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ВАРИАЦИИ КАЧЕСТВА ВОДЫ В ЛАДОЖСКОМ ОЗЕРЕ В ВЕСЕННИЙ ПЕРИОД В 2016 И 2017 гг.: СПУТНИКОВЫЕ НАБЛЮДЕНИЯ

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Приведены и обсуждаются результаты спутниковых наблюдений за качеством вод в Ладожском озере в весенний период в 2016–2017 гг. Концентрация хлорофилла *а* фитопланктона, как и другие гидробиологические параметры, наименее изучены в период полного или частичного покрытия льдом как на Ладоге и Онеге, так и на многих великих озерах мира. В последние 30 лет при заметном потеплении климата Ладожское озеро не каждый год покрывается льдом, и в этом случае имеется возможность оценки параметров качества воды. Полученные впервые статистические данные по качеству воды в Ладожском озере свидетельствуют о том, что, вопреки ожиданиям, концентрации хлорофилла *а* уже в марте не нулевые (хотя и достаточно низкие: ≤ 1 мкг/л) не только в литоральных, но даже в некоторых пелагиальных районах озера, и вероятно обусловлены клетками фитопланктона, вегетировавшего в зимний период подо льдом. Весенние концентрации взвешенного неорганического вещества обнаруживаются в широком диапазоне значений (0.1–3.5 мг/л) в зависимости от года и конкретной части акватории озера. Диапазон концентраций окрашенного растворенного органического вещества обнаружены в диапазоне от <4.5 до 12–15 мгС/л) с наименьшими значениями в пелагиальных районах и наибольшими — в литоральных, в частности, в районе Волховской губы. С началом летнего периода указанные показатели в среднем по озеру слабо возрастают, оставаясь существенно ниже своих характерных значений для июля месяца.

Ключевые слова: Ладожское озеро, спутниковое дистанционное зондирование, алгоритм восстановления качество воды, хлорофилл *а*, взвешенное вещество, окрашенное растворенное органическое вещество, временной ряд, гидродинамика.

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INTERANNUAL WATER QUALITY VARIATIONS IN LAKE LADOGA IN SPRING DURING 2016 AND 2017: SATELLITE OBSERVATIONS

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Reported and analyzed the results of satellite observations of Lake Ladoga water quality parameters (WQPs) primarily in spring 2016 and 2017. Our retrievals indicate that even in March, soon after the inception of ice cover melting, the concentration of chlorophyll *a* (C_{chl}) is non-zero (but yet very low) not only in the lateral but also pelagic waters of the lake. Arguably, the non-zero *chl* concentrations arise from the phytoplankton that vegetated under ice and then moved up to the surface as the ice sheets began melting. Spring-time concentrations of inorganic suspended matter (C_{sm}) are year-specific and range between 0.1 and 3.5 mg/l with the elevated values inherent in lateral waters, especially in the vicinity of river outflows. Similar spatial patterns are found for the distributions of colored dissolved organic matter concentrations (C_{dom}). The lowest values of C_{dom} (<4.5 mgC/l) occurred in the pelagic waters, whereas the highest ones (12–15 mgC/l) resided in the lateral zone, in particular, within/adjacent to the Volkhovskaya Gouba. With the beginning of summer, the above concentrations, C_{chl}, C_{sm}, and C_{dom}, start growing, remaining however less than they are in July.

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Key words: Lake Ladoga, satellite remote sensing, water quality retrieval algorithms, chlorophyll *a*, suspended inorganic matter, colored dissolved organic matter, time series, hydrodynamics, mesoscale process.

1. Introducton

In the community of remote sensing workers, concentrations of phytoplankton chlorophyll *a*, suspended minerals and colored dissolved organic matter are traditionally subsumed under the category of water quality parameters (WQPs) [1]. Although this is a rather conditional notion, it proves to be fairly useful when it comes to the problems of eutrophication, and naturally or anthropogenically driven input of mineral matter and humus from the watershed [2, 3].

Shipborne investigation of the above WQPs inherent in large fresh water bodies at high latitudes during early-spring are unattainable as research vessel cruising during this time of year is prohibited due to various reasons, among which are ice fields in the coastal zone, sporadically floating floes in the pelagic zone, and frequently severe weather conditions.

Meanwhile, such lacunas in our knowledge of what actually happens in large northern lakes during the transitional period between winter and summer is an essential drawback in understanding of the lake ecosystem continuous working.

Application of satellite remote sensing means promises to bridge the gap as satellite sensors overfly the target water body and collect data throughout the year. However, the task of inferring WQPs from satellite data on inland water bodies is challenging regardless of the period of spaceborne observations. The problem resides in the optical complexity inherent in inland water bodies: the radiometric impact of phytoplankton in such waters is in separately accompanied by the respective impacts (that extend over the entire visible part of the spectrum) of coexisting in water suspended minerals and colored dissolved organic matter [4]. The attempts to ignore this phenomenon and retrieve with the standard NASA and ESA regression algorithms (that were developed exclusively for clear/pelagic waters [5]) the concentration of only one WQP component (e. g. phytoplankton chlorophyll *a*) from light coming out of water lead to heavily wrong results [see e. g. 6]. To overcome this impediment, sophisticated techniques need to be developed to allow disentangling the optical signal captured by the satellite sensor in order to attribute its components to specific WQPs, and finally, through applying bio-optical retrieval algorithms, quantify the concentrations of the desired WQPs.

Here we report on our 2-year study of WQPs in Lake Ladoga with the emphasis on spring and early summer months. Following the terminology widely accepted in environmental remote sensing [7], the term WQPs stands for the concentrations of (*i*) phytoplankton chlorophyll *a* (C_{chl}), (*ii*) suspended mineral matter (C_{sm}) and (*iii*) colored dissolved organic matter (C_{dom}).

2. Data sources

Spectral remote sensing reflectance, $R_{rs}(\lambda)$ is one of the prime parameters relevant to studies of the aquatic environments. $R_{rs}(\lambda)$ is the spectral radiance coming out of the water column normalized to the atmospherically corrected spectral irradiance incident upon the atmosphere-water interface [8]. Importantly, $R_{rs}(\lambda)$ is functionally related to subsurface remote sensing reflectance, $R_{rsw}(\lambda)$, which, as it is shown below, is used in the bio-optical retrieval algorithm employed in this work.

Data on this parameter are available from OC CCI (Ocean Color Climate Change Initiative, ESA (http://www.esa-oceancolour-cci.org/, accessed 27.09.2019). The OC CCI data are bridged and harmonized ocean colour information from three sensors, viz SeaWiFS (Sea-Viewing Wide Field-of-View Sensor), MERIS (Medium Resolution Imaging Spectrometer), and MODIS (Moderate-resolution Imaging Spectroradiometer), and are superior to the original ones as they provide a significantly increased cloud-free water surface cover and the length of timeseries. To assess the quality of OC CCI data the correspondence between daily-averaged spaceborne spectral values of R_{rs} in the spectral channels 412, 443, 490, 510, 555 и 670 nm and the respective *in situ* spectral values of R_{rs} obtained on the day of satellite overflight was appraised. It was done through analyzing the following statistically significant parameters as coefficients of correlation, *r* and determination, r^2, mean square error, MSE, mean absolute error, MAE. For this purpose, we exploited the SeaBASS (NASA) database relating to the time period 2001–2010. Marine stations are located in the Pacific along the California coastal zone, in the Atlantic (Mexican Gulf and Philadelphia shelf zone) as well in the US eastern coast waters extending from Southern Carolina to Bar Harbor (State Main in New England).

More than 580 matchup pairs of satellite *in situ* R_{rs} values were used for our quantitative comparison. Matchup pairs satisfied the following requirements: the least time span between the *in situ* measurement and the sensor overflight, the pixel accurately encompassed the measurement station location, the least contamination of the swath area with clouds, and finally, the longest time series provided by each of the aforementioned three shipborne products. The comparison results proved a very good consistency between in situ and OC CCI data, and gave the credit to the quality of the initial raw data further submitted to processing.

To reduce the size of computations to a reasonable level, at the next step it was mandatory to identify the permissible temporal and spatial resolution that would permit to avoid any loss of significant information. In each pixel of the daily image of Lake Ladoga, the value of the standard deviation, SD (sr^{-1}) of $R_{rs}(\lambda)$ from its counterpart averaged over 4 km, 9 km, and 8 days and one month were quantified. It was found that for our aims a 4 km- and 8 day-spatio-temporal averaging (resolution) is quite acceptable. This result should not be considered as trivial because it stems out from the established specific parameters spatio-temporal inhomogeneity inherent in WQP fields that was quantitatively investigated by us previously: the values of SD (sr^{-1}) for $R_{rs}(\lambda)$ were determined daily within the algal bloom (*1*) at a spatial resolution of 4 km^2 and 9 km^2, and (*2*) a time resolution of 8 days and 1 month. The SD (sr^{-1}) values proved to be about 10^{-3} and 10^{-2} for the spatial resolution of 4 km^2 and 9 km^2, and about 10^{-4} and 10^{-2} for the time resolution of 8 days and1 month, respectively. Thus, the 4 km^2- and 8-day resolution option proved to be acceptable [9]. Therefore, in the present study we employed the OC CCI data at a 4 km and 8 day resolution for inspecting the dynamic of the situation across Lake Ladoga, and a 1 day resolution when having revealed the best day for analysis.

3. Description of methodology: the bio-optical algorithm for WQP retrievals

As emphasized above, lacustrine water is generally optically complex (see above). Lake Ladoga is a typical example of such waters and as such requires specialized bio-optical retrieval algorithms for its examination by means of remote sensing. For optically complex waters the BOREALI and Neural Network algorithm was employed.

Developed at the Nansen Centre in St. Petersburg [7], the BOREALI algorithm provides a *simultaneous* retrieval from $R_{rs}(\lambda)$ data of the above three WQPs parameters, i. e. C_{chl}, C_{sm}, and C_{dom} that are also traditionally called colour producing agents, CPAs [4]. The BOREALI algorithm employs the observed/retrieved spectral subsurface remote sensing reflectance, R_{rsw}, which is the up-welling spectral radiance just beneath the water–air interface normalized to the downwelling spectral irradiance at the same level [10]. R_{rsw} has a direct relation to $R_{rs}(\lambda)$ [10]. Like $R_{rs}(\lambda)$, R_{rsw} is a function of both CPA concentrations in the water column and the spectral values of bulk water coefficients of absorption and backscattering that result from summation of products of each coexisting CPA concentration (i. e. C_i) and their respective specific spectral absorption and backscattering coefficients. Through varying the concentration vector $C = \sum_n C_i$ (where *i* is a CPA [viz. *chl*, *sm*, *dom*], *n* = number of CPAs) and minimization at each wavelength of the function $f(\mathbf{C})$ of squares of residuals of the difference between the observed/retrieved and simulated spectral values of R_{rsw}, the absolute minimum can be found with the Levenberg–Marquardt finite difference algorithm [11,12]. The concentration vector value corresponding to the attained *absolute* minimum of the function $f(\mathbf{C})$ is the solution of the inverse problem, i. e. the establishment of the desired CPA concentrations.

Simulation of R_{rsw} spectra and hence running the BOREALI algorithm requires not only some parameterization relating $R_{rsw}(\lambda)$ to bulk water spectral absorption and backscattering coefficients [13], but also the specific hydro-optical model inherent in the target waters.

The BOREALI code outfitted with the waterbody-specific hydro-optical model has been successfully employed for the retrieval of WQPs (CPAs) not only in Lakes Ladoga and Onega, but also in the Great American Lakes and the White, Bering and Kara seas [7, 14–17].

In the present study we employed the hydro-optical model developed by Pozdnyakov et al. [7] specifically for the transformed trophic and ecological state of Lake Ladoga. The model (table 1) is a collection of tabulated spectral values of CPA specific absorption and backscattering coefficients (i. e. normalized to the respective CPA concentration).

Table 1

Lake Ladoga hydro-optical model: spectral specific absorption a^* and backscattering b_b^* cross sections for phytoplankton (*chl*), suspended minerals (*sm*) and colored dissolved organic matter (*dom*) [7]. a^*_{dom} corresponds to the unit concentration of *dom* measured in the carbon units.

λ, nm	a^*_{Chl} m^2/mg	a^*_{sm} m^2/g	a^*_{dom} m^2/gC	a^*_{bChl} m^2/mg	b^*_{bsm} m^2/g
410	0.03800	0.26500	0.28000	0.001240	0.02300
430	0.04000	0.23000	0.25000	0.001230	0.02500
450	0.04100	0.20000	0.23000	0.001210	0.02700
470	0.04000	0.18000	0.18000	0.001200	0.02900

Fin table 1

λ, nm	a^*_{Chl} m²/mg	a^*_{sm} m²/g	a^*_{dom} m²/gC	a^*_{bChl} m²/mg	b^*_{bsm} m²/g
490	0.03400	0.16000	0.16000	0.001210	0.03050
510	0.02800	0.14500	0.14000	0.001240	0.03200
530	0.02200	0.13000	0.12500	0.001270	0.03300
550	0.01800	0.12000	0.11000	0.001290	0.03350
570	0.01500	0.11000	0.10000	0.001280	0.03300
590	0.01300	0.10500	0.09000	0.001270	0.03250
610	0.01200	0.10000	0.08000	0.001270	003200
630	0.01200	0.10000	0.07000	0.001260	0.03100
650	0.02000	0.10500	0.06000	0.001220	0.02900
670	0.02500	0.11500	0.05000	0.001160	0.02700
690	0.01600	0.12500	0.05000	0.001080	0.02500

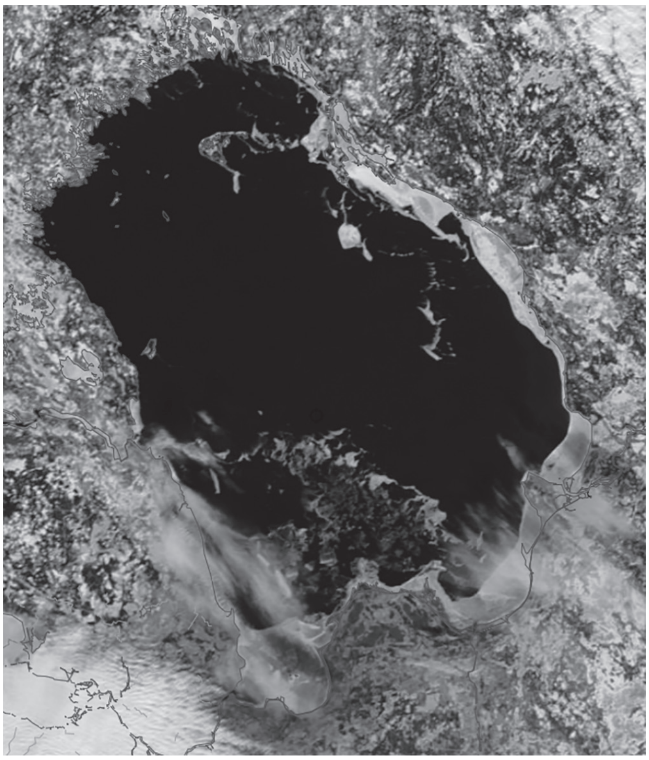

Fig. 1. A panchromatic MODIS-Aqua image of Lake Ladoga (NASA WorldView site) at a 250 m spatial resolution taken on March 16, 2016.

The assessed average retrieval error of the BOREALI algorithm for each of the WQPs does not exceed 15 % [15].

As in spring there are floating floes and even large ice sheets across Lake Ladoga (e. g. fig. 1), a special algorithm has been developed to identify such locations and exclude them from further analysis. This algorithm detects pixels with $R_{rs}(\lambda)$ whose spectral characteristics are untypical of open-water areas and at the same time typical of ice or snow- on- ice surfaces [18]. Based on (*i*) the available spectral characteristic of freshwater ice [19], (*ii*) spring-time panchromatic images of Lake Ladoga (NASA data), and (*iii*) R_{rs} spectral curvature data from floes/ice cover, statistically confident R_{rsw} thresholds were established. The algorithm tests all R_{rsw} spectra from each scene and automatically identifies and delineates ice-free areas.

4. Results and discussion

Due to frequent cloudiness and presence of floes and ice sheets in spring and especially early spring (as exemplified in fig. 1), the areas open to study WQPs prove to be limited and scattered across Lake Ladoga. However, even such data are of significant value as they are the only ones attainable at this time of year.

In light of the above limitations, we were able to confidently restore the WQP parameters for only one date in 2016 (March 16), and four dates in 2017 (March 12, 16, 21 [fig. 2, see Inset], and 23). As table 2 illustrates, the C_{chl} values were pretty low (<1 μg/l), but, however, not zero as it could be expected [20]. The C_{sm} concentrations were found within the range 0.1–3.5 mg/l. The DOC content in the surface waters was in the range (5–15 mgC/l).

Table 2

Ranges of WQP concentrations retrieved in March 2016 and 2017

WQP	March, 2016	March, 2017
chl, μg/l	0.1–1	0.6–0.8
sm, mg/l	0.1–0.6	< 0.5–3.5
doc, mgC/l	4.5–10.5	4.5–15

It can be supposed that non-zero *chl* concentrations in March were due to the under-ice phytoplankton that moved up to the surface as the ice sheets began melting. Indeed, within the formed ice-free areas, the algal cells found themselves in favorable conditions in terms of the available photosynthetically active radiation (PAR) and increased upward fluxes of nutrients due to wind-driven vertical fluxes of water [21].

We conjecture that the relatively enhanced concentrations of *sm* observed in Ladoga, especially in 2017, were due to the release (with the onset of ice cover melting) of airborne solid particles/aerosol accumulated over the winter period. Such reports are many from different lacustrine and marine environments [22].

The observed range of *doc* concentrations corresponds well with the available in situ data: there are reports [23] that in some parts of Lake Ladoga *doc* concentrations in spring could be very low (about 4 mg/l), especially in the upper-most surface layers. Nonetheless, according to the OC CCI data from the peripheral waters within the areas adjacent to river outflows, *allochthonous* C_{dom} in May can be as high as 10–12 mgC/l [7, 24]. These assessments are in good agreement with the data reported herein. The propagation trajectory of waters that are the Volkhov River outflow and the associated enhancements in C_{sm} and C_{doc} are perfectly visible in our data for early summer (fig. 3, see Inset). Some enhanced concentrations of *sm* and *doc* within the shallow bay Shlisselbourgskaya Gouba are, presumably, a result of early warming of this aquatic body, and wind-driven resuspension of buried organic and inorganic matter.

5. Conclusion

In view of the fact that we applied the algorithm capable of disentangling the concomitant optical influences of WQPs on the light signal emerging from water, we believe that the WQP values reported herein for early spring in Lake Ladoga, are most reliable especially in off-coastal waters (i. e. they have never been obtained either from board of ship or remotely) and unique by themselves. Unlike, for instance, the data (and only for chl! with the values exceeding 20 mgm^{-3}!!!!) provided at the NASA site for March 212017 (https://worldview.earthdata.nasa.gov/?v=25.27,58.12,37.12,63.94&t=2017–03–21-T14 %3A00 %3A00Z&l=MODIS_Aqua_Chlorophyll_A, Coastlines), the retrieved concentrations not solely of chl, but also of sm and doc appear quite realistic in light of the biogeochemistry known for this water body and multidecadal in situ measurements in summer and autumn. The present study is a harbinger of further satellite observations that are certainly mandatory to increase both the statistical significance of the WQPs ranges as well as their representativeness through collecting information from as many as possible ice-free zones across the lake surface. This can be done by means of extending the satellite observations over a longer row of years.

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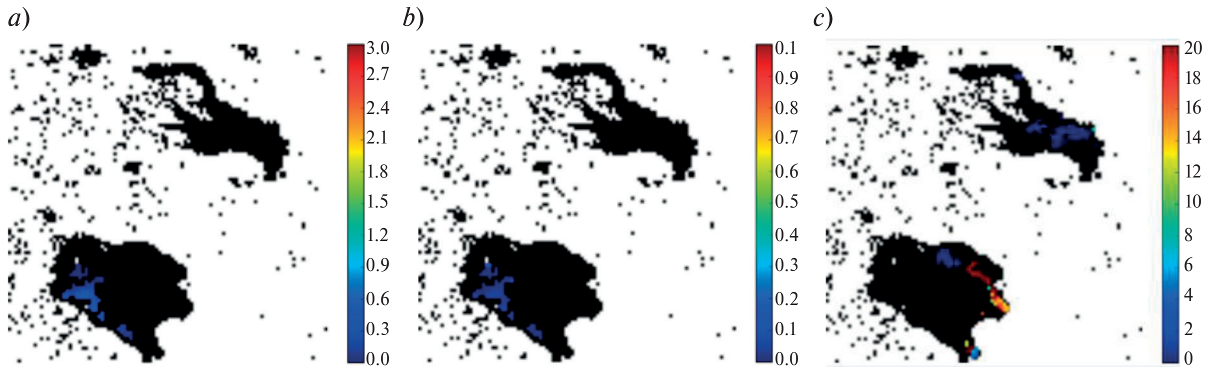

Fig. 2. Retrieved ranges of concentrations of phytoplankton *chl* (μg/l) (*a*), suspended minerals, *sm* (mg/l) (*b*), and colored dissolved organic matter (*c*), *doc* (mgC/l) in Lake Ladoga for March 21, 2017. Note: White-colour areas are the watershed of Lake Ladoga and Lake Onega (respectively, low and upper parts of the plates). The nature of the black spots beyond the surface of the above lakes is unclear, and thus should be disregarded.

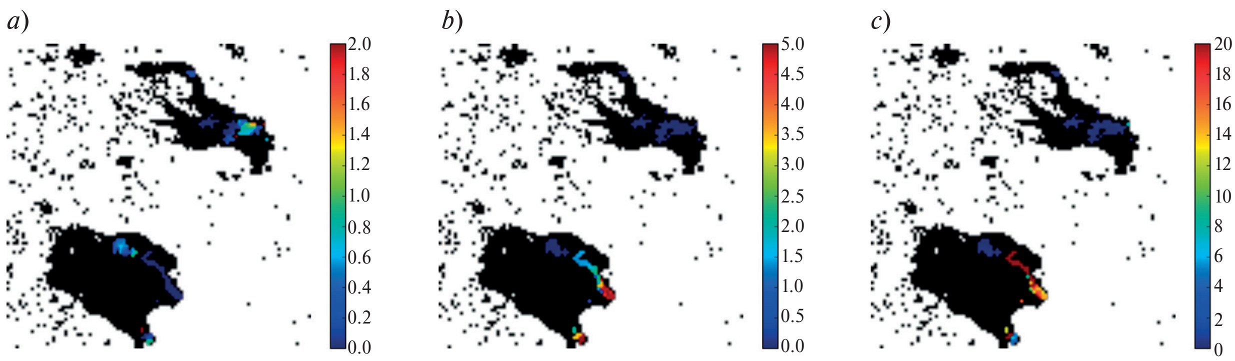

Fig. 3. Results of retrieval of concentrations of phytoplankton *chl* (μg/l) (*a*), suspended minerals, *sm* (mg/l) (*b*), and colored dissolved organic matter (*c*), *doc* (mgC/l) in Lake Ladoga for June 04, 2017. Note: as for fig. 2.