Cyanobacterial bloom in the world largest freshwater lake Baikal

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Abstract. Lake Baikal is a UNESCO World Heritage Site and holds 20% of the world's freshwater reserves. On July 26, 2016, a cyanobacterial bloom of a green colour a few kilometers in size with a bad odor was discovered by local people in the Barguzinsky Bay on the eastern shore of Lake Baikal. Our study showed very high concentration of chlorophyll $a$ ($41.7 \text{ g/m}^3$) in the sample of bloom. We found that the bloom was dominated by a nitrogen-fixing heterocystous cyanobacteria of the genus *Dolichospermum*. The mass accumulation of cyanobacteria in the lake water with an extremely high chlorophyll $a$ concentration can be explained by a combination of several factors: the discharge of biologically-available nutrients, including phosphorus, into the water of Lake Baikal; low wind speed and weak water mixing; buoyant cyanobacterial cells on the lake surface, which drifted towards the eastern coast, where the maximum concentration of chlorophyll $a$ was recorded. In the center of the Barguzinsky Bay and in the open part of Lake Baikal, according to satellite data, the chlorophyll $a$ concentration is several orders of magnitude lower than at the shoreline.

1. Introduction

Eutrophication is defined by the European Commission as the “enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned” [1]. By the end of the 20th century eutrophication became one the major problem of lakes and reservoirs around the world. According to the Survey of the State of the World's Lakes performed at the beginning of 1990s, eutrophication took place in 54% of Asian lakes, 53% of European lakes, 48% of lakes in North America, 41% of lakes in South America, and 28% of lakes in Africa [2].

Lake Baikal is a UNESCO World Heritage Site and holds 20% of the world's freshwater reserves. Since 2011 a massive development of the filamentous green algae was regularly observed in the nearshore zone of the lake. Also the blooms of the potentially toxic planktonic cyanobacteria of the genera *Dolichospermum* (formerly *Anabaena*) and *Microcystis* were observed in the surface layers of the lake [3, 4]. These genera are capable of synthesizing a wide range of neurotoxins and hepatotoxins including microcystin, cylindropermopsin, saxitoxin and anatoxin-a [5]. The warmest shallow bays, which are also attractive for tourists, are most susceptible to eutrophication. The discharge of untreated sewage from tourist hotels, municipal sewage treatment plants and ships is considered to be the main anthropogenic source of biologically-available nutrients entering the lake [6].
On July 26, 2016, an odoriferous, bright green cyanobacterial bloom a few kilometers across was discovered by local people in the Barguzinsky Bay on the eastern shore of Lake Baikal near the village of Ust-Barguzin, Buryat Republic. The aim of our work was to study the phototrophic microorganisms and to analyze the chlorophyll $a$ concentration in the Barguzinsky Bay on the basis of sample analysis and satellite data.

![Figure 1. Location of the Barguzinsky Bay on the eastern coast of Lake Baikal (left). Satellite image of Barguzinsky Bay as of July 27, 2016 showing the algal bloom near the eastern shore (right). The image was obtained from Copernicus Sentinel data 2016. UB - the location of the Ust-Barguzin village.](image)

2. Materials and methods

Green-colored water sample was collected from the coastal zone of the Barguzinsky Bay near Ust-Barguzin village, coordinates N 53°24', E 108°59' (figure 1). Sample (1.5 L volume) was collected on July 29, 2016 and immediately brought to laboratory at the ambient conditions. The taxonomic composition of cyanobacteria and eukaryotic microalgae was determined using determination manuals [7-9]. The concentration of the chlorophyll $a$ was determined spectrophotometrically in the 80% ethanol extracts from the biomass [10].

Analysis of chlorophyll $a$ content based on satellite data was carried out using data obtained with the help of the MODIS sensors installed on the Aqua satellite launched in 1999 and Terra satellite in 2002. Both sensors are currently active (as of October 30, 2017). The sensor resolution is 1 km. Satellite data are available at [https://oceancolor.gsfc.nasa.gov/data/aqua/](https://oceancolor.gsfc.nasa.gov/data/aqua/). The concentration of chlorophyll $a$ was determined according to the procedure Ocean Color Chlorophyll (OC) v6 [11]. The verification of the satellite data was performed using the ground-truth data collected during CONTINENT project [12, 13]. To calculate the quantitative indicators characterizing the lake, specially designed scripts written in Python were used. All data were processed on the supercomputer of the NRC Kurchatov Institute. Satellite data related to Lake Baikal were selected by using a shp-file with data on the shoreline of Lake Baikal obtained using the resource Marine Regions [14]. To improve the quality of the program, three successive approximations of the lake territory were made with polygons with increasing accuracy. The output was obtained in the following format: the date of measurement, the area of the territory at which the concentration was successfully measured, the share of the area with data from the total lake area, the mean chlorophyll $a$ concentration in the accessible area. The weather conditions in the Barguzinsky Bay area in July 2016 were studied using the World
Meteorological Organization database [15]. The identification number of the meteorological station in the village of Ust-Barguzin located on the shore of Barguzinsky Bay is WMOID 30635.

3. Analysis of sample from Barguzinsky Bay
Examinations of sample using optical microscopy showed that the filamentous heterocystous cyanobacterium of the genus *Dolichospermum* with curved trichomes and gas vacuoles was dominant [16]. Subdominant was the filamentous heterocystous cyanobacterium *Gloeotrichia* sp. (figure 2). In addition, the representatives of the unicellular cyanobacteria of the genus *Synechocystis* and eukaryotic microalgae of the genera *Scenedesmus*, *Nitzschia* and *Aulacoseira* were determined. The chlorophyll *a* content in the sample was 41.7 g/m³. This is an extremely high value characteristic of eutrophic water bodies. The value obtained is comparable with the concentration of chlorophyll *a* found by Zohary and Breen (1989) when studying *Microcystis aeruginosa* hyperscums in a hypertrophic South African lake. These authors registered a concentration of chlorophyll *a* exceeding 100 g/m³ [17].

![Figure 2. Cyanobacteria from Barguzinsky Bay. A. Filaments of *Dolichospermum* sp. (magnification 1000X), B. Colony of *Gloeotrichia* sp. (magnification 100X).](image)

The dominance of chlorophyll *a* (665 nm) in the absorption spectrum and the low level of chlorophyll *b* (648 nm) also indicate the dominance of cyanobacteria in the sample (figure 3).

![Figure 3. Absorption spectrum of cyanobacterial bloom biomass in ethanol.](image)
4. Chlorophyll a distribution in Lake Baikal according to satellite data
During each passage of the satellite, a large percentage of the lake area remained inaccessible to the spectrometer measurements. Successful measurements were obtained using Aqua and Terra 15, 16, 20, 23, 25, 27 July 2016 (table 1) satellites.

| Date       | Barguzinsky Bay |
|------------|-----------------|
|            | Aqua | Terra | Aqua | Terra |
| 15.7.16    | 43.42| 41    | 22.82| 23.33 |
| 16.7.16    | 70.83| 90.08 | 24.03| 28.32 |
| 20.7.16    | 50.39| 173.65| 11.08| 18.17 |
| 23.7.16    | 46.35| 40.85 | 9.65 | 11.5  |
| 25.7.16    | 4.35 | n.d.  | 6.8  | 34.5  |
| 27.7.16    | 48.22| 82.2  | 6.83 | 3.35  |

n.d. – no data available

In the eastern part of Barguzinsky Bay, a square with a perimeter of 2 km was chosen with a center with coordinates of N 53°24', E 108°55'. This location of the square was chosen to exclude the signal from land and coastal vegetation entering the analyzed data array. For this square, the concentrations of chlorophyll a measured by the Aqua and Terra satellites were determined from July 15 to July 31. Successful measurements were carried out by both satellites only on the following days: 15, 16, 20, 23, 27 July. On July 25, the data were obtained only using the Aqua satellite. The data obtained with the help of satellite observations show that the concentration of chlorophyll a in the water of the Barguzinsky Bay significantly exceeds the average concentration of chlorophyll a in the water of Lake Baikal, except July 23, 2016. On the 27 July the content of chlorophyll a measured by the Aqua and Terra satellites in the water of Barguzinsky Bay was 48.22 and 82.2 mg/m³, while the average concentration of chlorophyll a in the water of Lake Baikal was 6.83 and 3.35 mg/m³. However, it should be taken into consideration that in the Barguzinsky Bay a high terrigenous input can significantly influence the satellite-derived chlorophyll a data [12].

5. Weather parameters in the Barguzinsky Bay area in July 2016
Analysis of weather conditions shows that in July 2016 in Barguzinsky Bay there was a low wind speed. The average value was 1.8 m/s, the maximum value was 6 m/s, which corresponds to calm to moderate winds (figure 4). The average air temperature in July was 18 °C, the minimum temperature was 8.2 °C, and the maximum temperature was 27.8 °C. Before sampling, the maximum wind speed was observed on July 23 (6 m/s), whereas from July 24 to July 29 the wind speed in Barguzinsky Bay was low. The average value was 1.7 m / s, the maximum value was 4 m/s, which corresponds to calm to gentle breeze weather conditions. The dominant wind direction was western, in the direction of the eastern shore of the lake (figure 5).
6. Conclusions
Analysis of the obtained data shows that the cyanobacterial bloom in the Barguzinsky Bay of Lake Baikal in July 2016 was dominated by heterocystous cyanobacteria of the genus *Dolichospermum*. They are able to fix atmospheric nitrogen to circumvent N limitation and hence their growth is most likely limited by phosphorus availability. They also contain gas vacuoles which allow the cells to float to the surface of the lake in the absence of strong wind mixing of the lake's water. The mass accumulation of cyanobacteria in the lake water with such a high chlorophyll $a$ concentration can be explained by a combination of several factors: the discharge of biogenic elements, including phosphorus, into the water of Lake Baikal; low wind speed and weak water mixing; the floating of cyanobacterial cells on the lake surface and their drift by west wind in the direction of the eastern coast. A similar scenario was proposed by Zohary and Breen for hyperscum formation by *Microcystis aeruginosa* when extremely high concentrations of chlorophyll $a$ were reached in a hypereutrophic reservoir [17]. The maximum concentration of chlorophyll $a$ was found near the shoreline. In the central part of the Barguzinsky Bay and in the open part of Lake Baikal, according to satellite data, the chlorophyll $a$ concentration several orders of magnitude lower than that of the shoreline.
Acknowledgement
The authors would like to thank Mikhail Ovdin, Alexander Altaev, Nikolai Buduev and Darima Barkhutova for their support and assistance with a collection of samples from Lake Baikal. This work has been carried out using computing resources of the federal collective usage center Complex for Simulation and Data Processing for Mega-science Facilities at NRC “Kurchatov Institute”, http://ckp.nrcki.ru/. This work was supported by Ministry of Education and Science of the Russian Federation (project № 14.574.21.0148, identifier RFMEFI57417X0148).

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