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Interannual Variations of Limnological and Ecological Characteristics in Acidic Lake Katanuma

Shikano, Shuichi*, Eisuke Kikuchi, Shigeto Takagi[1] and Hideyuki Doi[1]

(Center for Northeast Asian Studies, Tohoku University, Kawauchi 41, Sendai 980-8576, Japan
[1]Graduate School of Life Sciences, Tohoku University, Katahira 2-1-1, Sendai 980-8577, Japan)

We observed the physical, chemical, and biological characteristics of an acidic lake, Lake Katanuma, from 1998 to 2002 at weekly or biweekly intervals, except during the winter. This volcanic lake has a dimictic thermal pattern. In summer, the volcanic heat supply at the lake bottom results in weak thermal stratification. In 1998, 1999, and 2002, short-term holomixis was observed during the stratification period, when the anoxic, hydrogen sulfide-rich water from the hypolimnion spread across the entire lake. In contrast, distinct short-term holomixis did not occur during the stratification period in 2000 and 2001. However, the early onset of the autumn turnover in August 2000 and 2001 caused anoxic conditions to persist throughout the entire water column for more than 2 weeks. The anoxic and hydrogen sulfide-rich conditions affected population densities of chironomid larvae (*Chironomus acerbiphilus*) and planktonic algae (*Chlamydomonas acidophila*), both dominant species in Lake Katanuma. Thus, the interannual variations of limnological characteristics influenced the seasonal population changes of these species.

Key words : short-term turnover, dissolved oxygen, hydrogen sulfide, chironomid larvae, *Chlamydomonas*

INTRODUCTION

Long-term observations of benthic and planktonic communities and their limnological environments are essential for understanding the interannual variations of lake ecosystems. Lake Katanuma in the Naruko volcanic crater in northern Japan receives volcanic heat from the lake bottom (Satake, 1975). Although the seasonal changes of water temperature in Lake Katanuma were essentially dimictic, the temperature difference between the epilimnion and hypolimnion during stratification periods was as small as 3-7°C owing to the heat supply (Satake and Saijo, 1978; Shikano *et al.*, 2004). In some crater lakes, the lake water temperature depends on geothermal heat flux from the lake bottom, and this heat flux may change with volcanic activity (Brown *et al.*, 1989; Rowe *et al.*, 1992; Ohba *et al.*, 1994). The fluctuation of the heat flux from the lake bottom ranged from 29.0 to 35.8 W m^{-2} in Lake Katanuma. Therefore, the stratification and circulation conditions in the lake water changed from year to year (Shikano *et al.*, 2004).

Although the pH of the water in Lake Katanuma ranges from 2.0-2.2, high densities of chironomid larvae (*Chironomus acerbiphilus*), benthic algae (*Pinnularia acidojaponica*), and planktonic algae (*Chlamydomonas acidophila*) have frequently been observed (Fujimatsu, 1938; Satake and Saijo, 1974; Doi *et al.*, 2001). Since stratification and circulation conditions fluctuate interannually, the population changes in these species

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* Corresponding Author: Tel: +81-22-795-7563, Fax: +81-22-795-7563, E-mail: shikano@cneas.tohoku.ac.jp

could be affected by such interannual variations in limnological characteristics. By conducting weekly or biweekly limnological and biological surveys at Lake Katanuma from 1998 to 2002, in all seasons except winter, this study obtained the frequent and continuous temperature and environmental data needed to examine interannual variations in abiotic factors and the population dynamics of the lake's inhabitants.

MATERIALS AND METHODS

Lake Katanuma is located in the north of Miyagi Prefecture, Japan (38° 44.0′N, 140° 43.5′E) at an altitude of 306 m above sea level. The lake has a surface area of 124,000 m^2 and a maximum depth of ca. 21 m. Sampling was carried out on a weekly or biweekly basis from 1998 to 2002, except during the winter months. Samples were taken from a sampling station moored at the deepest point of the lake, near the center. A Van Dorn water sampler collected 3−L samples at seven different depths (0, 1, 2, 4, 6, 10, and 15 m). Dissolved oxygen (DO) was determined by Winkler's method and hydrogen sulfide was measured using a No. 211 detector tube (Gastec). Temperature was measured with a U−22 water quality monitor (Horiba) at 11 different depths (0, 1, 2, 3, 4, 5, 6, 8, 10, 13, and 15 m). Temperature loggers (StowAway TidbiT) recorded long−term continuous measurements of water temperatures at depths of 1, 4, 6, and 10 m at 30−minute intervals.

We measured chlorophyll *a* concentrations as *Chlamydomonas acidophila* densities. One hundred milliliters of the lake water was filtrated with a Whatman GF/F filter. Chlorophyll *a* was extracted in *N*, *N*−dimethylformamaide (Moran and Porath, 1980) and the concentration was measured using a fluorometer (Turner Designs). Chironomid samples were collected at depths of 1, 2, 4, 6, 10, and 15 m in 1998 and 1999, and at depths of 2, 4, and 10 m from 2000 to 2002. We collected three or five replicates of chironomid larvae using an Ekman−Birge grab sampler, which sampled an area of 0.15 × 0.15 m^2. All samples were fixed in 4% neutralized formalin solution immediately after collection. Larvae were sieved through 0.130−mm mesh and preserved in 70% ethanol solution in the laboratory. The larvae were classified into four instars based on their head capsule width.

RESULTS AND DISCUSSION

Stratification with a thermocline depth of 3−5 m was formed from April to August in 1998. During this period, oxygenated water with no gaseous hydrogen sulfide was detected in the epilimnion, while oxygen depletion and accumulated hydrogen sulfide were prominent in the hypolimnion (Fig. 1A). When air temperature declined 4−8°C from the epilimnion temperature, short−term mixing from the surface to the bottom occurred on 12 June and 24 July in 1998. These short−term turnovers led to oxygen depletion and the spread of hydrogen sulfide throughout the water column (Fig. 1B). The temperature loggers also recorded short−term holomixis for 1−8 days three times in 1999 and 2002, respectively. In contrast, short−term holomixis was not observed during the stratification periods in 2000 and 2001. Therefore, hydrogen sulfide gradually accumulated in the hypolimnion from April to August in both 2000 and 2001 (Fig. 1C). When the autumn turnover began, the accumulated hydrogen sulfide in the hypolimnion was oxidized and the dissolved oxygen was completely consumed. Anoxic conditions from the surface to the bottom then continued for more

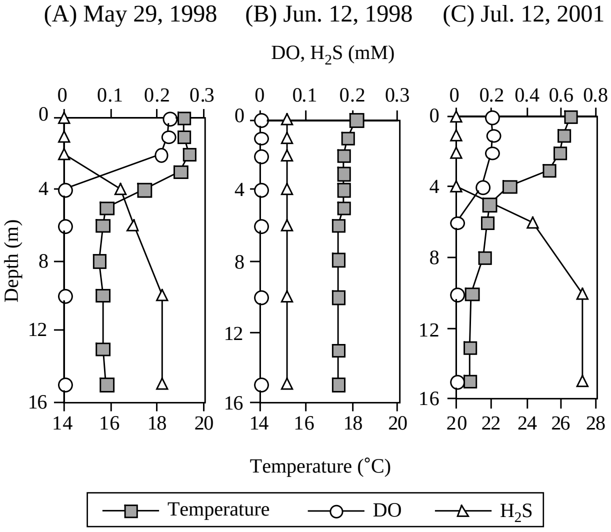
(A) May 29, 1998 (B) Jun. 12, 1998 (C) Jul. 12, 2001

Fig. 1. Vertical distribution of temperature, dissolved oxygen, and hydrogen sulfide during periods of (A) stratification and (B) short−term holomixis in 1998 and (C) stratification in 2001.

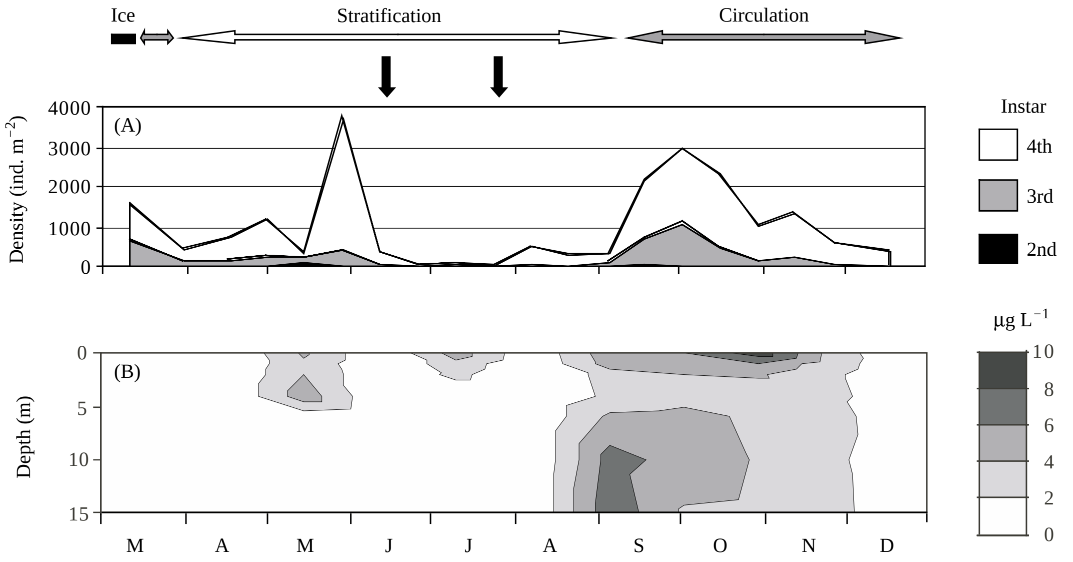

Fig. 2. Seasonal changes in (A) the mean density of chironomid larvae and (B) the vertical disturbution of chlorophyll *a* concentrations in 1998. Vertical arrows indicate the short-term holomixis. Horizontal thick line, open arrows, and closed arrows above the upper panel repesent the periods of ice cover, strarification, and circulation, respectively.

than 2 weeks. The anoxic conditions and the hydrogen sulfide disappeared completely from the entire water column from mid-September. Over the 5 years of the study, the frequency of short-term holomixis events varied from year to year (Shikano *et al.*, 2004).

The density of *C. acerbiphilus* larvae was strongly affected by the short-term holomixis and autumn turnover. The larvae collected in grab samples were mainly 3rd and 4th instars, but the planktonic 1st-instar larvae were never found in benthic samples. Chironomid larvae were mainly distributed in the sediments above the thermocline during the stratification period. When short-term holomixis occurred, most chironomid larvae swam into the surface water and then they were stranded at the edge of the lake and numerous dead larvae accumulated on the shore after a few days of holomixis. As a result, the density of chironomid larvae decreased dramatically immediately following holomixis (Fig. 2A). The recovery in larval densities after these decreases seemed to depend on the duration of the oxygen depletion. We observed the drastic decreases after the short-term holomixis in 1998, 1999, and 2002. In these years, the densities of *C. acerbiphilus* recovered after the circulation period began (Fig. 2A). During the circulation period, larvae were found in the sediments throughout the water column. In contrast, the accumulated hydrogen sulfide in the hypolimnion led to anoxic conditions throughout the water column for more than two weeks in both 2000 and 2001. In these years, chironomid larvae were scarce for about two months after the autumn turnover began.

Although the densities of *C. acidophila* showed large interannual fluctuations, they were found only in oxygenated water: the epilimnion during the stratification period and the entire water column during the circulation period (Fig. 2B). However, *C. acidophila* almost disappeared during and after the short-term holomixis in 1998, 1999, and 2002. In these years, the recovery of *C. acidopila* populations were observed after the autumn turnover began. In 2000 and 2001, oxygen depletion lasting for more than 2 weeks after the autumn turnover prevented the quick recovery of phytoplankton populations.

Seasonal changes in populations of chironomid larvae and planktonic algae were influenced by interannual variations in oxygen depletion and hydrogen sulfide levels, which were in turn affected by geothermal activity and weather conditions.

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