea.

After ice melt, the surface layer slightly freshens, but the degree of desalination is less than in other studied lakes. For three years of observations, the salinity never dropped below 22 psu. Like in the lake Kislo-Sladkoe, the less dense surface layer serves as an insulator for the solar pond effect increasing the temperature at a depth of 2-3.5 m. Temperature and salinity are almost constant in the bottom layer.

In the lagoon on Cape Zeleny the winter vertical stratification depends on the height of autumn spring tides, which influence the extent of flushing similar to Kislo-Sladkoe lake. Due to the relatively lower salinity of inflowing seawater it sprawls to the intermediate level according to its density. In winter, when the water temperature in the sea is below 0°C, its density increases enough to reach the bottom. At this time, the ice cover strengthens the bar and restricts penetration of water from the sea. Certain combinations of climatic factors may cause complete seasonal isolation that needs to be checked.

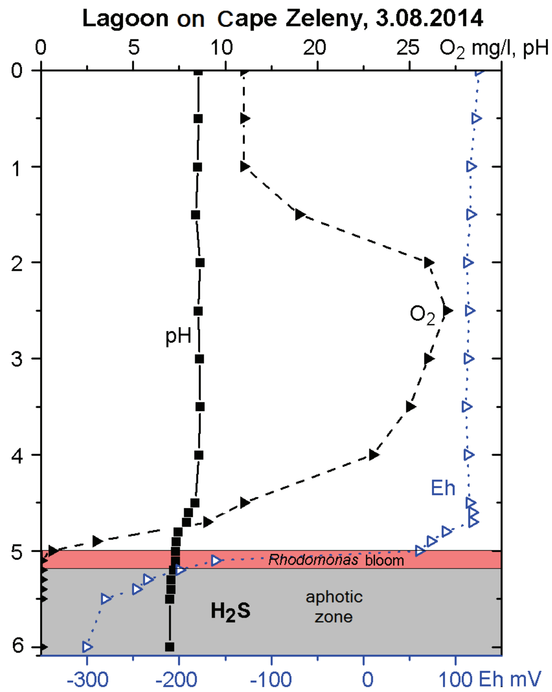


Figure 8: PH, redox potential, and dissolved oxygen concentration in the lagoon on Cape Zeleny. All features decline from the redox zone to the bottom. Some increase of pH at 2 m depth can be explained by intensive photosynthesis.

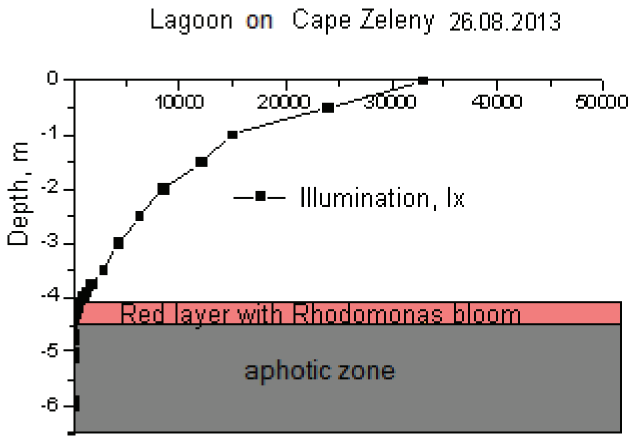


Figure 9: Illumination in the lagoon on Cape Zeleny. Microorganisms in the redox zone completely absorb the light.

Annual brine downfall, on the one hand, can be considered as a factor of seasonal mixing, but on the other hand, it strengthens vertical stratification maintaining a dynamic equilibrium between the layers with different densities.

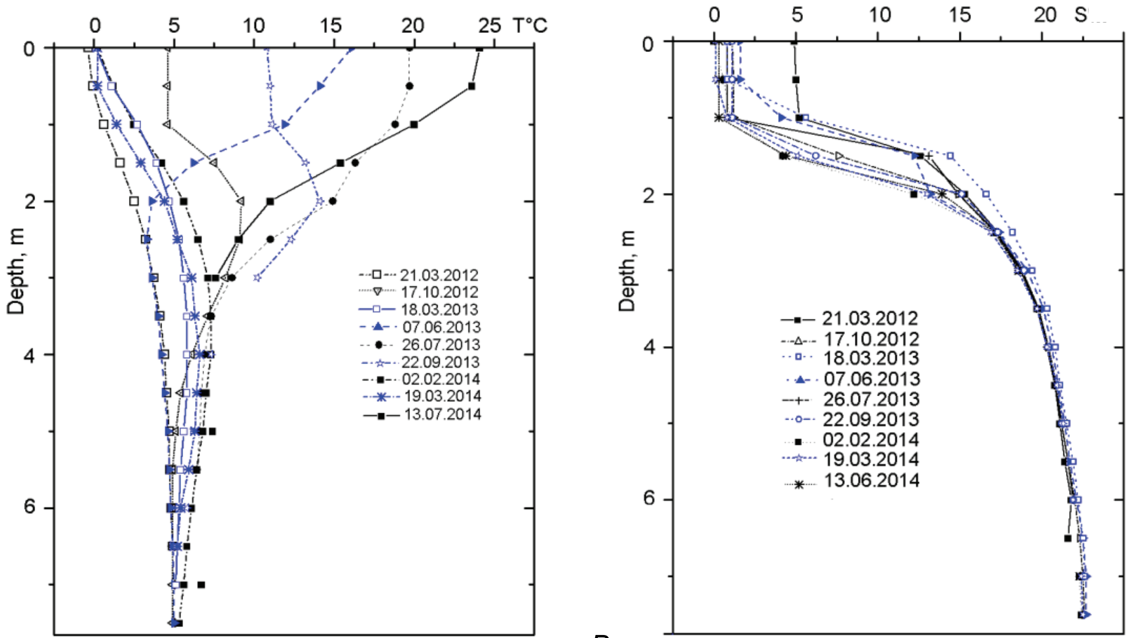
The lagoon on Cape Zeleny is one more water object with the phenomenon of a red water layer formed by the bloom of cryptophyte algae *Rhodomonas* sp. (7). Below the red layer, the water may appear green due to the development of anaerobic green sulfur bacteria (11,7). Measurements of illumination at different depths show that the red layer completely absorbs light (Figure 9).

Lake Trekhtzvetnoe ("Tricolour")

The lake is elevated beyond tidal influence. The name Trekhtzvetnoe means "tricolour"; we apply this to the lake nameless before, because of the impressive differences in the colour of its three layers. The upper, fresh mixolimnion from the surface to 1 m depth is brownish due to humic substances entering the lake from the surrounding swamp. From 1 to 1.5 m there is pycnocline with a steep salinity gradient. Underneath the water is salty. The middle water layer from 1.5 m to 1.75-1.9 m is aerobic; the border between aerobic and anaerobic layers can be observed at a depth of 1.75-1.9 m depending on the seasonal water level fluctuations. At the same time, this boundary serves as a chemocline or redox zone, all over the year its colour is bright green as a result of the mass development of green sulfur bacteria (11).

Below the redox zone there is a hydrosulfide salty water layer coloured in lemon yellow, turbid due to sulfur crystals. When lifting to the air gas bubbles appear in the water samples, presumably methane.

Among the known lakes separated from the White Sea the lake Trekhtzvetnoe meets the meromictic concept best. The vertical stratification was constant throughout the year and over the three years of observation (Figure 10).



A B

Figure 10: Annual variability of temperature (A) and salinity (B) in the lake Trekhtzvetnoe. Seasonal changes spread over upper 2.5 m, below conditions are constant.

The penetration of oxygen into the lake is limited by the chemocline level at 1.75-1.9 m. Underneath, the redox potential becomes negative, and pH decreases (Figure 11). Due to the meromictic structure, a sufficient amount of organic substances and the presence of sulfates in the lower water mass sulfate-reducing bacteria produce large quantities of hydrogen sulfide (5). One of the leaders in content of hydrogen sulfide is the Black Sea, where the H_2S concentration reaches 9.6 mg/l in anaerobic deep water (12). In the Norwegian Framvaren Fjord with the highest level of H_2S (6,000 µM which corresponds to 204 mg/l) ever reported for an open anoxic basin, the H_2S concentration is 25 times higher than in the Black Sea (13,14). In the monimolimnion of Trekhtzvetnoe Lake, the content of hydrogen sulfide reaches 630 mg/l which is double and triple the amount of the Framavaren Fjord value (5).

Light penetration in this lake is limited by the upper 1.5 m (Figure 12). The green layer located below is muddy because of the huge number of bacteria and completely absorbs light; so most of the water column in this lake stays in the aphotic zone.

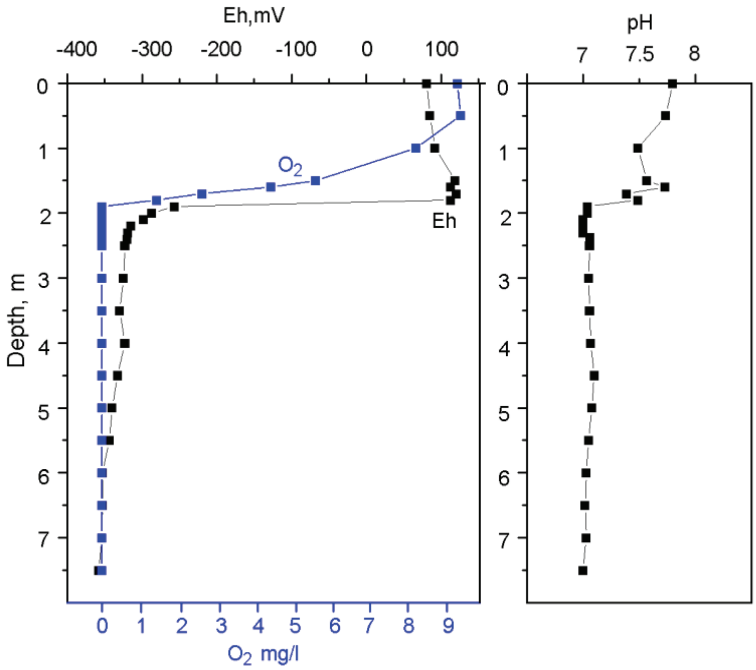


Figure 11: Eh, pH and dissolved oxygen concentration in the lake Trekhtzvetnoe in June 2014. Redox zone situated at a depth of 1.8-2.1 m.

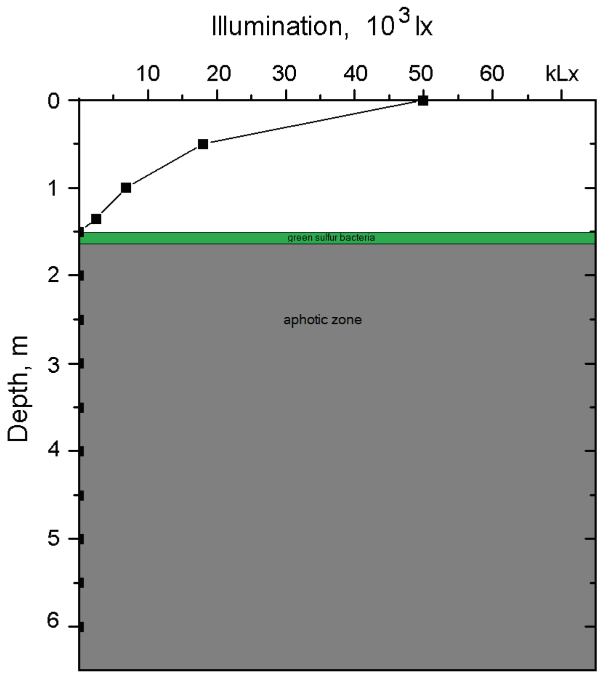


Figure 12: Illumination in the lake Trekhtzvetnoe. Sunlight penetrates the upper 1.5 m to the bacterial green layer.

Lake Nizhnee Ershovskoe

Together with the freshwater Ershovskoe Upper Lake this lake remained from an ancient strait. It is is separated from the sea by rocky rise with a freshwater creek falling to the sea.

Most of the water column is almost fresh (0.1-0.7 psu) (Figure 13). This lake has been considered as completely freshwater, until paleo-limnologists from the Botanical Institute of Rostock (Germany) in 2006 found a layer of brackish water with a salinity of 10 psu near the bottom (15). They reported the lake level was 1.6 m; considering that the height of the tide can reach 2.2 m the researchers hypothesized seawater inflow during spring tides and storms. Our observations suggest that such events take place at least once in a few years.

In the bathymetry of the lake there are two hollows, 2.3 and 2.8 m deep, separated by a shallow rise just 0.5 m deep. Both hollows contain salt water near the bottom. Salinity is higher in the hollow situated close to the sea, and the level of salty water is higher compared with the hollow distant from the sea.

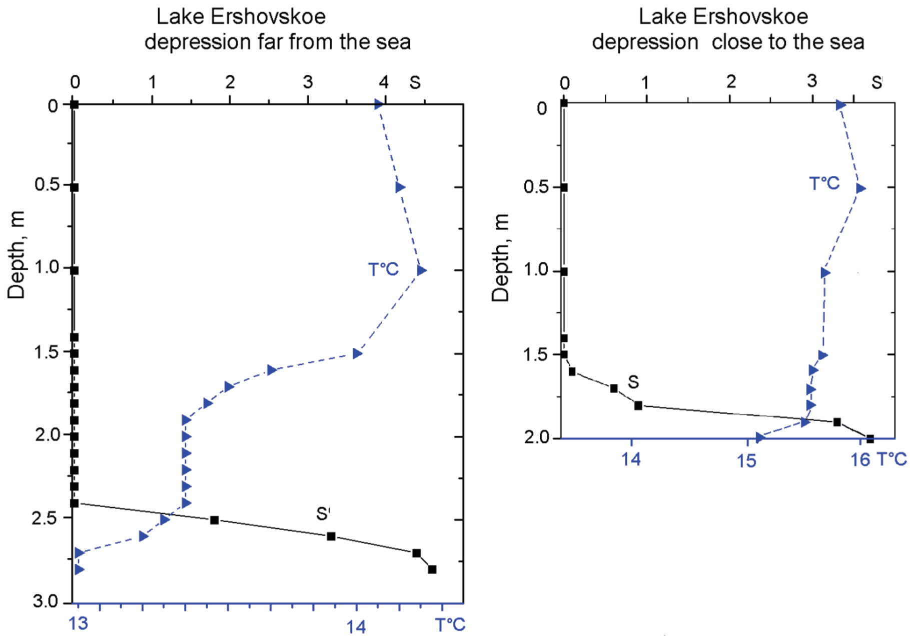


Figure 13: Profiles of temperature and salinity in the two depressions of the lake N. Ershovskoe in August 2014.

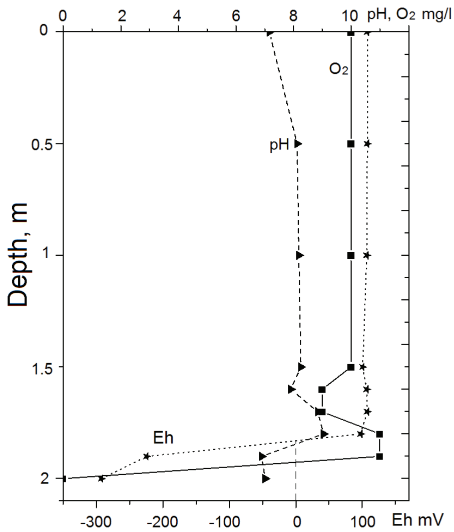


Figure 14: Profiles of dissolved oxygen concentration, Eh and pH in the Lake N. Ershovskoe, depression close to the sea, 25.08.2014.

The oxygen content, pH and redox potential values meet the three-layer model like the other lakes studied (Figure14). The upper layer is fresh and poor in plankton, the middle oxygenated saline layer favourable for phytoplankton growth and photosynthesis is very thin (about 0.5 m). The redox zone is coloured green because of unicellular algae bloom in upper sub-layer and green sulfur bacteria in the lower sub-layer (16). The redox layer depth position differs in two hollows, it is situated deeper in the hollow distant from the sea (2.4 m) and higher (1.8 m) in one close to the sea. As the lake is shallow, the anoxic zone is thin (less than 0.5 m).

Lake Elovoe

Lake Elovoe is a downstream basin in the chain of the four connected lakes. It is separated from the sea by a rocky barrier with fresh stream directed from the lake to the sea. There are no tidal fluctuations; seawater inflow is irregular and limited to floods caused by wind surges.

The water column consists of an almost fresh 1 m thick surface layer (0.1-0.4 psu) and an underlying salty water mass (16-25 psu) (Figure 15). The redox zone is found at a depth of 3-3.5 m, the conditions above are aerobic, and the sulfide layer is located below (Figure 16). The colour of the layer associated with the redox zone is brown due to the reproduction of bacteria. This layer prevents light penetration to the underlying layers (Figure 17).

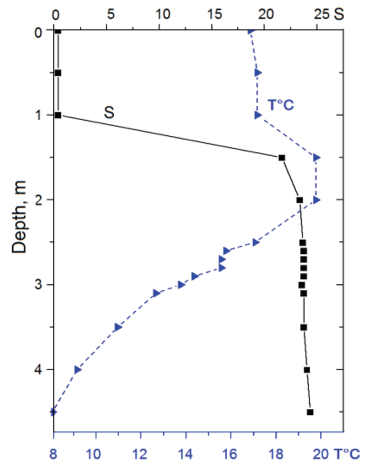


Figure 15: Profiles of temperature and salinity in the lake Elovoe, 28.08.2013.

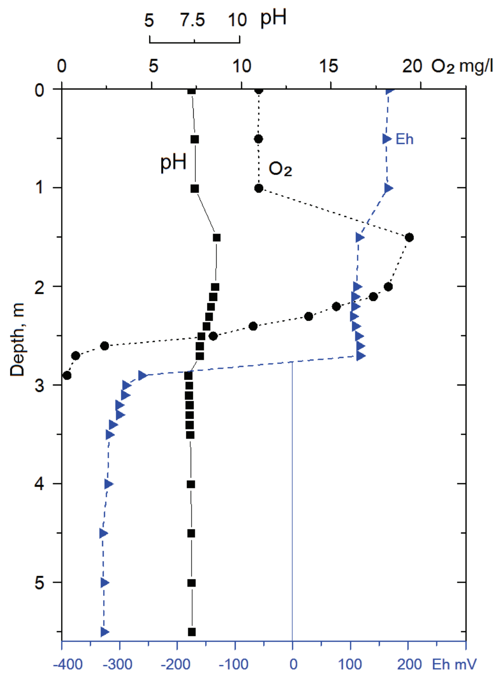


Figure16: Profiles of dissolved oxygen concentration (mg/l), Eh and pH in the lake Elovoe, 4.09.2014. The brown layer was situated at 2.9-3 m and coincided with the decrease of O_2, pH and Eh.

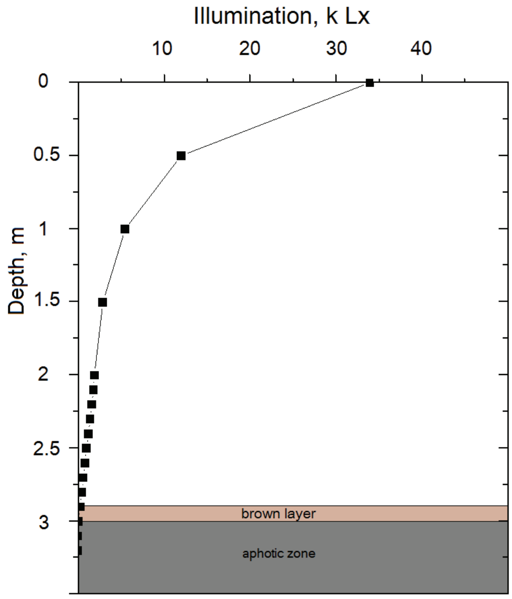


Figure 17: Illumination in the lake Trekhtzvetnoe. Below the brown layer the conditions are aphotic.

CONCLUSIONS

The described five reservoirs present different stages of isolation from the sea beginning with the lagoon with tidal fluctuations (lagoon on Cape Zeleny) to the meromictic reservoirs with a fresh upper layer and strong stratification (lakes Trekhtzvetnoe, Elovoe, N. Ershovskoe). The main feature of all lakes is strong vertical stratification supported by a dynamic equilibrium between fresh and salt water influx.

From the analysis of the vertical structure of the bottom sediments of fresh lakes on the Solovetsky Islands the duration of this stage was estimated to be 200-400 years (17).

According to the degree of isolation from the sea, weakening of the sea's influence and stabilization of vertical stratification in the studied water objects can be arranged in the following order (from youngest to oldest): Lagoon on Cape Zeleny, Lake Kislo-Sladkoe, Lake Elovoe, Lake N. Ershovskoe, Lake Trekhtzvetnoe.

Depending on the watershed area and the rate of fresh water sources the bay may develop in two ways: desalination (most reservoirs) or increasing salinity (lagoon on Cape Zeleny). Influx of salt water stimulates the process of bacterial sulfate reduction resulting in hydrogen sulfide in the lower water layer and proliferation of anaerobic phototrophic microorganisms, including green sulfur bacteria in the redox zone. Coloured microbial water layers in the redox zone are indicators of the stage of lake evolution. Red beds with cryptophyte algae bloom indicate early stages of the reservoir development, green layers with green sulfur bacteria indicating advanced stages. Development of microbial colour layers influences the vertical hydrological structure by depriving light of most of the water column.

The typical hydrological structure of separated salt lakes consists of an upper layer mixolimnion 1 to1.5 m thick and a monimolimnion divided into two layers: the upper photic aerobic and lower aphotic anaerobic layers. Between the main layers there are narrow transition zones with sharp gradients of physical and chemical parameters: a pycnocline on the border of freshened and salt layers, and a redox zone between aerobic and anaerobic layers. Each layer serves as a habitat for a particular ecological community: freshened for community with freshwater and euryhaline species, salt aerobic for marine organisms, anaerobic for thiobios, and redox zone for the community based on primary production including phytoplankton algae and anoxygenic photosynthesis provided by phototrophic bacteria (18).

Sharp vertical gradients require a special technique of sampling and measurement of physical and chemical parameters. They should precisely fall into the exact thin layer with vertical accuracy in centimetres and even millimetres. Conventional probes used in marine research do not provide such accuracy.

The existence of colour layers and accordance of the colour and taxonomic composition to various stages of isolation from the sea opens up the possibility for remote determination of the degree of isolation. The main problem is the small size of the lakes, the majority of them having linear dimensions of 200-500 m. When this problem is solved, remote sensing methods will enable us to identify new lakes and determine their stage of isolation from the sea, will make possible scans of remote areas and complete full inventories of reservoirs of this type, as well as provide data about the changes in coastal waters caused by climate change and sea-level dynamics.

REFERENCES

1 Romanenko F & O Shilova, 2012. The postglacial uplift of the Karelian coast of the White Sea according to radiocarbon and diatom analyses of lacustrine boggy deposits of Kindo peninsula. Doklady Earth Sciences, 442: 242-246. DOI: 10.1134/S1028334X12020079

2 Krasnova E D, A N Pantyulin, D N Matorin, D A Todorenko, T A Belevich & I A Milyutina, 2013. Nature of red layers in the lakes separating from the White Sea. In: Marine Biology, Geology, Oceanography Interdisciplinary Research in Marine Hospitals, Conference Proceedings, dedicated to the 75th anniversary of N. A. Pertsov White Sea Biological Station (27 February 1 March 2013, Moscow) (KMK, Moscow) 151-156 [in Russian: Краснова Е.Д., А.Н. Пантюлин, Д.Н. Маторин, Д.А. Тодоренко, Т.А. Белевич, И.А. Милютина, Д.А. Воронов, 2013. Природа красных слоев в водоемах, отделяющихся от Белого моря. В сб.: Материалы научной конференции «Морская биология, геология, океанология - междисциплинарные исследования на морских стационарах», посвященной 75-летию Беломорской биологической станции им. Н.А. Перцова (27 февраля – 1 марта 2013 г., Москва). М.: КМК: 151-156]

3 Krasnova E D, A N Pantyulin, T A Belevich, D A Voronov, N A Demidenko, L S Zhitina, L V Ilyash, N M Kokryatskaya, O N Lunina, M V Mardashova, A A Prudkovsky, A S Savvichev, A S Filippov & V P Shevchenko, 2013. Multidisciplinary studies of the separating lakes at different stage of isolation from the White Sea performed in March 2012. Oceanology, 53(5): 639-642. DOI: 10.1134/S0001437013050068

4 Krasnova E D, A N Pantyulin, T A Rogatykh & D A Voronov, 2013. Inventory of the lakes separated from the sea on the Karelian coast of the White Sea. In: The Study, Rational Use and Protection of Natural Resources of the White Sea. XII International Conference with the elements of a school for young scientists and graduate students. Collection of materials. Petrozavodsk, Russia (Karelian Research Centre, Russian Academy of Sciences, Petrozavodsk) 164-167 [in Russian: Краснова Е.Д., А.Н. Пантюлин, Т.А. Рогатых, Д.А. Воронов, 2013. Инвентаризация отделяющихся от моря водоемов на Карельском берегу Белого моря. В сб.: Проблемы изучения, рационального использования и охраны природных ресурсов Белого моря. XII Международная конференция с элементами школы для молодых ученых и аспирантов. Сборник материалов. Петрозаводск, Россия. Петрозаводск: Карельский научный центр РАН: 164-167]

5 Kokryatskaya N M, E D Krasnova, K V Titova & G N Losyuk, 2013. Formation of hydrogen sulfide defilement of the lakes separating from the sea (Kandalakshsky Bay, White Sea). In: Marine Biology, Geology, Oceanography Interdisciplinary Research in Marine Stations, Conference Proceedings dedicated to the 75th anniversary of N.A. Perzov White Sea Biological Station (27 February – 1 March 2013, Moscow) (KMK, Moscow) 123-126 [in Russian: Кокрятская Н.М., Е.Д. Краснова, К.В. Титова, Г.Н. Лосюк, 2013. Формирование

сероводородного заражения отшнуровывающихся от моря озер (Кандалакшский залив Белого моря). В сб.: Материалы научной конференции «Морская биология, геология, океанология - междисциплинарные исследования на морских стационарах», посвященной 75-летию Беломорской биологической станции им. Н.А. Перцова (27 февраля – 1 марта 2013 г., Москва). М.: КМК: 123-126]

6 Shaporenko S I, G A Koreneva, A N Pantyulin & N M Pertsova, 2005. Characteristics of the ecosystems of water bodies separating from Kandalaksha Bay of the White Sea. Water Resources, 32(5): 469-483. DOI: 10.1007/s11268-005-0060-x

7 Krasnova E D, A N Pantyulin, D N Matorin, D A Todorenko, T A Belevich, I Milyutina A & D A Voronov, 2014. Cryptomonad alga *Rhodomonas* sp. (*Cryptophyta, Pyrenomonadaceae*) bloom in the redox zone of the basins separating from the White Sea. Microbiology, 83(3): 270-277. DOI: 10.1134/S0026261714030102

8 Dugan H A & S F Lamoureux, 2011. The chemical development of a hypersaline coastal basin in the High Arctic. Limnology and Oceanography, 56(2): 495-507. DOI: 10.4319/lo.2011.56.2.0495

9 Krasnova E D, D A Voronov & A D Voronova, 2013. Effect of ice formation on the appearance of vertical stratification in saline lagoons separated from the White Sea. In: The Study, Rational Use and Protection of Natural Resources of the White Sea. XII International Conference with the elements of a school for young scientists and graduate students. Collection of materials. (Petrozavodsk: Karelian Research Centre, Russian Academy of Sciences, Petrozavodsk, Russia) 168-170 [in Russian: Краснова Е.Д., А.Д. Воронова, Д.А. Воронов, 2013. Влияние образования льда на формирование вертикальной стратификации в соленых лагунах, отделяющихся от Белого моря. В сб.: Проблемы изучения, рационального использования и охраны природных ресурсов Белого моря. XII Международная конференция с элементами школы для молодых ученых и аспирантов. Сборник материалов. Петрозаводск, Россия. Петрозаводск: Карельский научный центр РАН: 168-170]

10 Krasnova E D, D A Voronov & A D Voronova, 2013. The role of sea ice brine in the formation of vertical stratification in reservoirs, separated from the White Sea. In: Geology of Seas and Oceans: Proceedings of XX International Conference (school) on Marine Geology. V. III (GEOS, Moscow) 201-205 [in Russian: Краснова Е.Д., Д.А. Воронов, А.Д. Воронова, 2013. Роль вымораживания рассола из морского льда в формировании вертикальной стратификации в водоемах, отделяющихся от Белого моря. В сб.: Геология морей и океанов: Материалы XX Международной научной конференции (школы) по морской геологии. Т. III. М.: ГЕОС: 201-205]

11 Kharcheva A V, E D Krasnova, D A Voronov, O M Gorchkova, V I Yuzhakov & S V Patsaeva, 2013. Spectral-optical and physico-chemical properties of water in meromictic lakes in Kandalaksha Bay of the White Sea/ In: Geology of Seas and Oceans: Proceedings XX International Scientific Conference (school) on Marine Geology. V. III. (GEOS, Moscow) 261-265 [in Russian: Харчева А.В., Е.Д. Краснова, Д.А. Воронов, О.М. Горшкова, В.И. Южаков, С.В. Пацаева, 2013. Спектрально-оптические и физико-химические свойства воды в меромиктических водоемах Кандалакшского залива Белого моря. В сб.: Геология морей и океанов: Материалы XX Международной научной конференции (школы) по морской геологии. Т. III. М.: ГЕОС: 261-265].]

12 Nekludov I M, B V Bortz, O V Polevich, V I Tkacjenko & B A Shilyaev, 2006. Alternative hydrogen sulfide energy in the Black Sea. Status, problems and prospects. Alternative Energy and Ecology, 12(44): 23-30 [in Russian: Неклюдов И.М., Б.В. Борц, О.В. Полевич, В.И. Ткаченко, Б.А. Шиляев, 2006. Альтернативная сероводородная энергетика Черного

моря. Состояние, проблемы и перспективы. Альтернативная энергетика и экология, 12 (44): 23-30].]

13 Millero F J, 1991. The oxidation of H_2S in Framvaren Fjord. Limnology and Oceanography, 36: 1007-1014. http://www.aslo.org/lo/toc/vol_36/issue_5/1007.pdf (last date accessed: 11 Mar 2015)

14 Behnke A, J Bunge, K Barger, H-W Breiner, V Alla & T Stoeck, 2006. Microeukaryote community patterns along an O_2/H_2S gradient in a supersulfidic anoxic fjord (Framvaren, Norway). Applied and Environmental Microbiology, 72(5): 3626-3636. DOI: 10.1128/AEM.72.5.3626-3636.2006

15 Dreßler M, M Schult, M Schubert & J Buck, 2009. Basin elevation and salinity changes: late Holocene development of two freshwater lakes at the Karelian White Sea coast, northwest Russia as reflected in their sediments. Hydrobiologia, 631: 247-266. DOI 10.1007/s10750-009-9814-9

16 Kharcheva A V, A V Meschankin, I I Lyalin, E D Krasnova, D A Voronov & S V Patsaeva, 2014. The study of coastal meromictic water basins in the Kandalaksha Gulf of the White Sea by spectral and physicochemical methods. SPIE Proceedings, 90310T. DOI: 10.1117/12.2051737

17 Subetto D A, V P Shevchenko, A V Ludikova, D D Kuznetsov, T V Sapelko, A P Lisitsyn, V Ya Evzerov, P Van Beek, M Souhaut &, G D Subetto, 2012. Chronology of isolation of the Solovetskii archipelago lakes and current rates of lake sedimentation. Doklady Earth Sciences, 446 (1): 1042-1048. DOI: 10.1134/S1028334X12090140

18 Savvichev A S, O N Lunina, I I Rusanov, E E Zakharova, E F Veslopolova & M V Ivanov, 2014. Microbiological and isotopic geochemical investigation of lake Kislo-Sladkoe, a meromictic water body at the Kandalaksha Bay shore (White Sea). Microbiology, 83(1-2), 56-66. DOI: 10.1134/S0026261714010111