DOI: 10.15356/2071-9388_03v09_2016_05

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OPTICAL PROPERTIES OF LAKE VENDYURSKOE

ABSTRACT. We conducted a field study on light conditions in a small boreal Karelian Lake Vendyurskoe over two years. Albedo of ice-covered lake varied from 0.9 to 0.1, and the euphotic zone depth exceeded 3.5 m during the melting stage. The Secchi disc depth changed from 2.5 m after ice-break to 3.7 m at the stage of early summer. The vertical distribution of the photosynthetically active solar radiation (PAR) attenuation coefficient for water K_W was characterized by high spatial (vertical) and temporal (seasonal and interannual) variability which can be connected with the dynamics of plankton cells. The highest values of K_W reached 2–2.8 m^{-1} in the upper 0.5 m layer of a water column, and decreased to 0.5–1.5 m^{-1} with increasing depth. The highest values of K_W were marked in the end of ice-covered period.

KEY WORDS: ice-covered lake, albedo, photosynthetically active radiation, under-ice irradiance, PAR attenuation coefficient.

INTRODUCTION

Solar radiation is one of the most important parameters in functioning of the lake ecosystem. Radiative heating of water, spring under-ice convection, photosynthesis, the daily activity of the plankton and fish community – all of these processes are determined by the flux of solar radiation penetrating into a water column [Zaneveld et al., 1981; Mironov & Terzhevik, 2000; Mironov et al., 2002; Reynolds, 2006]. Snow-ice cover, high water color and turbidity, and large concentrations of phytoplankton in the surface layers of the reservoir are the key factors that limit the penetration of solar radiation into a water column [Chekhin, 1987; Arst et al., 2008]. The attenuation of the solar flux within the snow-ice cover has been studied quite well [Petrov et al., 2005; Arst et al., 2006, 2008; Lei et al., 2011; Zdorovennova et al., 2013]. At the same time under-ice light measurements are rare and often limited to the upper meter of a water column [Leppäranta et al., 2003; Arst et al., 2006]. Thus, parameterization of attenuation of the solar radiation within ice-covered lakes is an important task of modern physical limnology.

In order to obtain a better knowledge on the distribution of light in shallow ice-covered boreal lakes, we performed field measurements of solar radiation fluxes at the upper and lower boundary of ice and within a water column of Lake Vendyurskoe (Karelia, Russia). The aim of research was to study the spatial and temporal dynamics of PAR flux in a water column during late winter, spring, and early summer.

MATERIALS AND METHODS

Measurements of solar radiation fluxes were carried out on a small Lake Vendyurskoe located in the south of Karelia (62°10′N, 33°10'E). Lake Vendyurskoe is a shallow lake of glacial origin. Surface area of the lake is 10.4 km^2, volume is $54.8 \cdot 10^6$ m^3, maximal and mean depths are 13.4 and 5.3 m, respectively. The duration of the ice season is 5–6.5 months: the ice-period starts between the first half of November and the beginning of December, and the ice-break occurs in the first half of May [Petrov et al., 2005; Zdorovennov et al., 2013].

Measurements of solar radiation fluxes at the surface of snow-ice cover and PAR-fluxes into a water column were conducted on 21–24 April 2013 and 26–31 March 2014 when the radiatively-driven convection under ice was in progress. Also PAR fluxes were measured during open water on 8 May 2013, 17–18 June 2013, 20–21 May 2014, and 11–15 June 2014. All measurements were performed at 1-min intervals.

The measuring station with a depth of 7.2 m was located at a distance of 300 m from the northern shore of the lake (Fig. 1, A). During the ice-covered period pyranometers were mounted on a special holder at a height of about one meter above the ice surface (Fig. 1, B).The downwelling and upwelling planar irradiance at the surface of snow-ice cover were measured with a "Star-shaped" pyranometer (Theodor Friderich & Co, Meteorologische Gerate und Systeme, Germany). Downwelling planar irradiance at the lower boundary of ice was measured with M-80m universal pyranometer (Gydrometpribor, USSR).

Measurements of PAR flux at the lower boundary of ice and within a water column were performed using sensors JFE Alec MkV-L ("Alec Electronics", Japan, 390–690 nm, range 0–2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, accuracy ±4 % FS, resolution 1 $\mu mol \cdot m^{-2} \cdot s^{-1}$). The PAR sensors were attached to the fishing line at intervals of 0.5–1 m to the depth of 7.2 m. The top sensor was located directly under the ice or at the depth of 0.2 m during open water measurements. A scheme of the observational site during ice-period is shown in Figure 1, B. The Secchi disk depth was measured during open water surveys in May and June 2013. The thickness of the snow and ice at the station of radiation was measured twice a day during 21–24 April 2013 and 26–31 March 2014.

The albedo α was calculated as a ratio of downwelling $E_d(0)$ and upwelling $E_u(0)$ global irradiances at the surface of the snow-ice cover:

$$\alpha = \frac{E_u(0)}{E_d(0)}. \tag{1}$$

Assuming exponential decay of PAR in a water column, the PAR attenuation coefficients for water K_w was calculated using the measured values of PAR at the top sensor and at different depths in water:

$$K_w(z, z_1) = -\frac{1}{z_1 - z} \ln\left(\frac{E_d(z_1)}{E_d(z)}\right). \tag{2}$$

The depth of the euphotic zone (the euphotic zone is a layer of the water column at the lower boundary of which irradiance drops to 1 % of the surface value and less [Jerlov, 1976; Chekhin, 1987]) was estimated based on the measurements of irradiance on the upper and lower boundaries of the snow-ice cover taking into account the albedo and calculated values of K_w, as in [Kirillin et al., 2012]:

$$z(1\%) = \ln[100(1-\alpha)\tau]/K_w, \tag{3}$$

where τ is the light transmittance of the snow-ice cover, defined as the ratio of transmitted irradiance to incident irradiance,

$$\tau = \frac{E_d(z)}{(1-\alpha)E_d(0)}. \tag{4}$$

Here $E_d(z)$ is the downwelling planar irradiance at the lower ice boundary.

Data from the weather station "Petrozavodsk" closest to Lake Vendyurskoe were used in the analysis of the weather conditions. Visual observations of cloud cover were conducted every three hours daily throughout the measurement period.

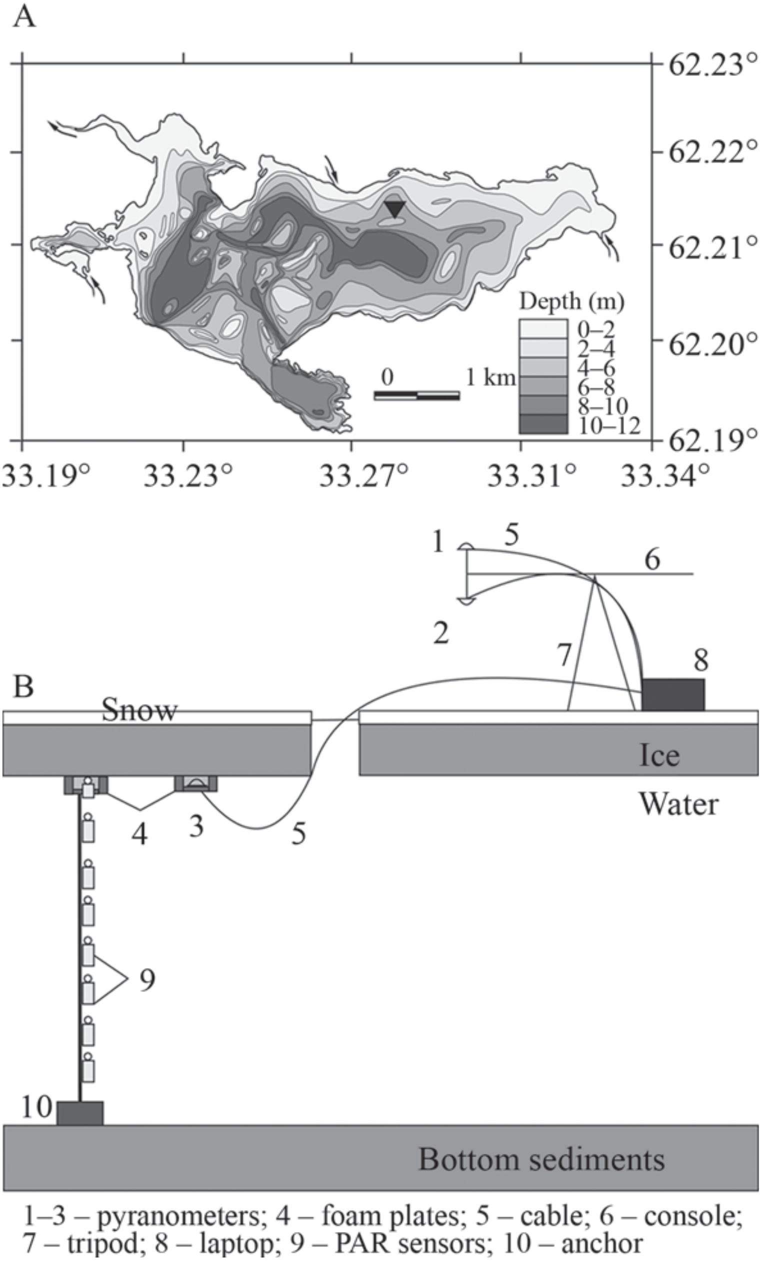

Fig. 1. Bathymetric map of Lake Vendyurskoe with the measurement station (black triangle) (A). A scheme of the observational site in April 2013 and March 2014 (B).

RESULTS AND DISCUSSION

Ice cover period

Weather and ice conditions differed significantly in April 2013 and March 2014. Intensive ice melting caused by the warm overcast weather (the air temperature reached +13 °C at daytime and decreased to −3 + 4 °C at night) was observed from 21 to 24 April 2013: the thickness of the ice-sheet decreased by 10 cm over four days (from 41 to 31 cm). The thickness of the white ice on 21 April was 6 cm, and that of congelation ice 35 cm. During the four days of observations, white ice melted completely, and the thickness of congelation ice decreased by four cm. The albedo of the lake's surface reduced from 0.35 to 0.13 over the same period, and light transmittance ranged between 0.4–0.5.

In contrast, the weather was cold on 26-31 March 2014. The air temperature increased to +4...+7 °C at daytime on 26 and 27 March, and +1 °C on 28–30 March. The night air temperature dropped to −1...−7 °C. It was clear on 26–28 March, it was cloudy on 29–30 March, and it snowed. The thickness of white ice was 10 cm and of the congelation ice 30 cm at the first day of observation. Each layer has decreased by one cm during the measurement period. The albedo was 0.35–0.45 during the first three days of measurements. On 29 March after the snowfall, there was a sharp increase in albedo to 0.85–0.9; albedo remained at a high level of 0.75–0.8 during the next three days. The light transmittance in the first days of measurements reached 0.3–0.4; after the snowfall, it decreased to 0–0.05.

The daytime maxima of downwelling planar irradiance at the surface of the snow-ice cover reached 550–800 W•m^{-2} on the background of clear or slightly overcast sky, and did not exceed 350 W•m^{-2} under completely overcast during both surveys. The downwelling planar irradiance at the lower ice boundary reached 100–200 W • m^{-2} during measurements of April 2013, and did not exceed100 W • m^{-2} on 26–28 March 2014. After the snowfall on 29 March 2014, the flux of solar radiation on the lower boundary of ice was significantly reduced.

The daily maxima of PAR flux reached 1500–2000 μmol • s^{-1} • m^{-2} at the lower boundary of ice on 21–23 April, and 900–1000 μmol • s^{-1} • m^{-2} on 26–28 March 2014; after a snowfall on 29 March, it fell down to 200 μmol • s^{-1} • m^{-2} and did not exceed 50 μmol • s^{-1} • m^{-2} on 30–31 March. The PAR flux decreased rapidly with depth: it was close to zero at a depth more than 3–4 m during both surveys.

On 21–24 April 2013, the depth of the euphotic zone, z(1 %), ranged within 3–3.8 m. On 26–28 March 2014, z(1 %) reached three meters and then, after a snowfall, rapidly decreased to zero.

Since the PAR flux at different depths of a water column was characterized by high variability, the PAR attenuation coefficient for water K_w was calculated using the 10-minute averaged PAR data. The maximal values of K_w 2–2.8 m^{-1} were confined to the under-ice layer 0–0.5 m during 21–24 April 2013 (Fig. 2, A). On 26–28 March 2014, K_w reached 2 m^{-1} in a layer of 0–1 m (Fig. 2, B), and dropped to 1–1.2 m^{-1} after 29 March. Values of K_w rapidly decreased to 1.4–1.8 m^{-1} (average 1.6 m^{-1}) at a depth of 0.5–1 m during April survey and to 0.5–1.4 m^{-1} (average 1.1 m^{-1}) at a depth of 1–2 m during March survey. Below, up to a depth of 3–4 m, K_w values were gradually reduced to 1.2 m^{-1} (with extremes 0.6–1.6 m^{-1}) during the April survey and to 0.5–0.7 m^{-1} during the March survey.

Open water period

Ice-off occurred on 3 May 2013. The measurements were performed on 8 May 2013 from 9:00 to 15:00. The weather was clear, warm, and windy: the air temperature varied from +9 to +16 °C during the measurement period, northwest wind reached 4–6 m·s^{-1}

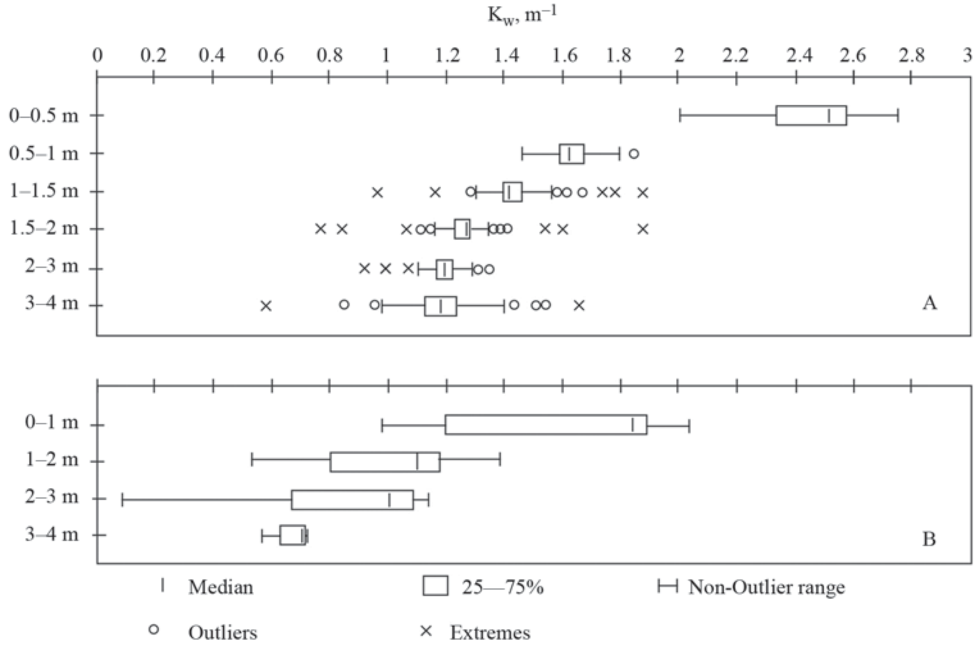

Fig. 2. Variability of PAR attenuation coefficient for water K_w (10-min averaging) in different layers of a water column on 21–24 April 2013 (A) and 26–31 March 2014 (B).

with gusts of up to 10 m • s^{-1}. Likely due to the waves, the upper PAR-sensor (located at a depth of 0.2 m) periodically reached the surface of the lake. Consequently, its records had a strongly fluctuating nature: the PAR flux varied in the range of 500–3000 μmol • s^{-1} • m^{-2}, with an average value of 1500 μmol • s^{-1} • m^{-2}. The flux of PAR decreased rapidly with increasing depth: to 500 μmol • s^{-1} • m^{-2} at a depth of 0.7 m, to 100 μmol • s^{-1} • m^{-2} at a depth of 1.7 m, and to 25 μmol • s^{-1} • m^{-2} at a depth of 3.2 m. It was close to zero deeper than 3.2 m. The Secchi disk depth varied 2.5–2.8 m.

The weather was cloudy and warm on 17–18 June 2013: the air temperature reached + 18 °C at daytime and + 9 °C at night; cloudiness was 50–100 %; southwest wind was 1–3 m • s^{-1}. The flux of PAR reached 3000 μmol • s^{-1} • m^{-2} at a depth of 0.2 m; its average value was 850 μmol • s^{-1} • m^{-2} at daytime. The transparency of the water column increased, compared with the May survey: the Secchi disk depth was 2.9–3.7 m. The PAR flux at a depth of 1.7 m periodically exceeded 500 μmol • s^{-1} • m^{-2}, at a depth of 3.2 m reached 100 μmol • s^{-1} • m^{-2}, at a depth of 4.2 m reached 35 μmol • s^{-1} • m^{-2}, and deeper it was close to zero.

The weather was extremely hot on 19-20 May 2014: the air temperature reached + 32 °C at daytime and + 20 °C at night; cloudiness was variable; southwest wind was 1–4 m • s^{-1}. The flux of PAR reached 2000 μmol • s^{-1} • m^{-2} at depth of 0.5 m; its average value was 650 μmol • s^{-1} • m^{-2} at daytime. The transparency of a water column was higher than in May 2013: the flux of PAR at a depth of 3, 4 and 5 m reached 90, 35 and 10 μmol • s^{-1} • m^{-2}, and deeper it was close to zero.

The weather was cool, windy and cloudy on 11–15 June 2014: the air temperature not exceeded +21 °C at daytime and dropped down to +5 + 9 °C at night; cloudiness was variable (4–8 points on the 8-point scale); northeast wind reached 1–5 m • s^{-1}. The flux of PAR exceeded 3000 μmol • s^{-1} • m^{-2} at a depth of 0.5 m on 12 and 13 June; but its value was less than 600 μmol • s^{-1} • m^{-2} on 14 June under overcast. The transparency of a water column was higher than in May 2014: the flux of PAR at a depth of 3, 4 and 5 m reached 150, 70 and 20 μmol • s^{-1} • m^{-2} and deeper it was close to zero.

The values of the PAR attenuation coefficient K_w during the open water in May and June 2013 and 2014 widely varied from 0.2 to 2.6 m^{-1} (Fig. 3). The highest values of K_w were observed in the surface layer of a water column at depth of 0.2–0.7 m in May 2013 (1.5–2.4 m^{-1} with average 1.9 m^{-1}) (Fig. 3, A) and in June 2013 (1.3–2 m^{-1} with average 1.7 m^{-1} and with extremes up to 2.5 m^{-1}) (Fig. 3, B), when the transparency of a water column was minimal. Exactly as during ice measurements, K_w rapidly decreased with increasing depth in the top-meter layer: its values were 0.8–1.8 m^{-1} (average 1.4 m^{-1}, sporadic outlier to 2.6 m^{-1}) at depth of 0.7–1.2 m in May 2013 and 0.9–1.4 m^{-1} (average 1.1 m^{-1}, extremes 0.4–1.8 m^{-1}) at the same depth in June 2013. Below, to depth of 3.2 m the average values of K_w were close to 1.2 m^{-1} in May 2013 and to 1 m^{-1} in June 2013.

In May and June 2014 K_w did not exceed 2.2 m^{-1} with average values 1.4–1.5 m^{-1} in the surface layer of 0.5–1 m (Fig. 3, C and D). The average values of K_w decreased to 1–1.1 m^{-1} at depth of 1.5–4 m during both surveys. During the May 2014 survey, the vertical distribution of K_w was more arranged, while it was characterized by a large number of extremes and outliers in June 2014.

A wide variability of parameters describing the snow-ice cover optical properties of small shallow lakes is the main feature of late winter. The albedo decreased rapidly, and ice transparency increased during melting of snow and ice. At same time, varying weather conditions, e.g., snowfall, led to a sharp increase of albedo and lower light transmittance. Our estimates of albedo and light transmittance during early spring are in good agreement with the results of previous measurements on Lake Vendyurskoe [Petrov et al., 2005; Leppäranta et al., 2010] and measurements on other lakes [Bolsenga & Vanderploeg, 1992; Arst et al., 2006; Lei et al., 2011].

If the snow layer is thick, the flux of solar radiation penetrating the ice underneath is negligible [Malm et al., 1997]. During intensive spring melting, the radiation flux in the under-ice layer rises, the depth of the euphotic zone also increases. Our estimations of the euphotic zone depth (from 3.5 m for clear ice to technically zero values after snow fall) are in a reasonable agreement with the results of other researchers. The estimates of the euphotic zone for different boreal lakes when ice is covered with snow are in the range of 0–1.3 m, and in the absence of snow within 0.5–4.7 m [Arst et al., 2006; Jakkila et al., 2009].

We have defined the range of variability of the PAR attenuation coefficient for water K_w from 0.5 to 2.8 m^{-1} for late winter period. Our estimations of K_w are in a good agreement with the data presented recently [Leppäranta et al., 2003; Arst et al., 2006, 2008]: according to the measurements in the Estonian and Finnish lakes, the diffuse PAR attenuation coefficient for under-ice water varied from 0.5 to 2.6 m^{-1}.

In our measurements, we found significant spatial and temporal variability of K_w. The increase in values of K_w occurs with the decrease in water transparency. In late winter, one of the probable reasons of lowering the water transparency is intensification of photosynthesis and increasing algal biomass. Measurements on the different types of lakes revealed that primary production in a water column is well correlated with the penetration of PAR through the ice [Tulonen et al., 1994; Fritsen & Priscu, 1999]. The melt water coming to the under-ice layer of the lake from the catchment area may be significantly less transparent and also cause fluctuations of K_w. In addition, increasing values of K_w after melting snow may be explained by the

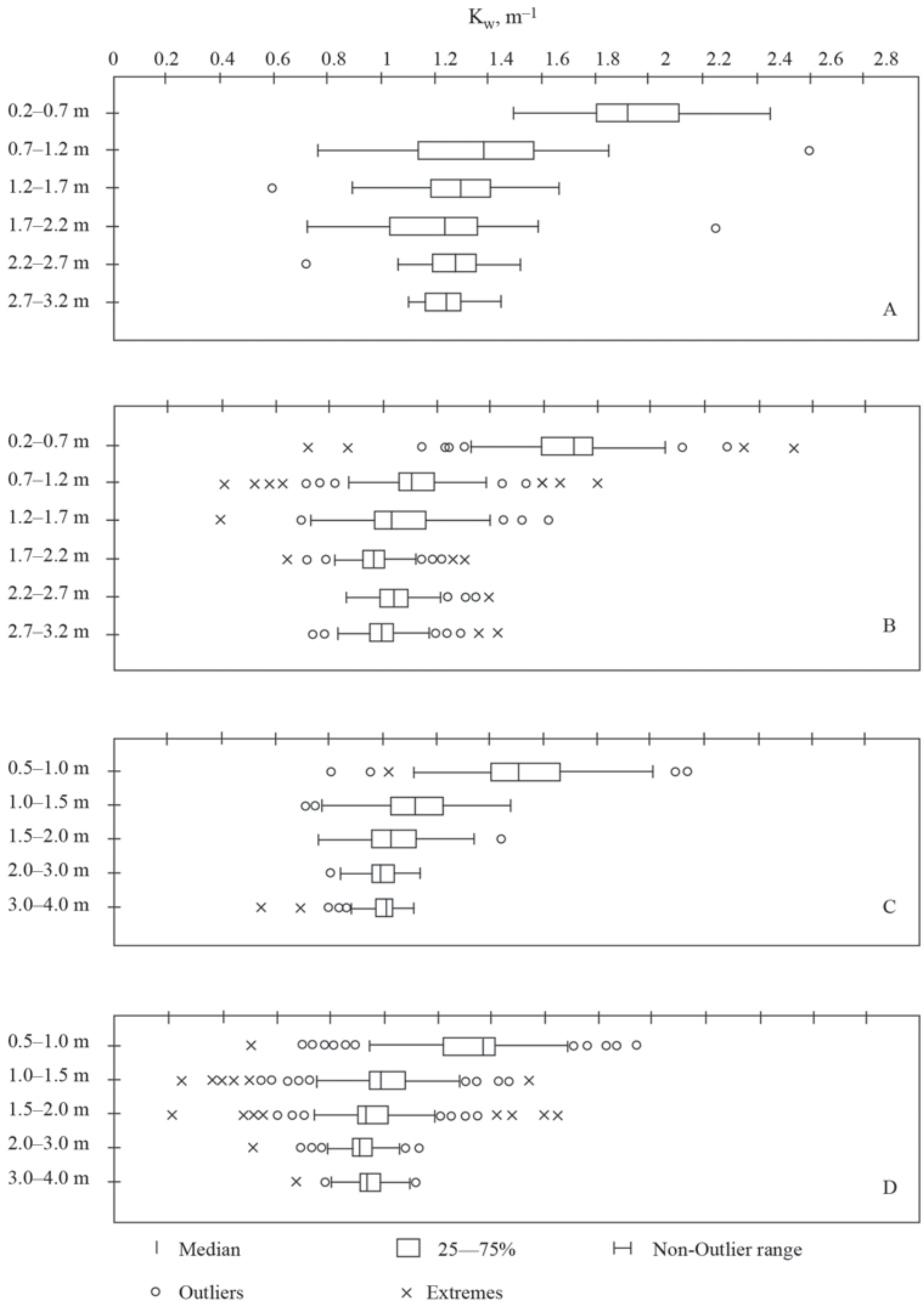

Fig. 3. Variability of PAR attenuation coefficient (10-min averaging) in different layers of a water column during May 2013 (A), June 2013 (B), May 2014 (C), and June 2014 (D).

difference in the spectral composition of irradiance below the snow-ice cover or clear ice [Arst et al., 2008].

Decreasing values of K_w along increasing depth is a sign that water transparency is minimal in the under-ice layer and increases in the underlying water. Apparently, this is due to the maxima of phytoplankton cells concentrated in the under-ice water layer where light conditions are most favorable. The vertical distribution pattern of algal biomass with a maximum in the under-ice layer has been observed in the different types of lakes during the development of the radiatively-driven convection [Belzile et al., 2001; Twiss et al., 2012]. On the other hand, it is known that the high level of illumination can lead to inhibition of photosynthesis in the sub-ice layer. In that case, the maximum concentration of plankton is located at a certain depth with the optimal light conditions [Vanderploeg et al., 1992; Jewson et al., 2009].

In our measurements, the values of K_w always decreased with increasing depth. Such a vertical variation of this parameter is described as typical in the study [Leppäranta et al., 2003]. The authors also describe the opposite situation, when the minimum value of K_w (0.8–1 m^{-1}) was confined to a 0.2 m layer of under-ice water of mesotrophic Lake Ülemiste, and at the depth of 1.2 m, the coefficient values increased twofold.

In our investigations, the highest values of K_w were observed in the 0.5-m under-ice layer of a water column in April 2013 (2.5–2.8 m^{-1}) and in the first days of measurements in March 2014 (1.9 m^{-1}) at the stage of the active ice melting, when the snow was absent, and the thickness of white ice did not exceed a few centimeters. Apparently, the amount of phytoplankton cells in the under-ice layer during the active stage of ice melting and favorable light conditions was significantly higher than on 29-31 March 2014 when after the snowfall the PAR penetration was limited.

The values of K_w in April, May and June 2013 were visibly higher than in March, May and June 2014. Presumably, this was due to a more active under-ice phytoplankton development in April 2013. Furthermore, in both years there was a gradual decrease in the coefficient values for three consecutive surveys: from the melting stage through homothermy to the stage of thermocline formation. Such a change of K_w should correspond to a gradual increase in water transparency, which was confirmed by measurements of a Secchi disk depth in May and June 2013. Possibly, the seasonal variation of phytoplankton concentration has a decisive influence on the transparency of the surface layer of Lake Vendyurskoe.

We have shown that the K_w value significantly changes not only during the transition period from winter to summer, but from year to year. Extensive analysis of optically active substances, light attenuation, and a Secchi depth were performed based on 10-year measurements on 14 Estonian and 7 Finnish lakes [Arst et al., 2008]. Significant seasonal and interannual variability of the PAR attenuation coefficient for water was noted, but no systematic temporal change could be detected.

The diffuse PAR attenuation coefficient for water K_w is used in the numerical modeling for a wide range of tasks: from heat-budget models of a mixed layer (see, e.g., Zaneveld et al., 1981) and under-ice convection [Matthews & Heaney, 1987; Mironov et al., 2002] to weather prediction (see, e.g., Mironov et al., 2010). It must be admitted that the variability of K_w is much better studied for open water as compared to the ice season.

There are a number of parameterizations for K_w in a water column [Henderson-Sellers, 1984]: from simple, taking into account the depth of the Secchi disk [Williams et al., 1981], to complex, using multiple coefficients, which vary depending on the level of turbidity of the reservoir [Zaneveld et al., 1981]. All of them assume a constant K_w value for a water column. From our estimates, it is particularly noteworthy to mention that a sharp decrease of K_w with depth is present in the most of calculated K_w profiles, demonstrating its spatial heterogeneity.

Analysis of our PAR measurements in a water column for two consecutive years, significantly different in weather and ice conditions, revealed that the coefficient values vary widely. The vertical profiles of K_w calculated from the instant values of the PAR flux at different depths, are characterized by significant variability. Two important consequences can be formulated: (1) instant PAR profiles are not suitable to calculating reliable estimates of K_w, and (2) existing approximations do not allow us to describe the spatial and temporal dynamics of this coefficient. To obtain realistic values of K_w it is necessary to measure the radiation fluxes at different depths in water column with a possibly small time interval for a few hours, and then to average obtained values for each depth.

Erroneous values of K_w may strongly affect results of numerical modeling. Given $K_w = 2$ m^{-1}, about 87 % of solar radiation penetrated into water would be "arrested" in the uppermost 1-m layer. In a case $K_w = 1$ m^{-1}, this value decreases to 63 %, resulting in artificial over-warming of underlying waters. In turn, a decrease of the density jump may develop comfortable conditions for deeper mixing.

CONCLUSIONS

The present study focuses on light conditions in a shallow lake at the stage of late winter, spring, and early summer and demonstrates the significant temporal variability of optical properties of the snow-ice cover and PAR attenuation coefficient for water K_w.

To study the temporal dynamics of the lake's optical properties during the transition from ice-covered period to open water, three surveys were carried out: (1) during the melting stage at the end of the ice-covered period (21–24 April 2013 and 26–31 March 2014), (2) shortly after ice-off at the stage of homothermy (8 May 2013 and 20–21 May 2014), and (3) early summer at the stage of formation of thermal stratification (17–18 June 2013 and 11–15 June 2014).

Analysis of observational data, containing downwelling and upwelling planar irradiance at the surface of snow-ice cover, downwelling irradiance at the lower ice boundary and PAR-flux at the lower boundary of ice and within a water column at different depths was performed. Weather conditions have a great impact on the optical properties of snow-ice cover, and, consequently, on the under-ice irradiance at the stage of active melting. As snow melts, albedo decreases, the light transmittance rises, and the depth of the euphotic zone gradually increases, reaching several meters. The presence of a snowfall invokes the sharp decrease in light amount under the ice. Only a few cm of fresh snow lead to a sharp increase in albedo, decreasing light transmittance to negligible values and reducing the depth of the euphotic zone to zero.

Measurements for two consecutive years revealed that the highest values of K_w were confined to the surface layer thickness of about 1 m; with increasing depth the coefficient typically decreased. Such a pattern of K_w vertical distribution represents an increase in water transparency with depth, presumably caused by the vertical distribution of phytoplankton cells with a maximum in the most illuminated surface layer. Significant spatial and temporal variability of K_w can be connected to the dynamics of plankton cells.

The observations have demonstrated that the coefficient values vary widely, thus the single PAR profiles are hardly acceptable to get reliable estimates of K_w for the practical use, e.g., in numerical simulations. The presence of strong gradients between K_w in the uppermost water layer and that in the rest of a water column requires the development of the depth-dependent K_w parameterization. These two conclusions can be considered as the novelty of our work.

Further research is expected to be focused on the parameterization of K_w as a function of depth during late winter and open-water periods.

ACKNOWLEDGEMENTS

The study was partially supported by the Russian Foundation for Basic Research (projects 13-05-00338, 14-05-91761, 14-05-00787) and by the European Commission (grant Marie Curie IRSES: GHG-LAKE № 612642). ■

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Received 12.11.2015 **Accepted 29.08.2016**

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