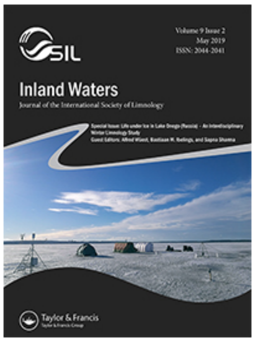

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EDITORIAL

Life under ice in Lake Onego (Russia) – an interdisciplinary winter limnology study

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Introduction

This special issue of *Inland Waters* focuses on recent under-ice research in Lake Onego, Russia. Compared to open waters, research on ice-covered lakes is sparse because of the demanding work environment and logistics in the field (Kirillin et al. 2012). In the past, large lakes in particular, such as the European Lakes Onego (61°36′10.52″N, 35°34′22.42″E) and Ladoga (61°00′0.00″N, 31°00′0.00″E), were not typically studied during their ice-cover periods. Today, however, substantial concerns exist about the potential effects of rapid climate warming and the resulting reduction in ice cover in high latitude lakes. Subsequently, scientific interest in boreal lakes has strongly increased (Brown and Duguay 2010). At the same time, these lakes are important for drinking water, transport, hydropower, and recreation (Rukhovets and Filatov 2010, Magnuson and Lathrop 2014) and represent outstanding biological resources. Therefore, the sustainable use of water and conservation of biodiversity in Lakes Ladoga and Onego were declared a high priority in 2013 by the Russian Security Council (http://kremlin.ru/events/president/news/19655).

Given these circumstances, a better understanding of the role of ice cover on ecological characteristics of these large lakes is required. Lake Onego, a lake of glacial-tectonic origin located in Karelia (Russia), offers a fascinating place for such studies. As the second largest lake on the European continent (9600 km^2, 292 km^3; Filatov and Rukhovets 2012), Lake Onego is ice covered for several months each winter, which strongly influences its characteristics, including the occurrence of endemic species. Excellent research infrastructure, collaboration opportunities, and expertise in winter limnology (Jonas et al. 2003) are available from the Northern Water Problems Institute, Karelian Research Center of the Russian Academy of Sciences (NWPI-KRC-RAS; http://nwpi.krc.karelia.ru/e/), located on the shore of Lake Onego in Petrozavodsk. The Limnology Center of the Swiss Federal Institute of Technology Lausanne (LIMNC-EPFL; https://www.epfl.ch/research/domains/limnc/) was proposed to launch a research initiative supported by the Fondation pour l'Etude des Eaux du Leman (FEEL). Hence, we designed a multidisciplinary project on Lake Onego during late winter and spring from 2015 to 2017 to investigate physical, geochemical, and biological under-ice processes in this seasonally ice-covered lake. Additional fields of research included hydrology, paleolimnology, and remote sensing. The LIMNC-EPFL and the NWPI-KRC-RAS jointly implemented this project.

The following 7 publications on Lake Onego are the outcome of this multidisciplinary project. We consider this contribution a first step toward a more integrated understanding of winter limnological processes and hope to stimulate follow-up investigations on these fascinating aquatic systems.

Fieldwork on Lake Onego

During the "Life Under Ice" project, researchers participated in 6 field expeditions on Lake Onego during March and June 2015, 2016, and 2017 (Table 1). Because Lake Onego is usually ice covered from December to May, the fieldwork took place on and under the ice and just after ice break-up. Measurements were mainly focused on Petrozavodsk Bay (PB: length ~15 km, width ~7 km, 16 m average depth), one of the largest bays of Lake Onego, located in the western part of the lake (Fig. 1). To investigate the spatial variation linked to the second largest tributary, River Shuya (RS), sampling

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‡Key organizers of the study.

Table 1. Locations and periods of fieldwork.

Fieldwork periods	Study site and position in Figure 1	# of researchers
14–26 March 2015	RS, Petrozavodsk Bay (IC), and open Lake Onego (C3)	39
2–5 June 2015	RS, Petrozavodsk Bay (IC, PB3), open Lake Onego (PO2, C2, C3)	11
9–23 March 2016	RS, Petrozavodsk Bay (PB1, PB2, IC, PB2.5, PB3) and open Lake Onego (C3)	43
2–6 June 2016	RS, Petrozavodsk Bay (PB1, PB2, IC, PB2.5, PB3), open Lake Onego (PO2, C2, C3), and two surface transects (PB and TS)	12
14–20 March 2017	RS, Petrozavodsk Bay (PB1, PB2, IC, PB2.5, PB3)	30
31 May to 5 June 2017	RS, Petrozavodsk Bay (PB1, PB2, IC, PB2.5, PB3), open Lake Onego (PO2, C2, C3), and a surface transect (T0)	11

was also conducted from RS to PB and to the open waters in 2016 and 2017.

In March each year, an ice camp (IC; Fig. 2a) was established for ~2 weeks in the center of PB, where depth reaches 27 m. At this site, various autonomous logging sensors were installed on the ice (e.g., meteorological station, pyranometer) and under the ice (e.g., pyranometers, thermistor chains, photosynthetic active radiation sensors,

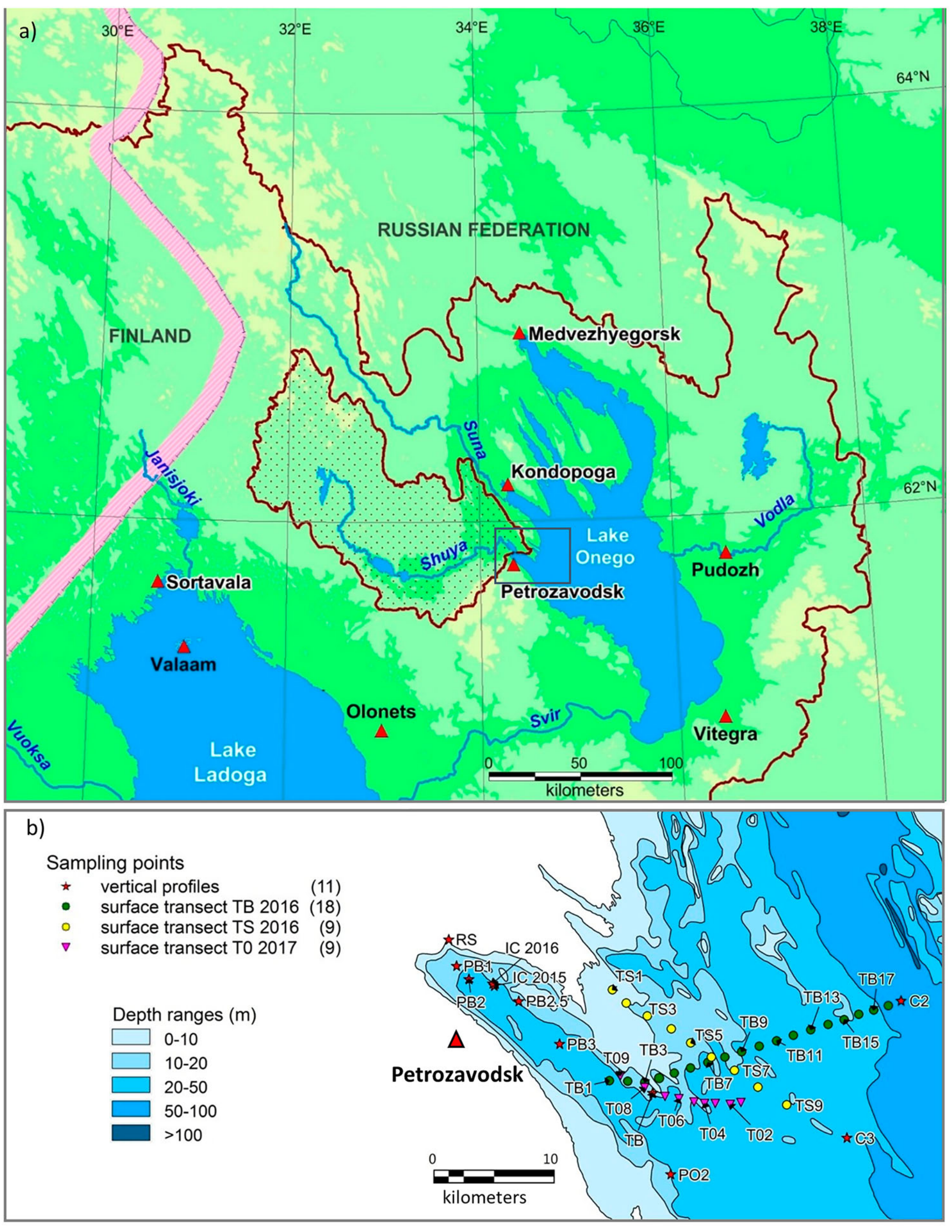

Figure 1. (a) Overview of the Lakes Onego and Ladoga catchment with the River Shuya catchment area highlighted. Hills are represented in yellow, mid levels in pale green, and lowlands in green. (b) Zoom on Petrozavodsk Bay (PB) and its immediate surrounding; bathymetric map with locations of ice camps and sampling areas.

Figure 2. (a) Ice camp on Lake Onego in March 2016, © Alexander Bahr (EPFL). (b) Hovercraft used for transportation in March 2017, © Hannah Chmiel (EPFL). (c) Working from ice in March 2016, © Natacha Pasche (EPFL).

current meters, carbon dioxide sensors). At least 2 researchers were continuously present to monitor the ice thickness and the water accumulation on ice and to take vertical profiles every hour with a CTD75M probe (Sea and Sun Technology, Germany) and a fluoroprobe (BBE Moldaenke, Germany). All researchers used a hovercraft (Fig. 2b) to access the IC and other sampling sites to take water, phytoplankton, and zooplankton samples, or other specific measurements (Fig. 2c), as well as to retrieve sediment cores. In June, the fieldwork took place on the research vessel ECOLOG, with a smaller research team investigating biology, chemistry, and greenhouse gases within the open water. Two additional sites were sampled in the open lake (Fig. 1b).

Overall, more than 75 researchers participated in this project from 17 different institutions and 5 countries (Table 2). The NWPI-KRC-RAS and the LIMNC-EPFL jointly organized the field expeditions and coordinated the 7 subprojects investigating physics of under-ice convection, phytoplankton, greenhouse gases, ecosystem functioning, sedimentology, and ice structure using remote sensing.

Highlights from the project

The publication by Filatov et al. (2019) addressed the issues of climate change in the Lake Onego region. To shed light on how much climate has already changed the hydrological properties of the Lake Onego watershed over the past decades, Filatov et al. (2019) investigated the water balance, water temperature, and ice-cover regime of Lakes Ladoga and Onego. Disappointingly, local warming and absence of ice-cover during the project period (2015–2017) precluded fieldwork on Lake Ladoga. Although work on ice was possible for Lake Onego, its total ice-cover duration has decreased by ~20 d/yr over the last 60 years (Filatov et al. 2019). Filatov et al. (2019) provided evidence of trends of increase

Table 2. Institutions that participated within the "Life under Ice" project.

Northern Water Problems Institute of the Karelian Research Centre of the Russian Academy of Sciences, NWPI-KRC-RAS
Limnological Institute, St-Petersburg, Russia
Arctic and Antarctic Research Institute, St-Petersburg, Russia
Nansen International Environments and Remote Sensing Center, St-Petersburg, Russia
EPFL, Limnology Center, Lausanne, Switzerland, LIMNC-EPFL
EPFL, Physics of Aquatic Systems Laboratory - Margaretha Kamprad Chair, Lausanne, Switzerland
EPFL, Distributed Intelligent Systems and Algorithms Laboratory, Lausanne, Switzerland
EPFL, Geodetic Engineering Laboratory, Lausanne, Switzerland
University of Geneva, Limnogeology and Geomicrobiology Group, Geneva, Switzerland
University of Geneva, Microbial Ecology Group, Geneva, Switzerland
University of Geneva, Environmental Biogeochemistry and Ecotoxicology Group, Geneva, Switzerland
Eawag, Surface Waters – Research and Management, Dübendorf and Kastanienbaum, Switzerland
Institut National de la Recherche Agronomique, Centre Alpin de Recherche sur les Réseaux Trophiques des Ecosystèmes Limniques, Thonon-les-Bains, France
Centre National de la Recherche Scientifique, Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Toulouse, France
Université de Savoie Mont Blanc, Chambéry, France
University of Constance, Limnological Institute, Constance, Germany
University of Uppsala, Department of Ecology and Genetics, Uppsala, Sweden

in air temperature, precipitation, and evaporation for both lakes. However, discharges and water levels showed no discernible changes over the last 60 years, although water inflows into both lakes increased during winter.

The RS inflow is the main driver for the water constituents in PB. The concentrations in PB are mostly related to those of the RS inflow and the rate of exchange between PB and the open water. Efremova et al. (2019) measured ionic composition, organic matter, nutrients, gas composition, trace elements, and mercury throughout 2016 to quantify PB water quality. Elevated humic content and levels of organic matter indicated that the RS input was eutrophic, whereas lower humic content and levels of organic matter indicated the oligotrophic character of the Lake Onego open waters. During the ice-covered period, the exchange between PB and the open waters is restricted and the hydrochemical regime becomes dominated by the RS inflow.

For all other water constituents in the PB, the winter inflow by the RS also played a major role (Efremova et al. 2019). Organic carbon in particular is predominantly imported by the eutrophic RS water, and the contribution by in situ primary production is relatively modest. Pasche et al. (2019) showed how the under-ice carbon dioxide (CO_2) and dissolved organic carbon decreased over the transect from the RS to the PB and into the open lake in March 2015 and 2016. The variability between the 2 winters was due to the inflow dynamics and the intensity of the radiatively induced convection (discussed later), which both influence the spatial and temporal patterns of CO_2. While the river inflow drives the CO_2 level, it is the transparency of ice and water that affects convection and the vertical homogeneity under the ice.

In addition to CO_2, methane is also produced, although to a lesser extent, in the anaerobic sediment of PB, even for the permanently oxic water column of Lake Onego. The observations by Thomas et al. (2019) revealed that methane production and oxidation is stronger close to the RS mouth because of the organic matter inflow and subsequent sedimentation in the PB. Close to the river mouth, the largest numbers of the methane-related functional genes pmoA and mcrA were associated with a specific functional microbial community, and methane production exceeded oxidation, resulting in an order of magnitude higher methane fluxes than in the rest of the bay. Toward the open water, however, the methane cycling in the sediment is vertically structured, with aerobic methane oxidation at the sediment surface, followed below by anaerobic oxidation and finally methane formation underneath. This vertical pattern is the result of both the redox gradient and human-induced changes in organic inputs to the bay (Thomas et al. 2019).

In late winter, as soon as the seasonal solar radiation increases and the snow on ice melts, the underlying water is warmed and thereby set in motion. Water colder than 4 °C, the temperature of maximum density, gets heavier as the sunlight warms the icy water surface. Therefore, the radiatively driven heating induces gravitationally unstable density profiles that lead to convection. Bouffard et al. (2016, 2019) and Bogdanov et al. (2019) investigated this type of under-ice convection in Lake Onego during 3 consecutive winters (March 2015–2017). Because the velocities of the convective thermals are often in the submillimetre per second range, only the largest convective cells could be identified by using acoustic velocity profilers (Bogdanov et al. 2019). However, it was possible to quantify (1) the vertical distribution of the source of the convective instability, (2) the convective mixed-layer thickness, and (3) the convective velocities. The unique aspect of the investigation by Bouffard et al. (2019) is the high accuracy and temporal resolution of the daily dynamics, allowing identification of day-night on-off forcing of the convectively mixed layer.

These convective thermal plumes move nutrients in and out of the light-exposed surface layer. These motions right below the ice are essential for phytoplankton growth because mixing keeps cells in suspension and prevents sedimentation losses (Bouffard et al. 2019). Suarez et al. (2019) investigated diurnal variations in the vertical distribution of phytoplankton, which are not only driven by convection and below-ice light availability but also by the moderate to high levels of coloured dissolved organic carbon. Access to light was restricted to a narrow euphotic zone in the morning, while cells were mixed through a deep aphotic layer in the afternoon. The low water transparency combined with deep mixing for most of the day and low nutrient levels resulted in especially low chlorophyll *a* concentrations in the lake. Whereas surface warming induced mixing and low chlorophyll *a* levels under the ice, as soon as the lake warms above 4 °C after ice break-up, warming restricts mixing and results in a sharp increase in phytoplankton biomass.

Lessons learned

The collaboration among researchers of various disciplines ranging from physics to biogeochemistry and biology offered a better interdisciplinary understanding of the under-ice processes that determine the functioning of this large, oligotrophic lake. Under-ice convection was particularly important. Whereas convection reduces sedimentation of phytoplankton, its impact in this lake, which has high dissolved organic carbon levels, is predominantly negative, restricting phytoplankton growth to brief periods of the day when mixing is weak. This restriction in primary productivity vanishes with increasing restratification of the Lake Onego water column after ice break-up. For PB, the inflow of the RS, bringing in nutrients and organic matter, plays a decisive role in the metabolism in the bay. Therefore, perhaps not surprisingly, the interaction among local, regional, and global processes determines the status of this large European lake.

Acknowledgements

The 7 publications in this Special Issue of *Inland Waters* entitled "Life under ice in Lake Onego (Russia) – an interdisciplinary winter limnology study" resulted from the international, interdisciplinary research project "Life Under Ice" (https://www.epfl.ch/research/domains/limnc/projects/onego/), which had the objective to investigate the processes during and after the ice-covered periods from 2015 to 2017. Funding for this study was mainly provided by the Swiss nonprofit FEEL, whose president, Prof Patrick Aebischer, and vice-president, Dr. Frederik Paulsen, provided generous support for this project to the NWPI-KRC-RAS and to the LIMNC-EPFL. Some of the work described in those papers received additional funding and staff contribution from EPFL, Eawag, University of Geneva, University of Constance, University of Uppsala, INRA-Thonon-les-Bains, University of Savoie, CNRS, NWPI-KRC-RAS, Nansen International Environmental and Remote Sensing Center, Arctic and Antarctic Research Institute, and the Limnological Institute in St. Petersburg. We are grateful for the various financial support we received.

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