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SEASONAL MIXING REGIME OF EURASIAN LAKES: MAJOR DRIVERS AND CLIMATIC TRENDS.

G. Kirillin, *Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany*
K. Sharsheeva, *Kyrgyz State Technical Univercity named after I. Razzakov, Bishkek, Kyrgyzstan*
N. Israilova, *Kyrgyz State Technical Univercity named after I. Razzakov, Bishkek, Kyrgyzstan*
S. Alymkulov, *Kyrgyz State Technical Univercity named after I. Razzakov, Bishkek, Kyrgyzstan*
A. Kurbaniyazov, *Yasavi International Kazakh-Turkish University, Turkestan, Kazakhstan*
P. Zavialov, *Shirshov Institute of Oceanology Russian Academy of Science, Moscow, Russia*

Annotation

We discuss and summarize recent findings from several lake regions of Eurasia to reveal the typical features of their mixing regime and major threats from the anthropogenic activities and global warming. The continental climate ensures high annual amplitudes in the heat supply; hence the majority of lakes, either in the Arctic or in the Central Asia, tend to dimictic behavior, being well mixed at least twice a year. However, salinization of arid lakes, trend to warmer winters in temperate regions, and deepening of Arctic lakes due to permafrost thaw can produce quick and drastic changes in the lake mixing regimes.

Keywords: Oligomictic lakes, meromictic lakes, global warming, melting of permafrost.

СЕЗОННЫЙ СМЕШАННЫЙ РЕЖИМ ЕВРАЗИЙСКИХ ОЗЕР: ОСНОВНЫЕ ДРАЙВЕРЫ И КЛИМАТИЧЕСКИЕ ТЕНДЕНЦИИ.

Кириллин Г., *Институт пресноводной экологии и внутреннего рыболовства Лейбница, Берлин, Германия*
Шаршеева К., *Кыргызский государственный технический университет им. И. Раззакова, Бишкек, Кыргызстан*
Исраилова Н., *Кыргызский государственный технический университет им. И. Раззакова, Бишкек, Кыргызстан*
Алымкулов С., *Кыргызский государственный технический университет им. И. Раззакова, Бишкек, Кыргызстан*
Курбаниязов А., *Международный казахстанско-турецкий университет им. Ясави, Туркестан, Казахстан*
Завьялов П., *Институт океанологии им. С.И. Ширшова РАН, Москва, Россия*

Аннотация

Обсуждены новые результаты исследований в различных озерных регионах Евразии с целью выявить типичные черты их гидрофизического режима и основные угрозы связанные с антропогенной активностью и глобальным потеплением. Континентальный климат характеризуется большими сезонными амплитудами потоков тепла, вследствие чего большинство озер от Арктики до Средней Азии имеет димиктический сезонный режим, полностью перемешиваясь, как минимум дважды в год. Однако, осолонение аридных озер, тенденция к теплым зимам в умеренных регионах и углубление термокарсовых озер Арктики в результате таяния мерзлоты — способны коренным образом и в короткое время изменить их гидрофизический режим.

Ключевые слова: Олигомиктические озера, меромиктические озера, глобальное потепление, таяние вечной мерзлоты.

Introduction. The continent of Eurasia hosts several major lake systems. Their value for the regional and global climate, water resources, and sustainable ecosystem functioning can hardly be overestimated. While some of the lake systems—like the "European Great Lakes" Ladoga and Onega, the post-glacial lakes of Fennoscandia, Lake Baikal—are relatively well investigated, many key lake regions have attracted the attention only recently (e.g. the thermokarst lake landscapes of Siberian tundra), or lack systematic studies almost completely (e.g. the large lakes of arid climatic zone of Central Asia).

Being the largest of the continents, Eurasia is characterized by the continental climate and its subtypes, cold semi-Arid, cold Arid, and sub-Arctic climates. Therefore, the absolute majority of Eurasian lakes undergo strong seasonal variations in the heat exchange with the atmosphere, with typical surface temperatures varying in the range of tens of degrees Celsius within a year, and crossing the value of the maximum density for freshwater of ~4°C. This fact determines the main feature of their physical regime: stable vertical stratification with respect to temperature during the most part of the year, interrupted by two complete mixing events (overturns) twice a year, when lake temperatures arrive at the maximum density value. Hence, the main distinctive feature of Eurasian lakes is *dimixis* in terms of Hutchinson's classification [Hutchinson and Löffler 1956, Kirillin and Shatwell 2016]. Below, we analyze factors able to disrupt regular seasonal mixing of lakes and discuss possible ecological consequences of it.

Thermokarst lakes: Probability of polymictic-dimictic transition. Thermokarst lakes, i.e. those created by melting permafrost are inherent features of tundra landscape. Intense research on thermokarst lakes in the last several decades has been motivated by a potentially increasing role of melting permafrost in the global carbon cycle and release of greenhouse gases. Being very shallow, the lakes are supposed to be *polymictic*, well-mixed down to the bottom during the most part of the year. Observations from several small lakes in the delta of the Lena River [Boike et al. 2016] demonstrated that shallow thermokarst lakes can be stratified for several weeks in summer. Using these observations as a starting point, we investigated variations in the mixing regime driven by the potential deepening of lakes driven by the permafrost melting. Under equal climatic forcing, lake depth is the primary factor determining the duration of summer stratification (the second one being the water transparency, Kirillin and Shatwell, 2016). Sensitivity model runs with the lake depth varying in the range 2-12 m using the same meteorological input data demonstrated that lakes in this climatic zone with mean depths >5 m should have dimictic stratification regimes, i.e. develop continuous stratification in summer with duration of 1 month or longer (Figure 10). This also supports the observation of summer stratification in deeper (> 6 m) Alaskan thermokarst lakes (Sepulveda-Jáuregui et al., 2015). In lakes of about 8 m depth or more, the summer stratification duration significantly increases since high thermal inertia prevents vertical mixing during the autumn cooling in August-September (Figure 11). Hence, even the thermokarst lakes of sub-Arctic and Arctic tundra gain enough heat in summer to develop stable thermal stratification, so that all lakes with mean depths > 5 m are suggested to maintain continuous stratification for the largest part of the summer open water period [Boike et al. 2016]. The lack of the intense exchange of deep lake waters with the atmosphere during several months of stratification determines the biogeochemical processes in the lakes, which may have climatic effects on regional and global scales. The duration of the thermal stratification in summer affects the concentration and vertical distribution of dissolved oxygen: Longer summer stratification provokes deep anoxia and favors methanogenesis in the deep water column and upper sediment (Golosov et al., 2012). Lake sediments are thought to be one of the major sources of methane, having a strong influence on the greenhouse effect [Holgerson and Raymond 2016, Wik et al. 2016]. As stratification typically prevents oxidation of methane [McGinnis et al. 2015], the increase of lake depth due to thawing permafrost [Langer et al. 2016] may produce strong intensification of methane production and release to the atmosphere from the large areas of Siberian tundra. Thus, the transition of shallow *polymictic* (i.e. regularly mixed and oxidized to the bottom) lakes and ponds may play a significant role in the positive feedback between warming in the Arctic and methane release.

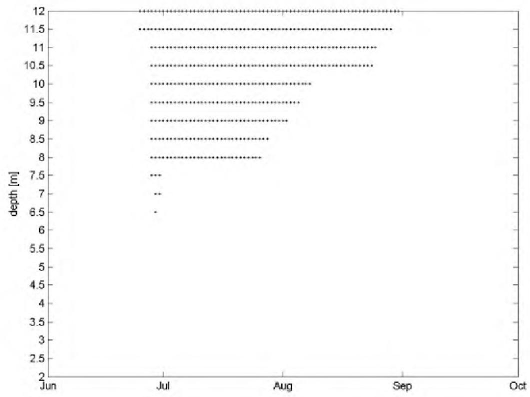

Figure 1. Duration of the summer stratification period vs. lake depth calculated with the FLake model for thermokarst lakes of Siberian tundra (Delta of the Lena River) Modified from (Boike et

Oligomictic and meromictic lakes of Cenral Asia. The lakes of the arid and alpine regions of Eurasia, such as Central Asia and Tyan-Shan, are especially sensitive to the regional hydrological balance. Due to dry climatic conditions, many of these lakes are endorheic, having no outflows, and are therefore subject to salinization, with dissolved salts affecting the hydrophysical conditions, in particular, vertical mixing. The mixing regime of brackish and saline lakes, especially the deep ones, is often not dimictic but rather *oligomictic*, having retention times of several years or decades, or *meromictic*, with salt stratification preventing the exchange of waters between different layers completely.

Oligomictic lakes (such as Lake Baikal and Issyk-Kul) reveal complex mechanisms of the deep water renewal, which apparently include horizontal exchange between lakes areas with various mean water depth driven by differential cooling and heating, large-amplitude internal waves and inflows. Hence, the lake waters remain well oxidized down to several hundred meters. Still, the exact mechanisms of the deep water renewal are not completely understood and require investigation in order to estimate the potential impact of changes in the heat and water budget on the deep lakes. The major effect of the regular deep mixing consists in supply of the dissolved oxygen (DO), which ensures the high water quality and low trophic status of deep waters. Here we use recent observations on the oxygen concentrations in Lake Issyk-Kul to reveal major sources and sinks of the DO and to estimate the rate of vertical mixing in near-bottom waters of the lake. The dissolved oxygen soundings were performed in mid-June and made it possible to identify an exceptionally important phenomenon in the dynamics of the Issyk-Kul ecosystem: the presence of a deep maximum of dissolved oxygen associated with the production of micro- and picoplankton (photosynthesizing algae a few micrometers in size). Detailed oxygen profiles obtained with the help of a fast-response oxygen logger RINKO-I (manufactured by JFE Advantech, Japan) allowed determining the depth of occurrence of the maximum, as well as peak values of concentrations. With an average oxygen saturation of about 70% over the water column, the concentration of dissolved oxygen in the peak reaches 98% (Fig. 2).

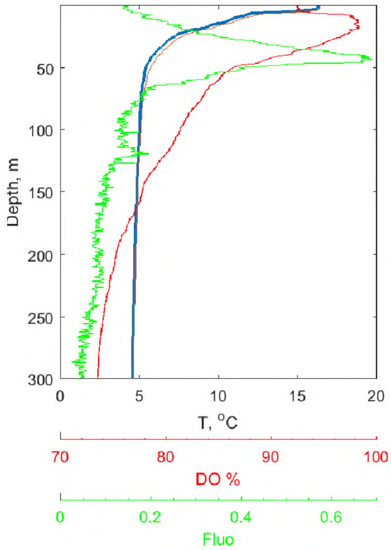

Figure 2. Vertical profiles of temperature (blue), fluorescence (green) and dissolved oxygen (red) in the central part of Lake Issyk-Kul

The peak itself is located at depths of 25-40 m, which is approximately 2 times deeper than the Secchi (transparency) depth (Fig. 3). The maximum of oxygen does not always exactly coincide with the maximum of fluorescence (biomass of plankton): the latter lies 10-20 m deeper (Fig. 2). The most obvious reason for this discrepancy between the maximum of biomass and plankton production is the limiting factor of the underwater solar radiation: in highly transparent of Issyk-Kul waters, plankton is able to slowly accumulate significant biomass at great depths (up to 50 m), but the most active photosynthesis occurs on shallower horizons, directly under the thermocline (a layer of vertical temperature jump). These preliminary conclusions require however further justification, taking into account such factors as vertical stratification of different species of plankton, vertical oxygen transport by turbulence and internal waves, and increased oxygen consumption by heterotrophic microorganisms actively growing in a layer with a maximum biomass.

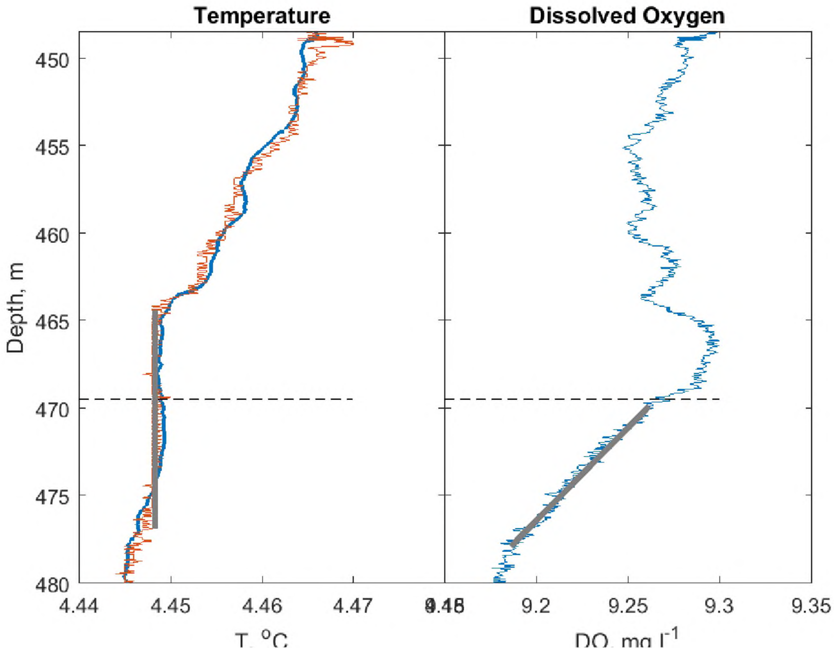

Figure 3. (left) Temperature and (right) dissolved oxygen profiles near the bottom of Issyk-Kul.

Detailed measurements of the oxygen distribution revealed another important aspect of the Issyk-Kul dynamics viz. the structure of the turbulent near-bottom boundary layer (BBL). Unlike temperature, which remains nearly homogeneous in the several ten meters thick hypolimnion, the oxygen profile demonstrates an appreciable decline of concentrations near the lake bottom, produced by the biochemical oxygen consumption in the lake sediment (Fig. 4). The vertical extension of the oxygen gradient allowed us to estimate with a high accuracy the thickness of the BBL as amounting at ~10 m. The linear decrease in the concentration of oxygen with depth in this layer indicates a quasi-stationary mode of vertical exchange. A rough estimation of the near-bottom turbulence can be derived from the BBL thickness of 10^1 m and a seasonal time scale of 10^2 days. These values provide the vertical exchange coefficients of 10^{-5} m^2 s^{-1}, i.e. at least 1000 times the rate of diffusion transfer of oxygen in a non-turbulent medium. The evidence of strong near-boundary turbulence confirms the initial hypothesis of intense bottom circulation in Issyk-Kul. The question about the generation mechanisms of this circulation remains open. A plausible hypothesis was proposed by Peeters et al. (2003), who suggested the major role played in the deep water renewal of horizontal density currents. The latter are driven in winter by differential cooling of the deep central part of the lake and shallow coastal areas. However, the new results can be also interpreted as indicators of intense deep mixing during the warming season that in turn suggests presence of additional deep mixing mechanisms. Potentially important contributors to the bottom mixing are the basin-scale waves (seiches), whose role in the transport of wind energy to deep lake areas is well-known (). Seiche dynamics in Issyk-Kul has not been thoroughly investigated to date, though can be suggested to be very energetic, taking into account strong winds, large lake size, and a regular shape of the lake.

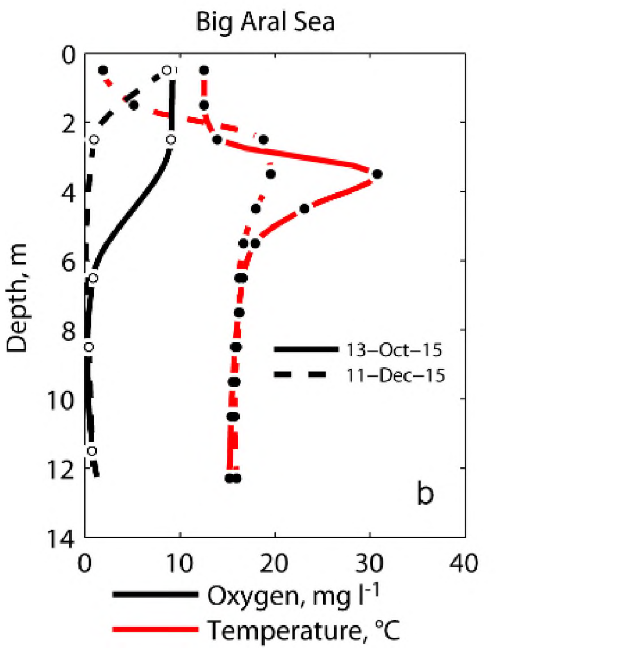

Fig 4. Vertical distribution of temperature and dissolved oxygen in the Big Aral Sea in October and December 2015.

The fact that anthropogenic alteration of the regional water budget may change completely the mixing regime of lakes is demonstrated by the notorious example of the Aral Sea. Formerly a brackish dimictic lake, the Aral Sea turned into a number of isolated water bodies with diverging characteristics, after losing about 80% of its water volume [Izhitskiy et al. 2016]. The second largest remaining basin, the *Small Aral*, is still dimictic, feed by the Syrdayia River and isolated by a man-made dam from the rest of the former water area. Yet, the largest remaining basin, the *Big Aral*, has lost completely the Amudarya inflow and became to a hypersaline meromictic lake revealing extraordinary physical conditions with acute effects on biogeochemical processes. The strong chemocline (halocline) persists in the lake at water depths of about 5 m. The origin of the chemocline is most probably endogenic, resulting from intrusion of water with different salinity from one of neighboring basins. However a biogenic contribution to the density gradient cannot be excluded: The epilimnion waters above the halocline are densely populated by zooplankton typical for hypersaline lakes (*Artemia Salina*), while the dead biological material accumulates in the halocline, with high rates of degradation, characterized by a strong peak of turbidity and drop of the dissolved oxygen content to zero. The high transparency of the upper layer allows effective storage of solar radiation in the upper several meters of the water column, while the strong vertical stability due to salt gradient prevents upward release of heat. As a result, the Big Aral represents now a “solar trap”, accumulating solar energy with a local temperature maximum forming at the chemocline. In

October, at the intense atmospheric cooling, the water temperatures in the chemocline exceeded 30°C, while surface temperatures were about 10°C, and the daily mean air temperatures were at 0°C (minimum values around –12°C). The thermal regime is unique for the Aral Sea; other hypersaline lakes, like the Dead Sea or Lake Urmia, do not undergo such strong seasonal variations in the surface heat fluxes. The newly formed meromictic regime implies consequences at the regional scales, in the biogeochemical regime, as the monimolimnion of the lake accumulates continuously increasing amount of methane during the last years, as well as in the regional climate, as lake represents in winter a warm spot on the surface, slowly releasing the accumulated heat onto the atmosphere.

Transition from dimictic to warm monomictic regime: effect of winter warming due to climate change. Changing of the seasonal mixing regime from dimictic to meromictic typically requires an anthropogenic intervention into the water budget, and endangers mostly the lakes of arid climate zone, where the hydrological regime is particularly vulnerable. There is however another potential threat for the lake mixing regimes, determined by the observed positive trend in surface lake temperatures. The latter is considered to be an indicator of global warming and is reported to be especially strong in northern temperate lakes in winter. The existing future climate scenarios predict that, if the warming trend persists for next several decades, dimictic lakes located in regions of Europe with mild temperate climate will never cool below the maximum density temperature, changing thus their mixing regime to *warm monomictic,* without a winter stratification period. The mixing regime transition will take place first in deeper lakes, while the shallower ones will possess the winter stratification for longer, i.e. the capacity to store heat throughout wintertime depends directly on the mean depth (Fig. 2). The consequences of the physical regime change for biogeochemistry of lakes may appear manifold. The absence of winter stratification suggests higher mixing rates and better oxygen supply to the hypolimnion in winter. On the other hand it also implies a stronger supply of nutrients to the epilimnion together with the better light conditions in an ice- and snow free lake, hence favoring phytoplankton development and eutrophication. Other potential negative effects of vanishing winter stratification are higher near-bottom temperatures in summer and a longer summer stratification period [Kirillin 2010]. Both factors favor bacterial activity in lake sediments, accelerate biodegradation of organic matter and, as a result, increase oxygen consumption and methane production. Deep anoxia in previously well-oxygenated lakes and a stronger contribution of these lakes to methane release may be hypothesized as possible global outcomes.

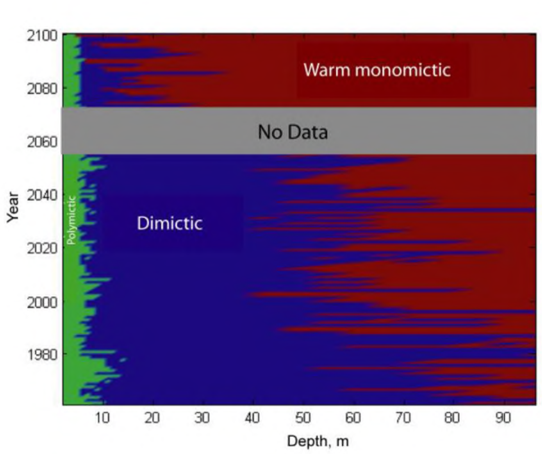

Fig. 5. Scenarios of the mixing regime transition in lakes of Western Europe after Kirillin [2010]

Conclusions. The above discussed recent findings demonstrate the fragility of the hydrophysical regime of Eurasian lakes. The continental climate ensures high annual amplitudes in the heat supply hence the majority of lakes, either in the Arctic or in the Central Asia, tend to dimictic behavior, being well mixed at least twice a year. Among the major threats to the seemingly stable seasonal mixing patterns of Eurasian lakes are anthropogenic salinization of arid lakes, trend to warmer winters in temperate regions, and deepening of Arctic lakes due to permafrost thaw.

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References

1. Boike J. и др. Thermal processes of thermokarst lakes in the continuous permafrost zone of northern Siberia - observations and modeling (Lena River Delta, Siberia) // Biogeosciences. 2015. T. 12. № 20. C. 5941–5965.
2. Holgerson M.A., Raymond P.A. Large contribution to inland water CO2 and CH4 emissions from very small ponds // Nat. Geosci. 2016. T. 9. № 3. C. 222-U150.
3. Hutchinson G. E., Löffler H. The thermal classification of lakes //Proceedings of the National Academy of Sciences. – 1956. – T. 42. – №. 2. – C. 84-86.
4. Izhitskiy A.S. и др. Present state of the Aral Sea: diverging physical and biological characteristics of the residual basins // Sci Rep. 2016. T. 6. C. 23906.
5. Kirillin G. Modeling the impact of global warming on water temperature and seasonal mixing regimes in small temperate lakes // Boreal Environ. Res. 2010. T. 15. № 2. C. 279–293.
6. Kirillin G., Shatwell T. Generalized scaling of seasonal thermal stratification in lakes //Earth-Science Reviews. – 2016. – T. 161. – C. 179-190.
7. Kirillin G., Terzhevik A. Thermal instability in freshwater lakes under ice: Effect of salt gradients or solar radiation? // Cold Regions Science and Technology. 2011. T. 65. № 2. C. 184–190.
8. Langer M. и др. Rapid degradation of permafrost underneath waterbodies in tundra landscapes-Toward a representation of thermokarst in land surface models // J. Geophys. Res.-Earth Surf. 2016. T. 121. № 12. C. 2446–2470.
9. McGinnis D. F. et al. Enhancing surface methane fluxes from an oligotrophic lake: exploring the microbubble hypothesis //Environmental science & technology. – 2015. – T. 49. – №. 2. – C. 873-880.
10. O'Reilly C.M. и др. Rapid and highly variable warming of lake surface waters around the globe // Geophys. Res. Lett. 2015. T. 42. № 24. C. 2015GL066235.
11. Wik M. и др. Climate-sensitive northern lakes and ponds are critical components of methane release // Nat. Geosci. 2016. T. 9. № 2. C. 99.