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Spectral light absorption by yellow substance and its dynamics in the surface layers of thermokarst lakes of the Central Yamal

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ABSTRACT. The article presents the experimental data on dynamics of light absorption by yellow substance in the surface layers of 52 thermokarst lakes of the Central Yamal obtained during hydrological, hydrobiological and hydrochemical field investigations in September 2018. In the study period, light absorption by yellow substance in the spectral range of 400–700 nm was calculated as 0.7–0.9 m^{-1}. We measured concentrations of the yellow substance C_{ys}, and chlorophyll *a* Chl_a. The latter had a maximum of 12.5 mg/m^3. Thirty-seven samples of fifty-two ones showed 10.0–14.5 mg/m^3, thus, corresponding to oligo- and mesotrophic reservoirs. Eutrophic samples (Chl_a > 30 mg/m^3) were not registered. The maximum chlorophyll concentration (18.8 mg/m^3) was detected at site 52. The concentrations of yellow substance in lakes (2.3–19.3 g/m^3) were determined through the optical method due to the measured coefficient of light absorption by the yellow substance at a wavelength of $\lambda = 450$ nm. The correlation between the Chl_a and C_{ys} concentrations in all samples indicated that a low concentration of chlorophyll (Chl_a < 10 mg/m^3) was randomly accompanied by a wide range of the C_{ys} attenuation (from 0.5 to 3.0 g/m^3), whereas its high concentrations – similarly, by random but significantly lower variation of C_{ys} (from 1.1 to 1.9 g/m^3).

Keywords: spectral transparency of water, coefficients of light attenuation and absorption, dissolved organic matter, yellow substance, chlorophyll, suspended matter, physical model, trophic status, thermokarst lakes

1. Introduction

Spectral attenuation $\varepsilon(\lambda)$, absorption $\kappa(\lambda)$, scattering $\sigma(\lambda)$ of light, including relative transparency, Z, on to a white Secchi disk, are among the most important hydrooptical characteristics of the ecological state of aquatic ecosystems. The study of these characteristics contributes to a better understanding of hydrophysical conditions of different-type ecosystems (oceans, seas, rivers, lakes, and reservoirs) (Kopelevich, 1983; Shifrin, 1983; Man'kovsky, 1996; Churilova et al., 2008; Efimova et al., 2016; Churilova et al., 2018).

When solving some problems related to environmental assessing aquatic ecosystems, the concentrations of the main optically active components are important. However, extreme diversity and spatiotemporal variability of a specific component of lakes (pure water, organo-mineral suspension, yellow substance, and chlorophyll) affecting the spectral contribution to total light attenuation pose great difficulties.

This work aims to study spatial variability of light absorption by the $\kappa_{ys}(\lambda)$ yellow substance at 400–700 nm and yellow substance concentrations in the thermokarst lakes of the Central Yamal in the autumn of 2018. Obviously, both contain information about the quantitative and qualitative composition of substances that present in the water bodies.

2. Material and methods

The study object is thermokarst lakes of the Yamalo-Nenets Autonomous Okrug (Central Yamal). On September 8–15, 2018, a total of 52 water samples were taken from the surface layer of water bodies, processed and analyzed (the dates and numbers of sampling stations and their coordinates are given in Table).

A PE-5400UF single-beam spectrophotometer was used in the mode of measuring spectral transparency (transmittance) of water to make laboratory measurements of light absorption by the $\kappa_{ys}(\lambda)$ yellow substance at 400–700 nm in an increment of 50 nm. To determine spectral water transparency,

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Table. Light absorption by the κ_{ys} yellow substance at $\lambda = 450$ nm and the C_{ys} yellow substance concentration in the surface layers of studied lakes (September, 2018)

Date	Station	Coordinate	$\kappa_{ys}(450)$, m^{-1}	C_{ys}, g/m^3
08.09.2018	1	70°34'09.68" 68°05'10.65"	1.3	6.1
08.09.2018	2	70°34'17.87" 68°06'17.91"	1.2	5.6
08.09.2018	3	70°30'48.60" 68°06'27.18"	1.2	5.6
08.09.2018	4	70°30'25.84" 68°17'45.21"	1	4.7
08.09.2018	5	70°30'11.46" 68°25'02.39"	3	14.1
08.09.2018	6	70°29'33.80" 68°24'26.55"	1.4	6.6
08.09.2018	7	70°27'56.34" 68°23'53.90"	1.2	5.6
09.09.2018	8	70°23'59.61" 68°12'19.85"	1.2	5.6
09.09.2018	9	70°24'39.39" 68°12'16.71"	0.8	3.7
09.09.2018	10	70°24'34.95"68°16'10.30"	1.1	5.1
09.09.2018	11	70°25'45.98" 68°17'07.05"	0.7	3.3
09.09.2018	12	70°25'52.98" 68°25'53.25"	1.2	5.6
09.09.2018	13	70°24'29.46" 68°19'50.47"	1.8	8.4
09.09.2018	14	70°24'27.78"68°19'49.92"	1.9	8.9
09.09.2018	15	70°23'46.33"68°29'46.58"	1.6	7.5
09.09.2018	16	70°19'45.38"68°24'36.77"	1.1	5.1
09.09.2018	17	70°20'05.35"68°21'01.51"	0.7	3.3
09.09.2018	18	70°20'41.66"68°30'43.12"	0.5	2.3
09.09.2018	19	70°21'52.13"68°27'57.61"	0.6	2.8
09.09.2018	20	70°22'03.06"68°26’50.72"	1.1	5.1
10.09.2018	21	70°21'03.54"68°50'26.59"	1.1	5.1
10.09.2018	22	70°20'04.01"68°38'27.11"	0.7	3.3
10.09.2018	23	70°20'16.65"68°37'38.54"	0.6	2.8
10.09.2018	24	70°19'20.08"68°32'37.36"	0.5	2.3
10.09.2018	25	70°21'10.88"68°35'46.80"	1.3	6.1
11.09.2018	26	70°27'38.70" 68°31'48.17"	2.3	10.8
11.09.2018	27	70°28'21.06"68°32'06.40"	1.6	7.5
11.09.2018	28	70°29'01.80" 68°32'46.92"	0.8	3.7
11.09.2018	29	70°29'56.71" 68°32'46.02"	0.9	4.2
11.09.2018	30	70°29'14.12" 68°35'22.58"	1.2	5.6
11.09.2018	31	70°29'08.45" 68°40'37.34"	2.7	12.7
11.09.2018	32	70°28'30.50" 68°41'11.74"	1.5	7
11.09.2018	33	70°28'21.80" 68°40'11.07"	1.4	6.6
11.09.2018	34	70°28'18.84"68°39'14.72"	1.2	5.6
11.09.2018	35	70°28'30.60" 68°39'27.67"	0.8	3.7
14.09.2018	36	70°17'02.19" 68°57'52.82"	0.6	2.8
14.09.2018	37	70°17'21.12" 68°59'16.48"	0.7	3.3
14.09.2018	38	70°16'07.57" 69°05'51.43"	1.1	5.1
14.09.2018	39	70°16'08.82" 69°06'08.85"	0.9	4.2
14.09.2018	40	70°14'51.05" 69°08'28.74"	3.4	16
14.09.2018	41	70°14'39.82" 69°08'10.95"	0.6	2.8
14.09.2018	42	70°14'03.59" 69°08'04.23"	1.3	6.1
15.09.2018	43	70°12'00.57" 69°00'23.73"	2.6	12.3
15.09.2018	44	70°12'58.86" 68°58'34.66"	1.5	7
15.09.2018	45	70°13'02.36" 68°59'09.06"	1	4.7
15.09.2018	46	70°17'33.37" 68°46'03.65"	1.1	5.1
15.09.2018	47	70°16'55.05" 68°44'03.55"	1.7	8
15.09.2018	48	70°16'41.89" 68°48'21.71"	1.1	5,1
08.09.2018	49	70°28'04.42" 68°22'07.07"	2	9.4
10.09.2018	50	70°19'02.97"68°30'13.56"	1.4	6.6
11.09.2018	51	70°28'42.92" 68°40'32.57"	4.1	19.3
13.09.2018	52	70°20'53.55" 68°18'46.09"	2.4	11.3

a spectrophotometric method was used based on measurements (a total of 364) of the ratio of two intensities of light fluxes passing through the studied and reference mediums. The latter was a distilled water of high purity (a control sample). After measuring spectral transparency of lake water treated from suspension and Chl_a through filtration using the "Vladipor" type MFAS-OS-1 membranes with a pore diameter of 0.45 μm, we defined light absorption by the $\kappa_{ys}(\lambda)$ yellow substance. The calculation of $\kappa_{ys}(\lambda)$ at the natural logarithmic base was carried out according to expression (1), in which, instead of $\varepsilon(\lambda)$, we used $\kappa_{ys}(\lambda)$ minus spectral index of pure water $\kappa_{pw}(\lambda)$.

$$\varepsilon(\lambda) = \left(\frac{1}{L}\right) \cdot \ln\left(\frac{1}{T(\lambda)}\right), \quad (1)$$

where L is the length of the cuvette; $T(\lambda) = I(\lambda) / I_0(\lambda)$ is the transparency (transmittance) in relative units; $I(\lambda)$, $I_0(\lambda)$ is the intensity of light passing and falling on the cuvette, respectively; λ is the wavelength of light.

The absolute error of $\varepsilon(\lambda)$ and $\kappa_{ys}(\lambda)$ is induced by the spectrophotometer instrument error at transmittance measurement ($\Delta T = 0.5\%$) and the error measurement of the cuvette length. In the experiment, we used cuvettes $L = 50$ mm long. The maximum absolute error in defining the light attenuation coefficient and light absorption by yellow substance was 0.1 m^{-1}.

The concentration of the C_{ys} yellow substance was determined from the expression given in (Man'kovsky, 2015)

$$C_{ys} = \kappa_{ys}(450) / \kappa_{sp.ys}(450), \quad (2)$$

where $\kappa_{sp.ys}(\lambda)$ is specific light absorption by the yellow substance from (Nyquist, 1979) at $\lambda = 450$ nm. The effective value of $\kappa_{ys}(\lambda)$ in the formula (2) is also identified using the above mentioned calculation scheme by summing up $\kappa_{pw}(\lambda)$.

Light absorption by yellow substance depends on the electronic transitions of molecules in organic compounds (Shifrin, 1983). Spectral dependence of light absorption by the $\kappa_{ys}(\lambda)$ yellow substance is described by the exponential law (Kopelevich, 1983)

$$\kappa_{ys}(\lambda) \sim e^{-\mu \cdot \lambda}, \quad (3)$$

where μ is the coefficient characterizing a curve slope of spectral absorption, which is different in various reservoirs.

Concentrations of chlorophyll *a* Chl_a were obtained due to remote sensing using the Sentinel-2 data.

3. Results and discussion

Because dissolved organic matter (DOM) of natural origin absorbs UV light and fluoresces due to the presence of humic compounds, its spectra are successfully used in solving such topical problems as the control over aquatic ecosystems and state. It enables us to detect contamination in the aquatic environment and trace its development in time, spread by depth change in concentrations. The DOM's part (called by Calle as yellow substance) is of particular optics interest. The rate of light absorption by yellow substance is directly proportional to its concentration that allows us to evaluate its content through optical properties.

The present study reports a significant difference in spectral light absorption by the $\kappa_{ys}(\lambda)$ yellow substance in the surface layers of 52 thermokarst lakes during the study period (September 8–15, 2018). For instance, at $\lambda = 450$ nm, the $\kappa_{ys}(\lambda)$ values varied within 0.5–3.4 m^{-1} with an average of 1.2 m^{-1} (Table). The calculated light absorption by the $\kappa_{ys}(\lambda)$ yellow substance at 400–700 nm was 0.7–9.4 m^{-1}. In our case, light absorption by the $\kappa_{ys}(\lambda)$ yellow substance in thermokarst lakes was much higher compared to other reservoirs. For instance, in the Mediterranean waters (Man'kovsky, 2011), at $\lambda = 550$ nm, this indicator was the lowest (0.0042 m^{-1}) compared to the Black (0.0106 m^{-1}) and Baltic Seas (0.0105 m^{-1}), oceanic waters (0.0086 m^{-1}1), and Lake Baikal (0.0096 m^{-1}). For optical classification of coastal and oceanic waters, the researchers (Prieur and Sathyendranath, 1981), along with absorption by phytoplankton pigments and inorganic particles, also used $\kappa_{ys}(\lambda)$ at 400–700 nm varying as 0.026–1.751 m^{-1}. A. Reinart et al. (2004) compared the obtained $\kappa_{ys}(\lambda)$ values for Lake Peipsi (Estonia) with those for lakes Vänern and Vättern (Sweden). Thus, the average spectral light absorption by yellow substance at 400 nm was 1.22 ± 2.6 (L. Peipsi), 1.05 ± 2.51 (L. Vänern) and 0.19 ± 0.52 m^{-1} (L. Vättern). O.B. Akulova et al. (2018) presented the experimental data (the summer of 2017) on changes in light absorption by the $\kappa_{ys}(\lambda)$ yellow substance in the surface layer of oligotrophic Lake Teletskoye. Here, $\kappa_{ys}(\lambda)$ is in the range from 0.6 to 1.1 m^{-1} (at $\lambda = 450$ nm), which is higher than in the oligotrophic water body, i.e. Lake Baikal. This correlates with another optical indicator that is relative water transparency on the Secchi disk. Seasonal variations of $\kappa_{ys}(\lambda)$ were studied in (Shi et al., 2017) on the example of a deep-water lake, i.e. Qiandaohu with its 90 investigated sites, where the average light absorption by yellow substance (at $\lambda = 440$ nm) was 0.05 ± 0.22, 0.12 ± 0.27, 0.05 ± 0.21, and 0.04 ± 0.21 m^{-1} in spring, summer, autumn, and winter, respectively. During the study of the $\kappa_{ys}(\lambda)$ dynamics in Chinese Lake Taihu (Hong et al., 2004) during 1994 and 1995, this indicator varied in different seasons from 0.180 to 1.854 m^{-1} (at $\lambda = 440$ nm). For lakes of South America in Northern Patagonia (Moreno Oeste, Mascardi Catedral, and Guillelmo), the average $\kappa_{ys}(\lambda)$ at $\lambda = 440$ nm ranged from 0.06 to 0.13 m^{-1}, and for lakes Morenito, Trébol and Escondido – from 0.27 to 1.96 m^{-1} (Pérez et al., 2002).

In the surface layers of thermokarst lakes, the maximum chlorophyll *a* concentration was around 12.5 mg/m^3. At thirty-seven sampling stations of fifty-two ones, Chl_a ranged from 10.0 to 14.5 mg/m^3, which corresponds to oligo- and mesotrophic reservoirs. Eutrophic samples ($Chl_a > 30$ mg/m^3) were not found. The maximum chlorophyll concentration (18.8 mg/m^3) was detected at site 52. The concentrations of yellow matter in the studied lakes determined through the optical method from the measured coefficient of light absorption by yellow substance at $\lambda = 450$ nm varied from 2.3 to 19.3 g/m^3. The correlation between the Chl_a and C_{ys} concentrations in all samples indicated that a low concentration of chlorophyll ($Chl_a < 10$ mg/m^3) was randomly accompanied by a wide range of the C_{ys} attenuation (from 0.5 to 3.0 g/m^3), whereas its high concentrations – similarly, by random but significantly lower variation of C_{ys} (from 1.1 to 1.9 g/m^3). For comparison, the concentrations of yellow substance in the surface layers of three different-type lakes of Altai Krai varied as follows: in eutrophic Lake Lapa it was much higher, 14.72–23.69 g/m^3; in eutrophic-hypereutrophic Lake Krasilovskoye – 14.21–29.72 g/m^3, and in hypereutrophic Lake Bolshoye Ostrovnoye – 16.79–27.37 g/m^3 (Akulova et al., 2017).

The obtained results are currently of much interest in understanding the processes occurring in the lacustrine environment. Monitoring of changes in the yellow substance content provides information about biological productivity, ecological purity and internal water dynamics of the studied objects. It is also topical for assessing man-induced ecological aftereffects and mitigating the environmental risk related to the water supply to population and industrial facilities.

4. Conclusions

1. The article presents the experimental data on dynamics of light absorption by yellow substance in the surface layers of 52 thermokarst lakes of the Central Yamal obtained during comprehensive studies in September 2018.
2. We obtained the new complete data on light absorption by the $\kappa_{ys}(\lambda)$ yellow substance, in the surface layers of the studied lakes.
3. We compared light absorption by yellow matter in the waters of thermokarst lakes of the Central Yamal with other different-type reservoirs. The results suggest that this indicator is much higher in thermokarst lakes than in marine and oceanic waters.
4. We calculated the concentrations of the C_{ys} yellow substance in water samples from the surface layers of the lakes.
5. The data on the spatial distribution of the chlorophyll **a** (Chl_a) concentrations in the studied lakes were obtained using the remote sensing method.

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