A Rapid Growth of *Aulacoseira granulata* (Bacillariophyceae) during the Typhoon Season in the South Basin of Lake Biwa

Shin-ichi NAKANO, Yasushi SEIKE, Tatsuki SEKINO, Minoru OKUMURA,
Keiichi KAWABATA, Kaoru FUJINAGA, Masami NAKANISHI, Osamu MITAMURA,
Michio KUMAGAI and Hiroshi HASHITANI

Abstract

Changes in the abundance of phytoplankton and in the concentrations of nutrients and suspended solids (SS) were followed at a sampling station in the southern basin of Lake Biwa during the Biwako Transport Experiment (BITE'93) from 24 August to 12 September, 1993. SS concentration increased rapidly when typhoon 9313 struck the lake on 4 September. On this occasion, concentrations of dissolved nitrogen and phosphorus increased, probably due to their release from the sediment resuspended by turbulent mixing. Between 3 and 10 September, the whole water column remained homothermal and was well mixed with the Brunt-Väisälä frequency remaining at 0 sec⁻¹. The predominant phytoplankton during the BITE'93 period was *Aulacoseira granulata*. Chlorophyll concentrations and algal densities started to increase before the passage of the typhoon (3 September). The alga proliferated rapidly to 7 September, and this was complemented by a decrease in nitrogen and phosphorus concentrations.

Key words : *Aulacoseira granulata*, physical mixing, Lake Biwa, BITE'93

1. Introduction

Physical processes are mainly responsible for transporting matter in lakes. The same processes transport phytoplankton to favourable or unfavourable environments, and it has been considered that such transportation influences the fate of phytoplankton. Although conceptual and theoretical models for changes in abundance, activity and species composition of phytoplankton with special reference to physical processes have been developed (REYNOLDS, 1989), lake-specific information on plankton dynamics is still limited.

Japan is often subject to typhoons during the autumn. Some of these reach the catchment of Lake Biwa (35°10'N, 136°00'E, altitude 85 m) and cause physical disturbance to the lake. However, information about the effect of such disturbances on phytoplankton in the lake is still scarce. We hypothesized that physical turbulence would result in destratification, or at least, an erosion of the temperature structure and an increase in the advection of nutrients into the upper water column which, in turn, would result

in changes in the activity and/or species composition of phytoplankton. Two typhoons struck the catchment area of Lake Biwa during September 1993, and, following one of them, there was rapid growth of diatoms. In the present article, we described the phytoplankton dynamics in the lake during this period with special reference to physical factors and examined the reality of our hypothesis.

2. Materials and methods

Water samples were collected during BITE'93 (Biwako Transport Experiment) between 24 August to 12 September, 1993 at Station S (35°03.600'N, 135°54.300'E, 3.6 m depth) in the South Basin of Lake Biwa at approximately 2-day intervals. The South Basin of Lake Biwa is 58 km² in area and contains 27.5 × 10⁹ m³ of water. Its maximum depth is 8.0 m, and the mean depth is 3.5 m. Its retention time during summer is variable, depending on the discharge controlled by the Seta River Weir: about 1 week for a wet summer, and 2 weeks for

a dry summer. The retention time during the BITEK period was about 1 week (JIAO *et al.*, in press). Vertical water temperature was measured every 10 cm with a CTD profiler (F-probe, Centre for Water Research, Australia). A 3 liter Van-Dorn water sampler was used to collect water samples from 0.5 m below the surface.

On each occasion, a portion of the water sample was filtered through a precombusted (430°C for 2 hr) Whatman GF/C filter. The filtrate was used for chemical analysis, and the seston retained on the filter was analysed for particulate matter and phytoplankton pigments. Two filters for each water sample were prepared: one for suspended solids (SS), the other for chlorophyll. SS concentration was determined after drying the seston retained on the filter at 105°C. Concentrations of chlorophyll on the filters were determined by the method of SCOR/UNESCO (1966).

Ammonium nitrogen ($\text{NH}_4^+\text{-N}$) was measured by the indophenol method (SAGI, 1966). Nitrite ($\text{NO}_2^-\text{-N}$) and nitrate nitrogen ($\text{NO}_3^-\text{-N}$) were determined by the method of BENDSCHNEIDER and ROBINSON (1952) and WOOD *et al.* (1967), respectively. Dissolved organic nitrogen (DON) was measured by the KJELDAHL-method, using SeOCl_2 as a catalyst. Dissolved inorganic phosphorus (DIP) was determined by the method of MURPHY and RILEY (1962), after preconcentration of phosphate (HASHITANI *et al.*, 1987). Total dissolved phosphorus (TDP) was determined by the method of MENZEL and CORWIN (1965), and dissolved organic phosphorus (DOP) was calculated by subtracting DIP from TDP.

A 200-ml sample of water was fixed with acidified Lugol's solution at a final concentration of 1%, and the phytoplankton samples were concentrated by natural sedimentation. Cells of phytoplankton were enumerated in a haemocytometer under a microscope.

Water density (ρ), uncorrected for solute concentration, was calculated using the sixth order equation (ZOHARY and ROBARTS, 1989) fitted to the density vs. water temperature data (HUTCHINSON, 1957).

$\rho = a + bT + cT^2 + dT^3 - eT^5 - fT^2$ where ρ is water density ($\text{kg}\cdot\text{m}^{-3}$), T is water temperature

(°C) and from a to f are constants as follows: $a = 9.9973 \times 10^2$; $b = 1.0785 \times 10^{-1}$; $c = 2.5328 \times 10^{-9}$; $d = 2.3833 \times 10^{-4}$; $e = 1.5762 \times 10^{-7}$; $f = 1.3060 \times 10^{-2}$. Density gradient ($d\rho/dz$, $\text{kg}\cdot\text{m}^{-3}\cdot\text{m}^{-1}$) was determined as follows:

$$d\rho/dz = (D_2 - D_1)/dz$$

where D_1 and D_2 are water density at two different depths (m), and dz is the intervals (m) of the depths. Finally, we calculated the Brunt-Väisälä Frequency (N^2 , sec^{-2}) as follows:

$$N^2 = (g/\rho_m)(d\rho_m/dz_m)$$

where g ($\text{m}\cdot\text{sec}^{-2}$) is gravitational acceleration, ρ_m ($\text{kg}\cdot\text{m}^{-3}$) is the mean water density of the water column and $d\rho_m/dz_m$ is the mean density gradient ($\text{kg}\cdot\text{m}^{-3}\cdot\text{m}^{-1}$) of the water column.

The data presented here are summarized in the BITEK baseline data overviews (KUMAGAI and NAKANO, 1996): meteorological data were derived from HAYAMI *et al.* (1996), water temperature data from KUMAGAI *et al.* (1996), chemical data from HASHITANI *et al.* (1996) and biological data from NAKANO *et al.* (1996).

3. Results and discussion

The average atmospheric temperature (Fig. 1A) was high (ca. 25°C) between 24 August and 4 September, though there was a large fluctuation between 24 and 29 August. It decreased rapidly on 5 September and increased again from 7 September. The average wind speed (Fig. 1B) was relatively high ($>5 \text{ m}\cdot\text{sec}^{-1}$) between 27 and 28 August. It remained low ($<2 \text{ m}\cdot\text{sec}^{-1}$) from 30 August to 3 September but rapidly increased (maximum $10.8 \text{ m}\cdot\text{sec}^{-1}$) on 4 September when typhoon 9313 struck the lake. The average wind speed increased again due to typhoon 9314 which struck the lake on 8 September, and relatively a high wind speed ($5.7 \text{ m}\cdot\text{sec}^{-1}$) was recorded on 9 September. Maximum insolation was high between 24 August and 5 September (ca. $10 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$), decreased rapidly to $1.6 \text{ MJ}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$ on 7 September and increased again from 8 September (Fig. 1C).

From 24 August to 1 September, the thermal stratification of lake water (Fig. 2A) was weak, and the water of the upper layer ($<1.8 \text{ m}$ depth, ca. 26°C) seemed to be well mixed when the

Fig. 1. Changes in the average atmospheric temperature (A), wind speed (B) and maximum insolation (C) during the BITEK period. Vertical bars indicate difference between the maximum and minimum values. Arrows indicate typhoon events.

average wind speed was high between 27 and 28 August (Fig. 1B). When the highest water temperature (28.1 °C) was recorded on 1 September, the Brunt-Väisälä frequency (Fig. 2B) also increased to the highest value of $1562 \times 10^{-6} \text{ sec}^{-2}$, indicating that thermal stratification was strongest on that occasion.

The thermal structure of lake water became

almost homothermal from 3 September as typhoon 9313 approached the lake. The Brunt-Väisälä frequency (Fig. 2B) was 0 sec^{-2} between 3 and 10 September, indicating that the lake was well mixed. This was due to typhoons 9313 and 9314 (Fig. 1B) and low maximum insolation (Fig. 1C). On 12 September, lake water started to thermally stratify again probably because of low wind speed (Fig. 1B) and increased insolation (Fig. 1C).

Concentrations of SS from 0.5 m below the surface increased slightly between 26 (3.5 $\text{mg} \cdot \text{l}^{-1}$) and 28 (4.5 $\text{mg} \cdot \text{l}^{-1}$) August (Fig. 3). They increased again from 3 September (4.5 $\text{mg} \cdot \text{l}^{-1}$) and reached a maximum concentration of 17.9 $\text{mg} \cdot \text{l}^{-1}$ on 4 September, the day when typhoon 9313 passed the study area. Thereafter, SS concentration continually decreased.

Concentrations of DIN ($\text{NO}_3^- \cdot \text{N} + \text{NO}_2^- \cdot \text{N} + \text{NH}_4^+ \cdot \text{N}$) (Fig. 4A) decreased consistently between 24 August (158 $\mu\text{gN} \cdot \text{l}^{-1}$) and 3 September (31 $\mu\text{gN} \cdot \text{l}^{-1}$). They increased during the passage of typhoon 9313 (4 September, 104 $\mu\text{gN} \cdot \text{l}^{-1}$), and thereafter decreased to 10 September (9 $\mu\text{gN} \cdot \text{l}^{-1}$). Concentrations of DON (Fig. 4A) fluctuated greatly between 50 and 340 $\mu\text{gN} \cdot \text{l}^{-1}$ during the study period, but the pattern was generally similar to that of DIN except for a large peak on 28 August (339 $\mu\text{gN} \cdot \text{l}^{-1}$) and another after 5 September (256 $\mu\text{gN} \cdot \text{l}^{-1}$).

DOP concentrations (Fig. 4B) decreased from 8.2 to 4.1 $\mu\text{gP} \cdot \text{l}^{-1}$ during the study period with some fluctuations. DIP concentration (Fig. 4B) increased on 4 September (2.5 $\mu\text{gP} \cdot \text{l}^{-1}$) and remained at a relatively high level (2.1 $\mu\text{gP} \cdot \text{l}^{-1}$) on 5 September, similar to the DIN concentration, but the concentrations were mostly low (<1.0 $\mu\text{gP} \cdot \text{l}^{-1}$) during the study period.

Chlorophyll concentrations (Fig. 5) were relatively low (<5.0 $\mu\text{g} \cdot \text{l}^{-1}$) between 24 August and 1 September. Unlike SS concentrations, chlorophyll concentrations did not increase significantly between 26 and 28 August. They started to increase from 3 September and reached a maximum (26 $\mu\text{g} \cdot \text{l}^{-1}$) on 10 September. The predominant species of phytoplankton was *Aulacoseira granulata* (Bacillariophyceae). *Aphanocapsa* sp. (Cyanophyceae) were also

Fig. 2. Changes in thermal structure (A) and Brunt-Väisälä frequency (B) at Station S during the BITEK period.

Fig. 3. Changes in concentration of suspended solids (SS) from 0.5 m below the surface at Station S during the BITEK period.

frequently observed, fluctuating around 2000 cells $\cdot \text{ml}^{-1}$. Abundance of this alga (ca. $3 \mu\text{m}^3 \cdot \text{cell}^{-1}$), however, was negligible compared with that of *A. granulata*. *A. granulata* increased from 3 September, attained a maximum density (375 cells $\cdot \text{ml}^{-1}$) on 7 September and thereafter decreased (Fig. 5).

As mentioned previously, typhoon 9313 struck the lake on 4 September, and the highest wind speed ($10.8 \text{ m} \cdot \text{sec}^{-1}$) was recorded. Since lake water had already been well mixed prior to this date ($N^2 = 0 \text{ sec}^{-2}$, Fig. 2B), strong winds due to the typhoon probably disturbed the bottom sediment of the lake and resuspended it. In Lake Biwa, such resuspension of bottom sediment can be predicted by a model based on field observations

Fig. 4. Changes in concentrations of dissolved inorganic nitrogen (DIN) and organic nitrogen (DON) (A), and those of dissolved inorganic phosphorus (DIP) and organic phosphorus (DOP) (B) from 0.5 m below the surface at Station S during the BITEK period.

(KUMAGAI, 1988).

Since winds due to the typhoon blew strongly, and the Brunt-Väisälä frequency was 0 sec^{-2} , a number of phytoplankton could have been resuspended on 4 September. However, the increase in chlorophyll concentration (Fig. 5A) on this occasion was negligible compared with that on 3 September (Fig. 3). One possible explanation for the smaller increase in chlorophyll concentration is that most of the phytoplankton cells on the sediments had already been recruited to the water column through the preceding mixing on 3 September, rather than resuspended during the following turbulence associated with typhoon 9313. Thus, even without remarkable physical events such as typhoons, *A. granulata* in the south basin of Lake Biwa may be resuspended when lake water is destratified and mixed.

The increase in concentrations of DIN, DON

Fig. 5. Changes in concentration of chlorophyll (A) and cell density of *Aulacoseira granulata* (Bacillariophyceae) (B) from 0.5 m below the surface at Station S during the BITEK period.

and DIP on 4 September (Fig. 4) were probably due to their release from the resuspended sediment. Increase of *A. granulata* was most prolific between 5 and 7 September (Fig. 5), and concentrations of DIN, DON and DIP decreased simultaneously. This was probably due to the utilization of these nutrients through the rapid growth of the alga.

Almost every year in the south basin of Lake Biwa, *Uroglena americana*, which causes a fresh water red tide, proliferates massively from May to mid-June. Dominant species of phytoplankton from mid-June to July are annually variable, and *A. granulata* dominates between August and October (Table 1). Environmental conditions during the autumn in this basin, therefore, are probably favourable to growth of this alga. Previous studies have demonstrated that growth of algae belonging to the genus *Aulacoseira* is turbulence-dependent: the algae needs turbulence

Table 1. Dominant phytoplankton species in the South Basin of Lake Biwa during the warm season from 1989 to 1993.*

	1988	1989	1990	1991	1992	1993
May	<i>Uroglena</i> <i>Stephanodiscus</i>	<i>Uroglena</i>	<i>Uroglena</i>	<i>Uroglena</i>	<i>Uroglena</i>	<i>Uroglena</i>
June	<i>Uroglena</i>	<i>Uroglena</i> <i>Stephanodiscus</i>	<i>Aulacoseira</i> <i>Chloococcus</i>	<i>Uroglena</i>	<i>Uroglena</i> <i>Aulacoseira</i>	<i>Closterium</i> <i>Aulacoseira</i>
July	<i>Schroederia</i>	<i>Stephanodiscus</i> <i>Cyclotella</i>	<i>Dichotomococcus</i> <i>Aulacoseira</i>	<i>Stephanodiscus</i> <i>Aulacoseira</i>	<i>Closterium</i> <i>Aulacoseira</i>	<i>Stephanodiscus</i> <i>Cyclotella</i>
August	<i>Stephanodiscus</i>	<i>Aulacoseira</i>	<i>Cyclotella</i> <i>Coelastrum</i>	<i>Aulacoseira</i>	<i>Aulacoseira</i>	<i>Aulacoseira</i>
September	<i>Aulacoseira</i>	<i>Stephanodiscus</i>	<i>Coelastrum</i> <i>Aulacoseira</i>	<i>Aulacoseira</i>	<i>Coelastrum</i> <i>Aulacoseira</i>	<i>Aulacoseira</i>
October	<i>Aulacoseira</i>	<i>Aulacoseira</i>	<i>Aulacoseira</i>	<i>Aulacoseira</i>	<i>Aulacoseira</i>	<i>Aulacoseira</i>

*Data were collected by the Shiga Prefectural Institute of Public Health and Environmental Science (1991 and 1995).

to maintain its position in the euphotic zone because of their high specific gravity (LUND, 1954; PETROVA, 1986). Net changes in abundance of *Aulacoseira* is mainly determined by the balance between the rates of sinking loss and resuspension (REYNOLDS *et al.*, 1986). Turbulence-dependent growth of *A. granulata* is also likely in the south basin of Lake Biwa (MIYAJIMA *et al.*, 1994).

In the present study, we followed a series of processes which supported our hypothesis that the growth of this alga was stimulated by the passage of a typhoon which suspended sediment and consequently increased the concentration of biologically available nutrients.

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- (Authors : Shin-ichi NAKANO^{1*}, Yasushi SEIKE², Tatsuki SEKINO³, Minoru OKUMURA², Keiichi KAWABATA⁴, Kaoru FUJINAGA², Masami NAKANISHI³, Osamu MITAMURA⁵, Michio KUMAGAI¹ and Hiroshi HASHITANI^{2*}; ¹Lake Biwa Research Institute, 1-10 Uchide-hama, Otsu, Shiga 520, Japan (^{1*}present address : Department of Agriculture, Ehime University, 3-5-7 Tarumi, Matsuyama, Ehime 790, Japan) ; ²Faculty of

Science, Shimane University 1060 Nishikawazu-cho, Matsue, Shimane 690, Japan ,^{2*}present address : Meteorology and Limnology Laboratory, Higashihonmachi 5-7-402, Matsue, Shimane 690, Japan ; ³Center for Ecological Research, Kyoto University, 4-1-23 Shimosakamoto, Otsu, Shiga 520, Japan; ⁴Faculty of Education, Kanazawa University, Kakumacho, Kanazawa, Ishikawa 920, Japan; ⁵Division of Natural Sciences, Osaka Kyoiku University, Kashiwara, Osaka 582, Japan.

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