Limnology (2000) 1:191–195

RESEARCH PAPER

Michio Kumagai · Shin-ichi Nakano · Chunmeng Jiao
Kazuhide Hayakawa · Shigeo Tsujimura
Takuo Nakajima · Jean-Jacques Frenette
Antonio Quesada

Effect of cyanobacterial blooms on thermal stratification

Received: September 25, 1999 / Accepted: January 6, 2000

Abstract Enclosure experiments were performed at Akanoi Bay, Lake Biwa, in 1995 to determine whether the blooms of cyanobacterial algae changed thermal stratification in the lake. We used four rectangular enclosures, each 10 m × 10 m, with a volume of 200 m^3, which were open to the sediments. Two enclosures, A and B, were mixed artificially by aquatic pumps from 1000 to 1400 every day, and the other two enclosures, C and D, were controls with no mixing. The experiment was conducted during late summer from August 3 to September 27. Chlorophyll *a* concentrations were highest in enclosure *D*, followed by enclosure C, both of which were controls without mixing. Enclosure A had lower concentrations than enclosures C and D, and enclosure B had the lowest concentrations. No large cyanobacterial algae blooms of *Anabaena* sp. and *Microcystis* sp. were seen in the mixed enclosures A and B. In enclosures C and D, blooms of *Anabaena* sp. occurred in the middle of August, and *Microcystis* sp. later became dominant in enclosure D at the end of August. In enclosure D, the water temperature changed over the diel cycle before August 17, with thermal stratification during the day and complete mixing at night. After August 17, as *Anabaena* sp. and *Microcystis* sp. became dominant, the temperature at the bottom of the enclosure did not change clearly over the 24-h cycle. The APE (available potential energy) density (a measure of water column stability) in the enclosures increased by almost 100% when the biovolume of *Anabaena* sp. + *Microcystis* sp. exceeded 20 $mm^3 l^{-1}$. These results indicate that blooms of *Anabaena* sp. and *Microcystis* sp. can increase the available potential energy in the water column and create more stable stratification for their growth.

Key words Enclosure experiment · Cyanobacterial algae blooms · Vertical mixing · Available potential energy · Thermal stratification

M. Kumagai (✉)
Lake Biwa Research Institute, 1-10 Uchidehama, Otsu, Shiga 520-0806, Japan
Tel. +81-77-526-4019; Fax +81-77-526-4803
e-mail: kumagai@lbri.go.jp

S. Nakano
Center for Marine Environmental Studies, Ehime University Matsuyama, Japan

C. Jiao · K. Hayakawa · S. Tsujimura · T. Nakajima
Lake Biwa Research Institute, 1-10 Uchidehama, Shiga, Japan

J.-J. Frenette
Département de Chimie-Biologie, Université du Québec à Trois-Rivières, Trois-Rivières (Québec), Canada

A. Quesada
Dpt. Biologia, Universidad Autonoma de Madrid, Madrid, Spain

Introduction

Can microorganisms in water change their environments on Earth? We know that some species of cyanobacteria in water produced oxygen in ancient times (about 2800 million years ago), and created the present atmosphere (Schopf 1992). This effect operated over an extremely long time scale and required huge amounts of energy. In modern-day ecosystems, it seems that microorganisms such as phytoplankton are continuing to change their local environment. For example, Mazumder et al. (1990) have shown that plankton can change the thermal structure and heat content of small lakes by modifying light penetration. Bloom-forming cyanobacteria may be especially effective in changing the physical and chemical properties of their surroundings to conditions that favor their continued growth and dominance (Vincent 1989).

Lake Biwa is the largest lake in Japan. It has suffered from cyanobacterial (blue-green algal) blooms of *Anabaena* sp. and *Microcystis* sp. in the eutrophicated areas of the South Basin since 1983, and these began to spread over the whole lake after the Biwako Transport Experiment (BITEX) in 1993 (Kumagai and Robarts 1996). Lake Biwa supplies drinking water to more than 13 million people in the Osaka, Kyoto, Kobe, and Nara area (Okuda et al. 1995). Some species of *Anabaena* sp. and *Microcystis* sp. are toxic when consumed in drinking water (Chorus and Bartram

1999), and there is therefore strong pressure to protect the lake from cyanobacterial blooms.

The Lake Biwa Research Institute has designed a series of enclosure experiments at Akanoi Bay, the largest and most eutrophic bay in the South Basin of Lake Biwa, to examine the causes of cyanobacterial blooms. Three different experiments were performed from 1995 to 1997 with a set of four enclosures. In 1995, we mixed two enclosures with aquatic pumps for 4 h (from 1000 to 1400) every day, and examined the relationship between cyanobacterial blooms and the intensity of thermal stratification in the water column. Addition of phosphorus was done in 1996, and some enclosures were covered with transparent plastic sheets to produce different thermal stratification regimes in 1997.

The effects of artificial mixing on phytoplankton have been investigated by several groups (e.g., Reynolds et al. 1984; Kromkamp et al. 1992; Hawkins and Griffiths 1993; Barbiero et al. 1996), and there is evidence that artificial mixing prevents blooms of *Microcystis* sp. (Visser et al. 1996). These results imply that thermal stratification of the water column is important for the formation of cyanobacterial blooms (Zhang and Prepas 1996). In the present paper, we show the change of *Anabaena* sp. and *Microcystis* sp. in the mixed and nonmixed enclosures carried out in 1995, and examine the possibility that changes in thermal stratification can be induced by cyanobacterial blooms.

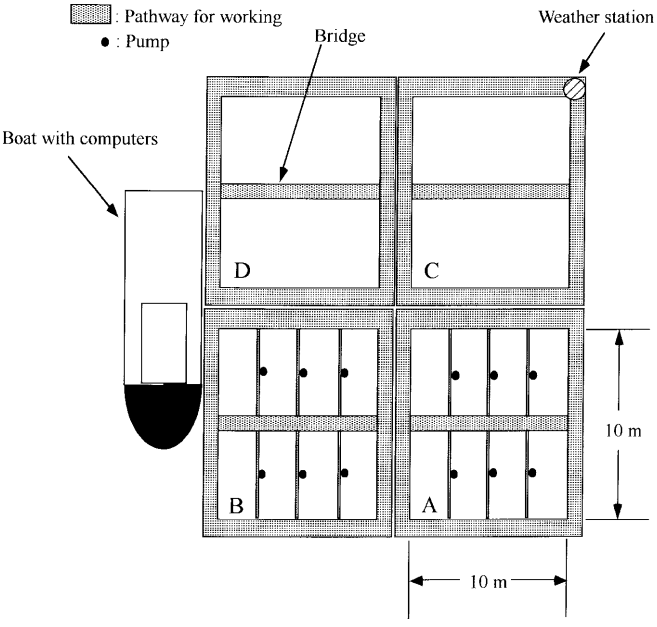


Fig. 1. Schematic view of the four enclosures deployed at Akanoi Bay. Enclosures *A* and *B* were mixed by aquatic pumps from 1000 to 1400 every day, and enclousres *C* and *D* were controls with no mixing. A boat was anchored to house the computers and generators for measurements

Methods

We used four sets of square enclosures, each 10 m × 10 m with a volume of 200 m^3 (Fig. 1). Enclosures A and B were mixed artificially by aquatic pumps from 1000 to 1400 every day. Another two enclosures, C and D, were controls that were not mixed. The experiment started on August 3 and ended on September 27, 1995. The mean depth of the experimental site was about 2 m, and we used 3-m-long plastic curtains to prevent horizontal water exchange. These curtains were made of ethylene vinyl acetate (EVA) sheets that were not toxic to microorganisms and allowed nearly 100% penetration of light (Toray, Otsu, Japan). The bottom end of the curtains was buried in the sediments, so that only bottom sediment could be a source of nutrients, except for rainfall in the enclosures. Six aquatic pumps were used to mix water in enclosures C and D, respectively. Each pump had a capacity of 180 l min^{-1}, and each outlet faced upward. With the use of six pumps, the mean period of water circulation in an enclosure was about 185 min.

Water samples were taken at 1000 before the pumps were switched on, and again at 1400 after they were switched off on August 3, 10, 16, 23, 30, and September 6, 13, 20, and 27. Column sampling was done with a long tube sampler, and nutrients such as phosphorus and nitrogen, chlorophyll *a*, and phytoplankton species in the water samples were analyzed (Nakano et al. 1999).

Five thermistor chains were deployed with 10-cm vertical intervals inside and outside the enclosures, and water temperature was measured every 2 min. These data were collected by computer and continuously stored electronically. The resolution of the thermistors was less than 0.1°C.

Results and discussion

Chlorophyll *a* concentrations increased rapidly after August 16 in the control enclosures C and D (Fig. 2). Chlorophyll *a* concentration in enclosure C reached a maximum of about 110 μg l^{-1} on August 23, then decreased. Enclosure D had a maximum chlorophyll *a* concentration of almost 150 μg l^{-1} on September 13. On the other hand, chlorophyll *a* concentrations in the mixed enclosure B were relatively constant throughout the experiment. Chlorophyll *a* concentration in enclosure A increased up to 60 μg l^{-1} on September 6. Chlorophyll *a* concentrations in both enclosures A and B dropped to <20 μg l^{-1} after September 9. These differences between the mixed enclosures could be due to differences in bottom sediment conditions, which were not necessarily the same. However, definite differences were seen between mixed and nonmixed (control) enclosures.

Nutrients for rapid growth of phytoplankton were probably supplied from the bottom sediments in the enclosures. PO_4-P flux from the bottom sediment in the enclosures was roughly estimated with a nutrient budget balance model. It was between 10 and 100 mg m^{-2} day^{-1}. These values are likely to be large enough to support the large increases in chlorophyll *a* concentration that were observed in enclosures C and D.

Figure 3 shows the average biovolume of *Anabaena* sp. and *Microcystis* sp. in the four enclosures for the overall period from August 3 to September 27. The nonmixed enclosures C and D had a much higher biovolume of *Anabaena* sp. and *Microcystis* sp. than the mixed enclosures A and B. These results imply that artificial mixing reduces the growth of *Anabaena* sp. and *Microcystis* sp.

Because enclosure D had the highest biovolume of *Anabaena* sp. and *Microcystis* sp., we focus on this enclosure. The biovolume of *Anabaena* sp. started to increase on August 16, and this species became dominant on August 23. Similarly, the concentration of PO_4-P in enclosure D increased on August 16, whereas dissolved inorganic nitrogen increased on August 23. A striking difference between enclosure D and the other enclosures was the rapid increase of the NH_4-N:NO_3-N ratio, which rose to values over 50 on August 23. The availability of ammonia is believed to be the regulatory factor for dominance by N_2-fixing phytoplankton such as *Anabaena* sp. (Blomqvist et al. 1994). After August 23, *Microcystis* sp. started to increase and became dominant on August 30. This bloom of *Microcystis* sp. continued until the end of the experiment on September 27.

Water temperature changes at 0.5 and 1.5 m in enclosure D are shown in Figure 4. Before August 17, there was a strong diel cycle in water temperature. The temperature increased during the day, producing vertical stratification. The temperature fell at night, and the water column became well mixed vertically. However, after August 17, although the water temperature at 0.5 m changed over the diel cycle, the water temperature at 1.5 m remained almost constant throughout the diel period. This pronounced difference in stratification corresponded to the period of increase of the bloom-forming cyanobacteria *Anabaena* sp. and *Microcystis* sp.

In order to understand the relationship between stratification and growth of *Anabaena* sp. and *Microcystis* sp., we calculated available potential energy (APE) density, defined as

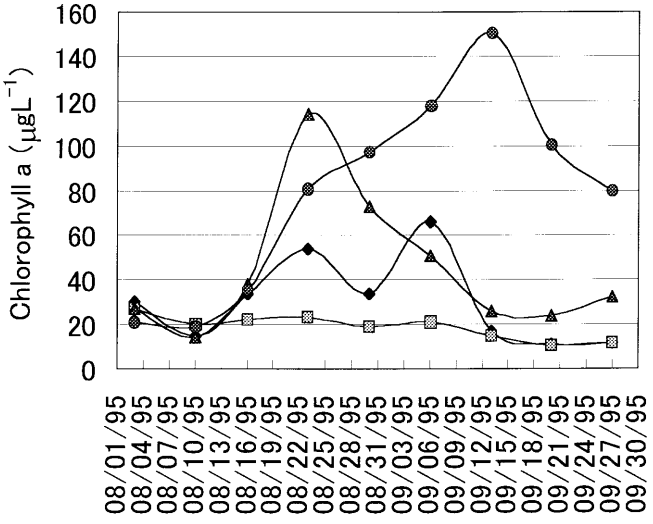


Fig. 2. Temporal change in chlorophyll *a* concentration of the water column in enclosures *A* (◆), *B* (■), *C* (▲), and *D* (●) from August 3 to September 27, 1995. A and B were mixed enclosures; C and D were nonmixed controls

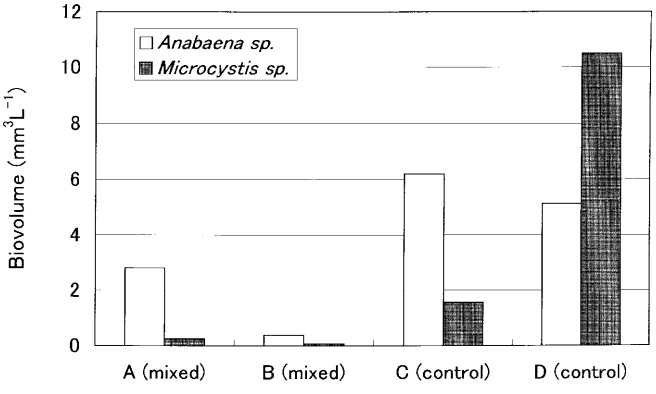
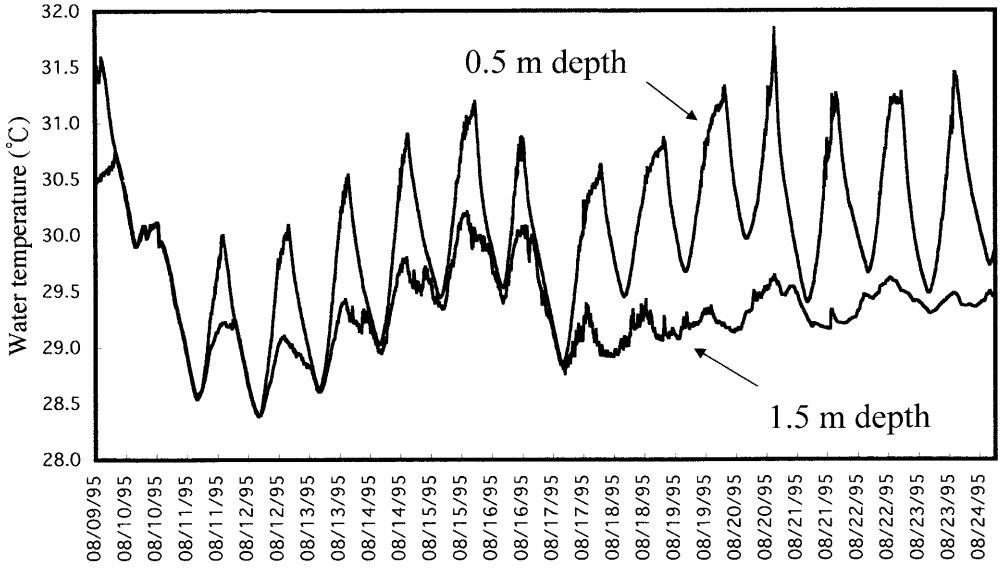


Fig. 3. Biovolume of *Anabaena* sp. and *Microcystis* sp. in enclosures *A*, *B*, *C*, and *D* averaged from August 3 to September 27, 1995

Fig. 4. Water temperature change in enclosure *D*. The upper temperature was measured at 0.5 m depth, and the lower temperature was measured at 1.5 m depth



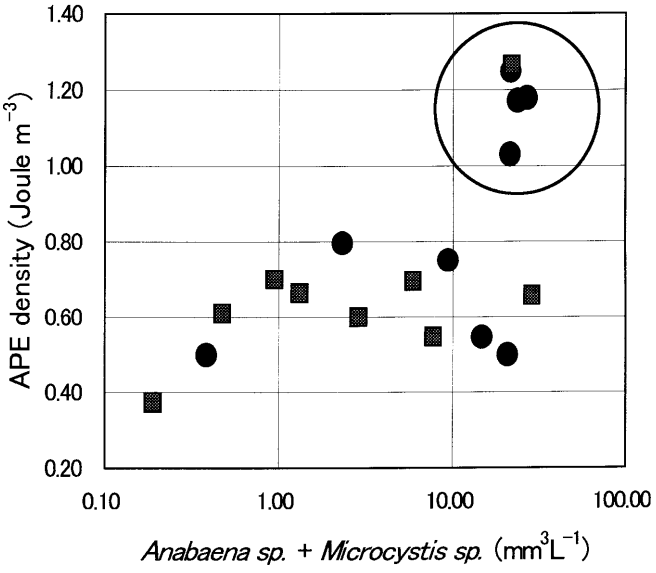


Fig. 5. Relationship between the biovolume of *Anabaena* sp. + *Microcystis* sp. and the APE (available potential energy) density. (■) Enclosure C, (●) enclosure D. The *large circle* indicates the rapid increase of APE density due to blooms of *Anabaena* sp. and *Microcystis* sp.

$$\text{APE density} = \frac{1}{D}\int_{-D}^{0}(\rho - \rho^*)g\,dz$$

where D is depth, ρ is density of water, ρ^* is vertically averaged density, g is the acceleration of gravity, and z is the vertical axis. APE equals the kinetic energy necessary to mix a water column completely. Thus, a higher APE density corresponds to more stable stratification, whereas a lower APE indicates a less stable stratification.

Figure 5 shows the relationship between the biovolume of *Anabaena* sp. and *Microcystis* sp. and APE density in enclosures C and D. As demarcated by the circle in this figure, a sharp increase in APE density accompanied the development of blooms of *Anabaena* sp. and *Microcystis* sp.

Stratification usually increases gradually as solar energy is absorbed through the water column. However, if floating phytoplankton, such as *Anabaena* sp. and *Microcystis* sp., increase rapidly, stratification can be more intense and can favor more stratification with high potential energy. In enclosure D, this stable stratification was not destroyed even at night, and oxygen supply from the surface was thereby reduced. This effect is likely to have induced oxygen depletion in the sediments and an increased flux of nutrients such as PO_4-P and NH_4-N from the bottom sediments. Higher nutrients in the water probably accelerated the growth of *Microcystis* sp. at the end of August and maintained it in September.

Our enclosure experiment results strongly support the hypothesis that heavy blooms of cyanobacterial algae can increase APE density and make stratification more stable. In this way, the bloom-forming species *Anabaena* sp. and *Microcystis* sp. appear to be able to modify their environment toward conditions that are favorable for their ongoing growth and existence.

Conclusions

The enclosure experiment performed at Akanoi Bay in Lake Biwa in 1995 produced an interesting result. We used four enclosures, two of them (A and B) artificially mixed and the other two (C and D) not mixed. No heavy cyanobacterial blooms of *Anabaena* sp. and *Microcystis* sp. were seen in the mixed enclosures. In the nonmixed enclosures, blooms of *Anabaena* sp. occurred in the middle of August, and a heavy bloom of *Microcystis* sp. appeared in enclosure D at the end of August.

After the bloom of *Anabaena* sp. and *Microcystis* sp. occurred in enclosure D, stratification persisted throughout the diel cycle even at night. The relationship between the biovolume of *Anabaena* sp. + *Microcystis* sp. and APE density shows that, at and above biovolume concentrations of $20\,mm^3l^{-1}$ of cyanobacteria, there was a rapid increase in APE density. This suggests that large blooms of cyanobacteria can increase the available potential energy in a water column and bring about more stable stratification for their growth.

Acknowledgments This paper is dedicated to the memory of Prof. Masahiko Higashi of Kyoto University. The authors want to express their sincere thanks to Drs. Colin Reynolds and Richard Robarts for their fruitful suggestions on this work. The authors are also grateful to their colleagues at the Lake Biwa Research Institute for their cooperation to promote this experiment. This study was financially supported by the Lake Biwa Research Institute and, in part, by a Grant-in-Aid for Scientific Research (11898018) from the Japan Society for the Promotion of Science.

References

Barbiero RP, Speziale BJ, Ashby SL (1996) Phytoplankton community succession in a lake subjected to artificial circulation. Hydrobiologia 331:109–120

Blomqvist P, Pettersson A, Hyenstrand P (1994) Ammonium-nitrogen: a key regulatory factor causing dominance of non-nitrogen-fixing cyanobacteria in aquatic systems. Arch Hydrobiol 132:141–164

Chorus I, Bartram J (1999) Toxic cyanobacteria in water. E&FN SPON, London

Hawkins PR, Griffiths DJ (1993) Artificial destratification of a small tropical reservoir: effects upon the phytoplankton. Hydrobiologia 254:169–181

Kromkamp J, Schanz F, Rijkeboer M, Berdalet E, Kim B, Gons HJ (1992) Influence of the mixing regime on the algal photosynthetic performance in laboratory scale enclosures. Hydrobiologia 238:111–118

Kumagai M, Robarts R (1996) Biwako Transport Experiment '93. Jpn J Limnol 57:367–558

Mazumder A, Taylor WD, McQueen DJ, Lean DRS (1990) Effects of fish and plankton on lake temperature and mixing depth. Science 247:312–315

Nakano S, Nakajima T, Hayakawa K, Kumagai M, Jiao C (1999) Blooms of the dinoflagellate *Ceratium hirundinella* in large enclosures. Jpn J Limnol 60:483–505

Okuda S, Imberger J, Kumagai M (1995) Physical processes in a large lake: Lake Biwa, Japan. Coastal and Estuarine Studies, American Geophysical Union, Washington

Reynolds CS, Wiseman SW, Clarke MJO (1984) Growth- and loss-rate responses of phytoplankton to intermittent artificial mixing and their potential application to the control of planktonic algal biomass. J Appl Ecol 21:11–39

Schopf JW (1992) Major events in the history of life. Jones and Bartlett, Boston

Vincent WF (1989) Cyanobacterial growth and dominance in two eutrophic lakes: review and synthesis. Arch Hydrobiol Beih 32:239–254

Visser PM, Ibelings W, Verr BVD, Koedood J, Mur LR (1996) Artificial mixing prevents nuisance blooms of the cyanobacterium *Microcystis* in Lake Nieuwe Merr, the Netherlands. Freshwater Biol 36:435–450

Zhang Y, Prepas EE (1996) Regulation of the dominance of planktonic diatoms and cyanobacteria in four eutrophic hardwater lakes by nutrients, water column stability, and temperature. Can J Fish Aquat Sci 53:621–633