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PHYTOPLANKTON,
PHYTOBENTHOS, AND PHYTOPERIPHYTON

Long-Term Dynamics of Lake Baikal Pelagic Phytoplankton under Climate Change

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Abstract—The effect that climate change in the Lake Baikal region has on the state of the lake plankton is discussed. The increase in water temperature in the photic layer and chlorophyll *a* content during direct stratification is demonstrated with the use of a database containing the results of plankton observations from 1951 to 2000. The number of small-cell algae belonging to the summer complex seems to increase, while the number of endemic large cell algae developing under the ice is characterized by negative trends.

Keywords: phytoplankton, chlorophyll *a*, Lake Baikal, climate change.

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INTRODUCTION

According to common opinion, the average global surface air temperature increased 0.74°C over the last century. Its future increase is estimated to be from 0.1 to 0.3°C for a decade and, by 2100, the long-term temperature norm can increase by 1.8–5.0°C [26]. The consequences of climate change for aquatic ecosystems can be assessed on the basis of modern limnology concepts about their structure and functioning [12, 13, 15, 25, 30]. Higher air temperatures can promote an increase in the surface water temperature in lakes. Climate changes can affect the physical and chemical processes in a body of water and its watershed and, as a result, influence the hydrochemical regime of waterbodies. Changes of hydrological and hydrochemical regimes can also affect the biota. In the first turn, the high development of phytoplankton and the transformation of its composition should be expected. Warmer temperatures and the long stable summer stratification of the water column caused by global warming stimulate the growth of small algae [6, 11, 14]. Experiments have demonstrated that, at increased temperatures, ultranannoplankton develops the most actively (0.2–2.0 μm), nannoplankton (2.0–20 μm) develops less intensively, and microplankton (20–200 μm) grows the least. Thus, the portion of small forms in phytoplankton increases [23]. Early ice break and the intensification of the inflow of nutrients from the watershed stimulates the mass development of small cosmopolite forms of diatoms [5, 20]. A significant increase in the production of small species has been documented in some Arctic lakes in the 20th century [21].

Studies of the consequences that climate changes have for the ecosystem of Lake Baikal, which is the world's largest storage basin of fresh drinking water, are of indubitable interest. A whole number of works [5, 19, 20, 28, 34] has been published on the effect that global warming has on some characteristics of the Lake Baikal ecosystem. However, complex studies on the response that the lake ecosystem has to changes in climate-forming factors have started recently and their main goal is to reveal the response of pelagic biota components. Based on common limnological logic, most attention should be paid to the dynamics of primary producers as a key link in the formation of the energy flux and the cycle of matter. Unlike small lakes, in Lake Baikal, like in the ocean, phytoplankton produces >90–95% of primary production [18]. Any deviations from the balanced functioning of phytoplankton will have significant consequences for the lake ecosystem. This work presents the results of a study which is in progress [1, 7, 10, 22, 27].

The aim of this work is to analyze the long-term dynamics of the characteristics of the state of the phytoplankton in Lake Baikal (chlorophyll *a* content and number of dominant species) under the effect of modern climate change.

MATERIALS AND METHODS

This study has been conducted using the Plankton Database [4], which includes information about year-round decadal collections of phytoplankton over the period from 1951 to 2000 at a station approximately 2.7 km offshore from the village of Bolshie Koty (51°54′12″N, 105°04′14″E). The water depth at this site was 800 m. The samples were collected with a 10 l bathometer between 0–50 m, where all active phytoplankton was concentrated [2]. Phytoplankton samples fixed with Utermohl solution were concentrated

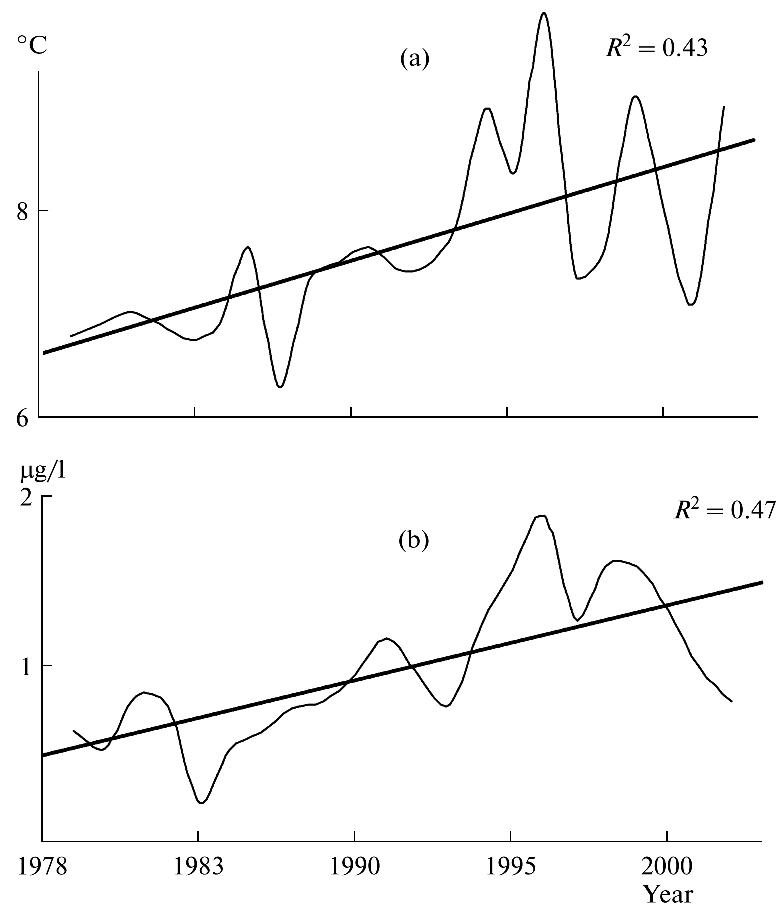

Fig. 1. Long-term dynamics of (a) water temperature and (b) chlorophyll *a* concentration in the 0- to 50-m layer during the period of direct temperature stratification. The inclined line is the trend line.

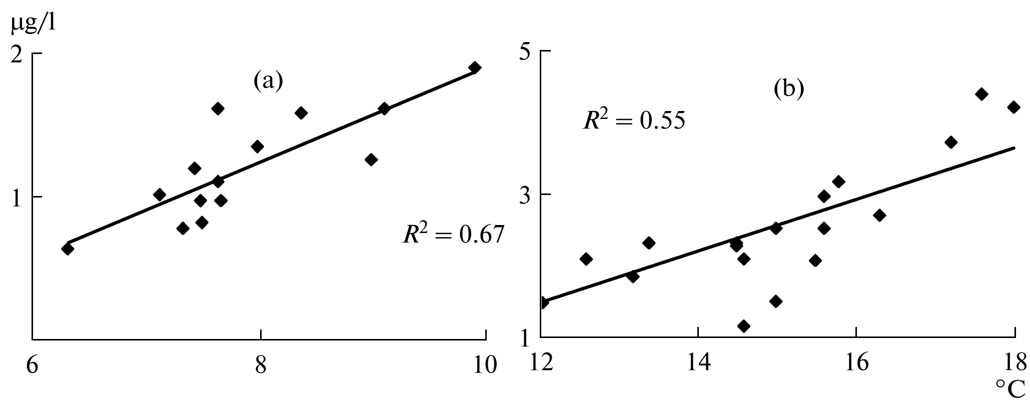

Fig. 2. The dependence that the (a) average and (b) maximum Chl *a* concentrations during the period of direct stratification have on water temperature.

using sedimentation. The cells were enumerated using a LEICA DMLB light microscope. The chlorophyll *a* content was determined using the standard spectrophotometric method [24]. The water temperature was measured with a mercury thermometer embedded in the bathometer. The data were processed using Excel.

RESULTS

The water temperature in the Lake Baikal pelagial during direct thermal stratification (from July to September) varies in a wide range (from 3.8 to 19.0°C). The average annual temperatures were 6.3–9.9°C; the

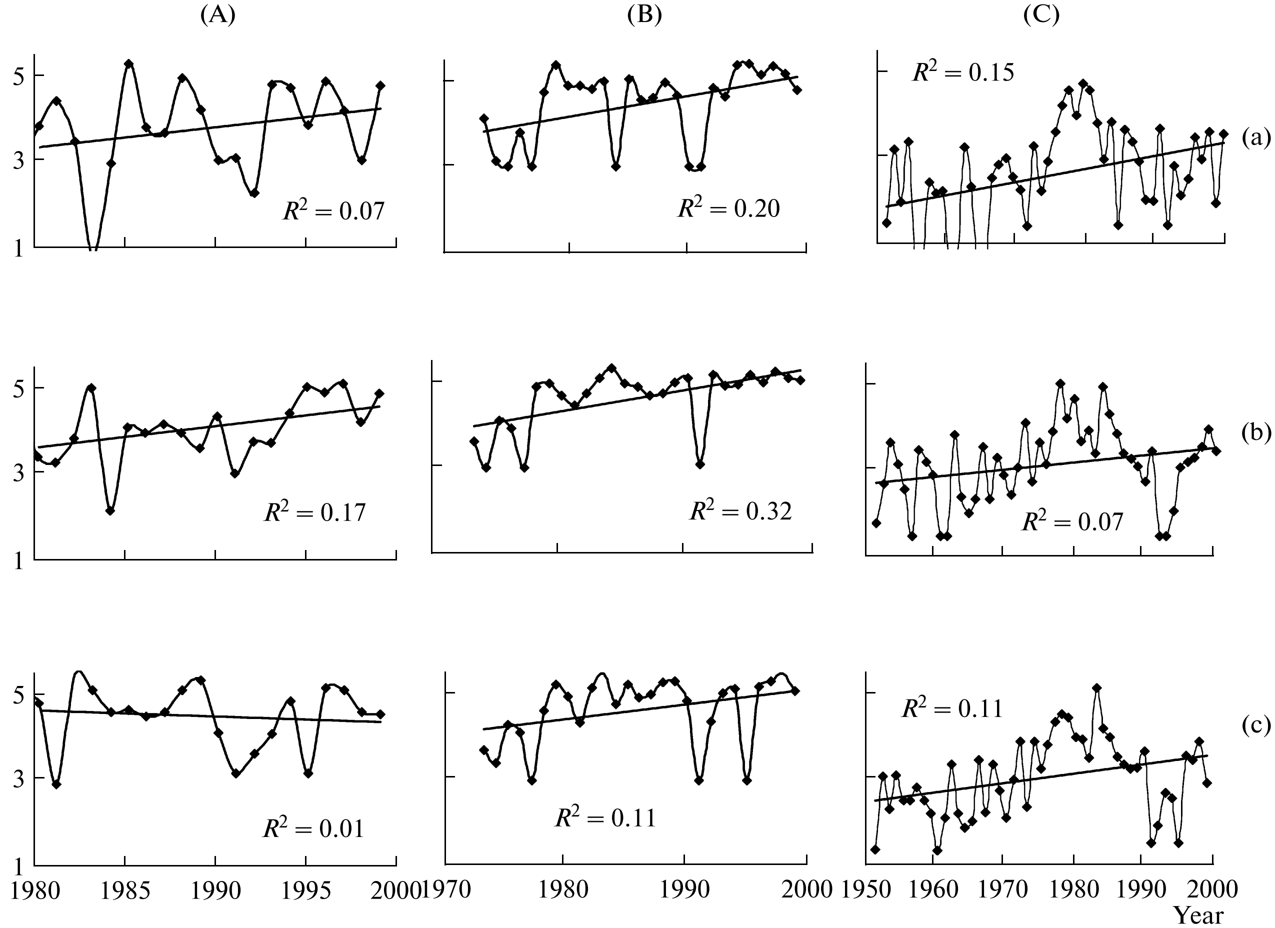

Fig. 3. Long-term dynamics of abundance (log cells/l) of (A) *Chrysochromulina parva*, (B) *Rhodomonas pusilla*, and (C) *Monoraphidium pseudomirabile* in summer: (a) July, (b) August, and (c) September. Average monthly values for the 0–50 m layer are presented. Other notations are the same as in Fig. 1.

average long-term temperatures were 7.6 ± 0.2°C. The water temperatures vary in an oscillatory way with a positive trend that can be traced by maximal and average values (Fig. 1). According to an equation that describes the trend line, the calculated average water temperature in 1979 was 6.8°C and, in 2002, it was 8.7°C. In the most heated surface layer, the differences in temperature are more distinct: the calculated temperature was 9.4°C in 1979 and 12.5°C in 2002.

The expressed positive trends of long-term dynamics of Chl *a* content, which is characterized by an increase in the maximum in the water column and average concentrations, coincide with the long-term variability of the water temperature (Fig. 1). The reliability of this trend is confirmed by the Cox–Stuart statistical test. In 1979–1990, all average annual values were lower than average long-term values; in 1991–2002 they were 25% lower. In the 1980s and 1990s, average concentrations of Chl *a* (0.69 ± 0.07 mg/m^3 and 1.29 ± 0.10 mg/m^3, correspondingly) differed significantly ($t = 4.75$, $p < 0.01$). According to the equation describing the trend, the calculated values equaled 0.61 mg/m^3 in 1979 and 1.54 mg/m^3 in 2002. The correlation between the Chl *a* concentration and water temperature during the direct temperature stratification is of a linear character (Fig. 2).

The summer phytoplankton complex that develops in July–September is mainly formed by three species with a high frequency of occurrence and domination and a high abundance. The abundance of *Chrysochromulina parva* Lackey (Chrysophyta) and *Monoraphidium pseudomirabile* (Korschik.) Hindak et Zagorenko (Chlorophyta) varied insignificantly during the whole long-term period; the coefficients of variation of average values (C_v) in summer months were 200 and 252–296%, correspondingly. For the first species, no statistically significant trends in long-term variations of abundance were detected. The abundance was within the limits of average long-term values in spite of annual variations. The positive trend for the second species was detected in July, but the tendency for its increased abundance was observed even in September. Until the mid-1970s, the abundance of the species did not exceed the average long-term abundance; its sig-

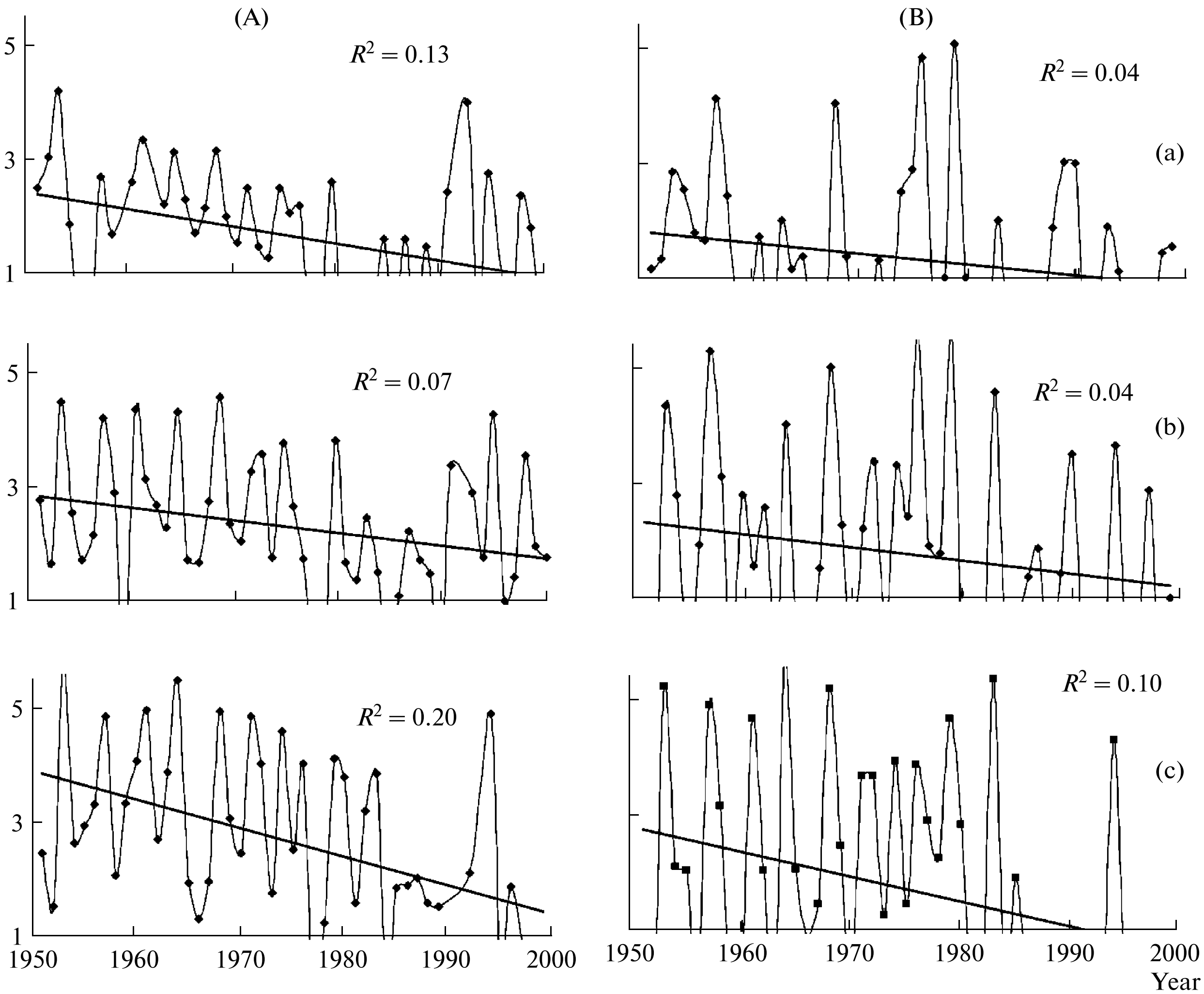

Fig. 4. Long-term dynamics of the abundance (log cells/l) of (A) *Aulacoseira baicalensis* and (B) *A. skvortzowii* during the under-ice period: (a) February, (b) March, and (c) April. Other notations are the same as in Figs. 1 and 3.

nificant increase was recorded at the end of the 1970s and the beginning of the 1980s. The number of *Rhodomonas pusilla* (Bachm.) Javor. (Cryptophyta) was more stable than the two other species (C_v = 71...98%). There was a positive statistically significant trend for August, but the tendency toward an increase in abundance was marked in July and August (Fig. 3).

The species of the under-ice complex are the most important for the planktonic algocenoses of the lake. They include five representatives of diatoms and one species of dinophyte algae.

The abundance of *Aulacoseira baicalensis* (K. Meyer) Simonsen is the most variable in February (C_v = 348%). Its negative trend is detected in all months, but it is statistically significant only in April ($R^2 = 0.19$) (Fig. 4). If we divide all period of studies into two intervals (1951–1975 and 1976–1999), no significant trends are detected for each of them, but the logarithms of average values differ significantly. The difference testifies to a sharp decrease in the species abundance in the second half of the 1980s. Statistically significant trends of the long-term variation in the abundance were not detected for *Aulacoseira skvortzowii* Edlund, Stoermer, Taylor, *Stephanodiscus meyerii* Genkal et Popovsk., *Cyclotella baicalensis* (K. Meyer) Skv., or *C. minuta* Antip. (Figs. 4–6), though for the latter species the trend was observed in January. The abundance of *Aulacoseira skvortzowii* was the most variable in May (C_v) = 644%) and the least variable was in April (312%). The negative statistically reliable trend was detected for April (R^2), but from 1986 to 1993 the species was absent in samples. The abundance of *Stephanodiscus meyerii* was the least variable in February (C_v = 326%). Until the mid-1980s, its value often exceeded the long-term average; in 1984–1994 the species abundance was extremely low or the species was absent in samples. The abundance of *Cyclotella baicalensis* was most variable in March (C_v = 257%) and only sometimes exceeded the long-term average. Annual variations of the number of *Gymnodinium baicalense* Antip.

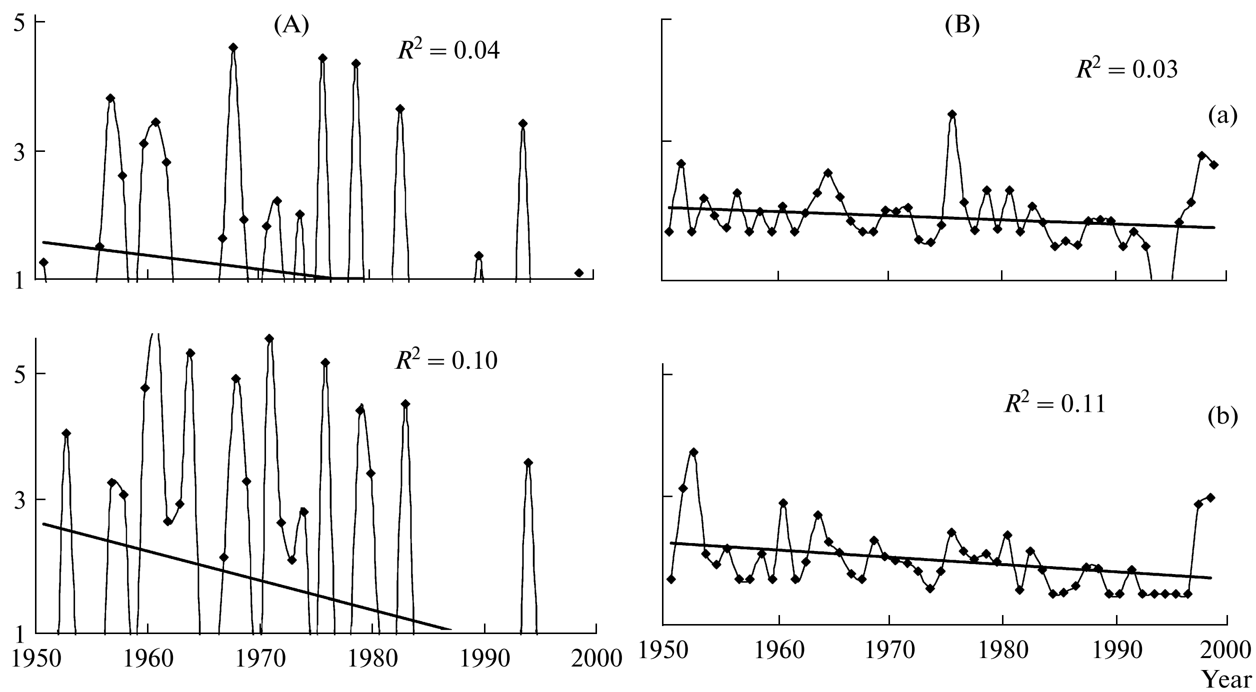

Fig. 5. Long-term dynamics of abundance (log cells/l) of (A) *Stephanodiscus meyerii* and (B) *Cyclotella baicalensis* during the ice period: (a) March and (b) April. Other notations are the same as in Figs. 1 and 3.

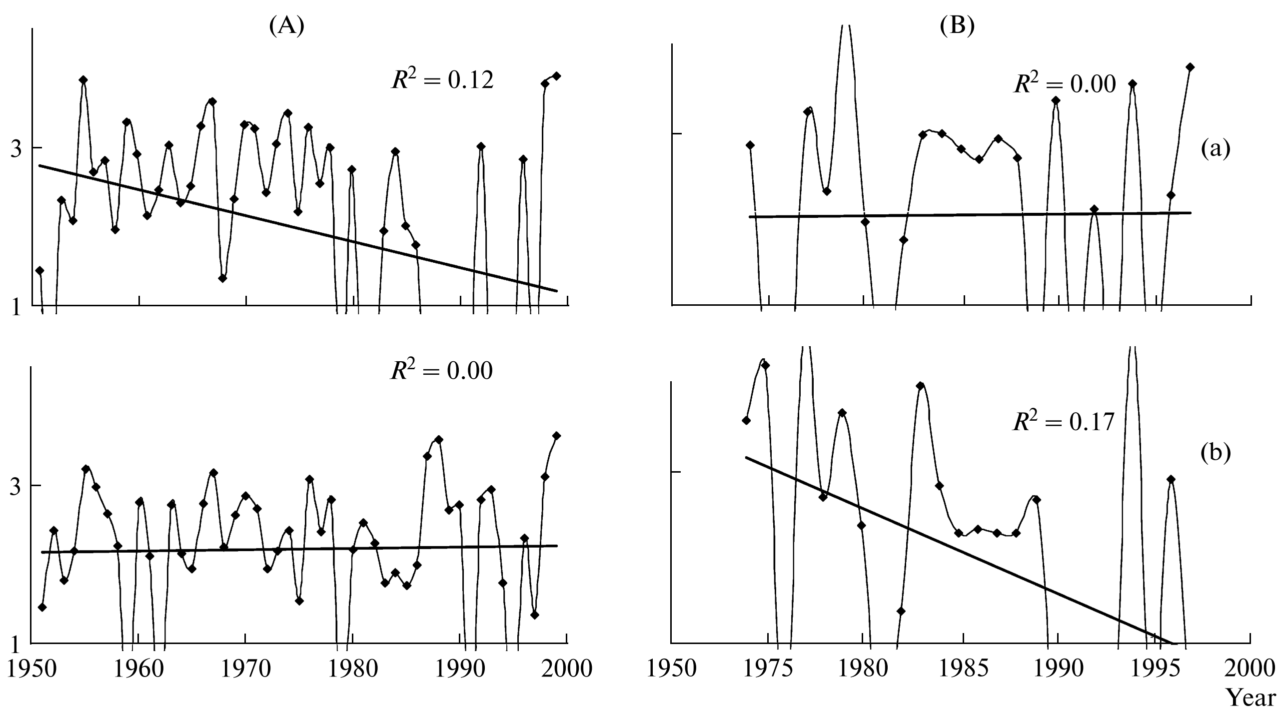

Fig. 6. Long-term dynamics of abundance (log cells/l) of (A) *Cyclotella minuta* ((a) January and (b) February) and (B) *Gymnodinium baicalense* during the ice period ((c) March and (d) April). Other notations are the same as in Figs. 1 and 3.

(Dinophyta) were also observed, but its average annual values did not exceed the limits of the long-term average. The variability of the abundance in March and April was similar (C_v = 295 and 241%, correspondingly), and there was a statistically significant trend of its long-term changes in April (Fig. 4).

DISCUSSION

The seasonal and long-term dynamics of plankton in the studied site reflects the features of biota typical for an open pelagial in Lake Baikal [2, 3, 17, 18]. The Chl *a* content characterizes the phytoplankton abundance. Unidirectional trends of water temperature and Chl *a* content variations testify to the fact that phytoplankton development during the direct thermal stratification is governed to a greater degree by water temperature. Its sufficient increase can lead to increased Chl *a* concentrations and primary production and, as a result, to a higher productivity of the lake pelagial on a whole. The high integral primary production can yield several scenarios of ecosystem development. The realization of each scenario will depend on the number of which species will vary and how it will affect the food webs.

In the phytoplankton of Lake Baikal, the abundance of two species of the summer complex *Monoraphidium pseudomirabile* and *Rhodomonas pusilla* increases. These species are widespread and are characterized by small cell volumes (from 10 to 150 μm^3). The increase in the share of small forms (in comparison to large ones) was observed Lake Balaton [9] and other Hungarian lakes [29]; Swedish lakes [31]; Lake Tahoe, USA [32, 33]; Mueggelsee, Germany [11]; and Lake Kinnereth, Israel [16, 35].

The ecosystem of Lake Baikal is characterized by an intensive under-ice development of large-celled (from 1000–2000 up to >10000 cells/μm^3) diatoms which are traditionally considered endemic for Lake Baikal (according to recent data, *Aulacoseira baicalensis*, *A. skvortzowii*, *Cyclotella baicalensis*, *C. minuta*; and *Stephanodiscus meyerii* should not be considered endemic, but instead relict forms, because they were found outside the lake as well [8]. It is these species that give high yields [2]. According to long-term observations, the number of large-celled species of the under-ice complex started to decrease since the first half of the 1980s, and the faults in the regularity of productive years and the time shift of maximum values of abundance are observed. Further studies are needed to understand the reasons for such faults, one of which can be climate change.

CONCLUSIONS

Over a period of long-term (1951–2000) studies, some tendencies were detected in a variation of indexes of a production link of the planktonic community in Lake Baikal. Since 1979, the positive trend of water temperature and Chl *a* content in a trophogenic (0–50 m) layer was detected during the direct stratification of the water column. The degree of summer phytoplankton development depends to a greater degree on water temperature, and an increase in the summer complex abundance occurs due to a sufficient increase in the abundance of small forms. On the contrary, the negative trend of the number of large-celled species of the under-ice complex was detected.

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