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NOTE

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Factors controlling hypolimnetic ammonia accumulation in a lake

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Abstract The factors controlling the degree of hypolimnetic ammonia accumulation in Lake Onogawa are discussed based on periodic observations since 1993. The standing stock of ammonia in the bottom 9 m of the water column was a good measurement for determining the extent of the hypolimnetic ammonia accumulation. It varied threefold from 144 mmol m^{-2} in 1998 to 429 mmol m^{-2} in 1996. The correlation between the annual maxima of the ammonia standing stocks and the annual maxima of the thickness of anoxic layers was significant at $P = 0.01$. This fact suggests that the degree of development of the anoxic layer is the primary factor controlling the extent of hypolimnetic ammonia accumulation. Sporadic local heavy rainfalls in 1998 perturbed the water column, and the formation of the anoxic layer was postponed more than one month, resulting in a lower level of hypolimnetic ammonia accumulation in 1998. A thick mineral deposit apparently formed during the local heavy rainfall and seemed to enclose the freshly deposited organic matter, which might be an effective source material of the hypolimnetic ammonia, and resulted in a low level of ammonia accumulation in 1999. By 2000, the lake seems to have recovered from the perturbation, suggesting that the major part of the hypolimnetic ammonia is derived from fresh organic matter deposited within a year.

Key words Lake Onogawa · Anoxic layer · Lake perturbation · Ammonia source

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Introduction

In aquatic environments, ammonia is generated by heterotrophic bacteria as a primary end product of the decomposition of organic matter, either directly from proteins or from other nitrogenous organic compounds. Ammonia is also excreted by aquatic animals. However, this process is quantitatively minor in comparison to bacterial deamination (Wetzel 1983).

Organic matter in lake sediments is also subjected to bacterial deamination, resulting in ammonia formation. A part of this ammonia is released from the sediments into the overlying water column. Under stratified conditions, if the water column is well oxygenated, the released ammonia is oxidized to nitrate by bacteria in the hypolimnion. Ammonia will accumulate in the hypolimnion if the water column is anoxic (Wetzel 1983). When lake water circulates, the accumulated ammonia will be distributed throughout the water column, and hence phytoplankton in the photosynthetic zone can use it as their nitrogen source. Because phytoplankton prefer ammonia to other nitrogen sources such as nitrate, nitrite, and urea (Eppley et al. 1969; McCarthy et al. 1977; Ault et al. 2000), hypolimnetic accumulation of ammonia is important from the viewpoint of primary productivity.

The extent of hypolimnetic ammonia accumulation differs from year to year in a lake. This note discusses the controlling factors on the degree of hypolimnetic ammonia accumulation in Lake Onogawa based on periodic observations since 1993.

Materials and methods

Lake Onogawa (37°40′N, 140°06′E) was formed at the time of the volcanic eruption of Mt. Bandai in 1888. One of the three summits of the volcano, 1.7 km^3 in volume (Murayama 1973), was blown away by the eruption, resulting in large-scale mudflows. These mudflows dammed many river valleys and formed some lake basins, including Lake Onogawa. Lake Onogawa lies 794 m above mean sea level, covers an area of 1.4 km^2, and has a maximum depth of 21 m (Horie 1962). It contains 0.014 km^3 of water (Satoh et al. 1995). Its trophic status is considered to be on the boundary between mesotrophic and eutrophic (Satoh et al. 1996).

Water samples were collected every 3 weeks from 1993 to 1998 and every 4 weeks in 1999 and 2000 from the same station, as mentioned in Satoh et al. (1996, 2001). The samples were collected at 2.5-m intervals from the surface to the bottom with a 6-l Van Dorn sampling bottle. The water samples were transported in heat-insulating boxes to a laboratory at Yamagata University and filtered through preignited (at 410°C for 4 h) Whatman GF/F glass fiber filters (nominal porosity, 0.7 μm) within 4 to 7 h after sampling in 1993 and 1994. The water samples from 1995 to 2000 were processed at a field station near the lake within 2 to 5 h after collection. The filtrates were stored frozen until the time of chemical analysis. Ammonia was determined in duplicate by using the phenol-hypochlorite method (Solōrzano 1969). Dissolved oxygen was determined by the Winkler method. The duplicate samples for dissolved oxygen were fixed on the boat and titrated at the laboratory, either at Yamagata University or the field station, on the same day as sample collection.

Results and discussion

Here, a layer in which the dissolved oxygen concentration was zero is called an anoxic layer.

Summer stratification starts in May in Lake Onogawa, and develops with time from June to August (Satoh et al. 1996, 2001). Before the complete water circulation in late October to early November, water circulates partially from September to October. Hypolimnetic dissolved oxygen decreases from spring and results in anoxic conditions in late July to early August (Fig. 1) (Satoh et al. 1996). The anoxic conditions last until the time of complete water circulation. In accordance with the decrease in dissolved oxygen, the concentration of hypolimnetic ammonia increases (Fig. 2) (Satoh et al. 1996, 2001). Usually it reaches the annual maximum just before the complete water circulation. Clear increases in the concentration of ammonia are seen in the bottom 9 m of the water column at the time of the annual peaks (Fig. 3). Thus, the standing stock of ammonia in the bottom 9 m of the water column is a good indicator for determining the extent of hypolimnetic ammonia accumulation. It varied three-fold from 144 mmol m^{-2} in 1998 to 429 mmol m^{-2} in 1996 (Fig. 4), whereas the annual maximum thickness of the anoxic layer ranged from 2.9 m in 1998 to 6.2 m in 1996 (Fig. 4).

Anoxic conditions favor the accumulation of ammonia. As might be expected, the standing stock of ammonia correlates well with the thickness of the anoxic layer (Fig. 4). The solid line in the figure shows the linear regression for all data from 1993 to 2000, and the dashed line shows the linear regression without the data in 1998 and 1999. The correla-

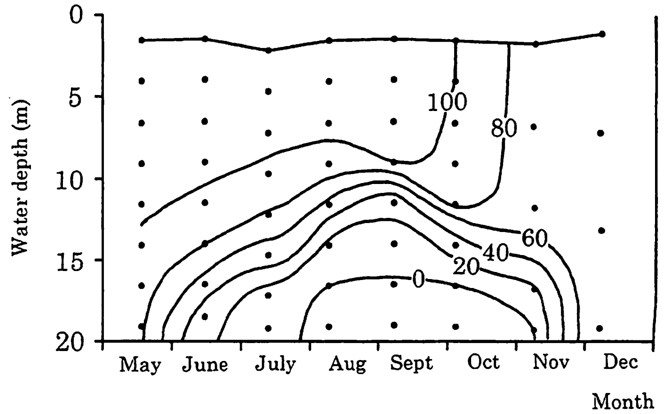

Fig. 1. Depth–time diagram for dissolved oxygen (%) in Lake Onogawa in 2000

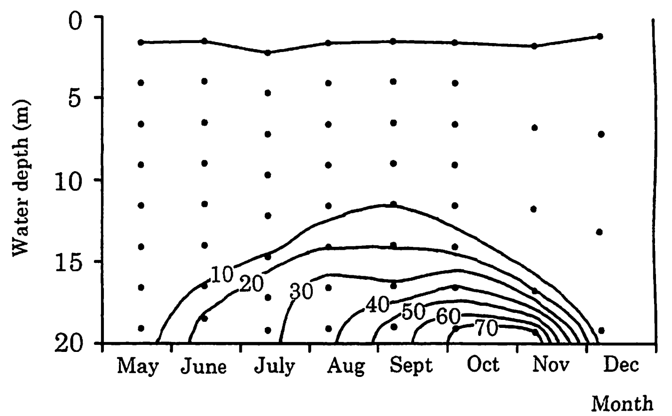

Fig. 2. Depth–time diagram for ammonia (μmol l^{-1}) in Lake Onogawa in 2000

tions between both measurements for the two cases are significant at $P = 0.01$, suggesting that the degree of development of the anoxic layer is the primary factor controlling the extent of hypolimnetic ammonia accumulation. Based on the coefficient of determination (R^2), the dashed line shows a slightly closer correlation than the solid line.

The reason two sets of linear regressions were performed is that Lake Onogawa suffered from local heavy rainfalls in August 1998, resulting in a serious perturbation of the water column (Satoh et al. 2001). At that time, oxygen was supplied to the depths, and the formation of the anoxic conditions was postponed by more than one month as compared with normal years. This, in turn, resulted in less accumulation of hypolimnetic ammonia (Satoh et al. 2001). This explains why the symbol of 1998 lies at the lowermost left in Fig. 4.

If the thickness of the anoxic layer is taken into account, the accumulation of ammonia still remained at a low level in 1999 (Fig. 4). The data point of 1995 lies closest to that of 1999 in Fig. 4. The anoxic layer was thicker in 1999 than in 1995, whereas the standing stock of ammonia was less in 1999 than in 1995. This is outside the general trend, in that the thicker the anoxic layer, the greater is the expected

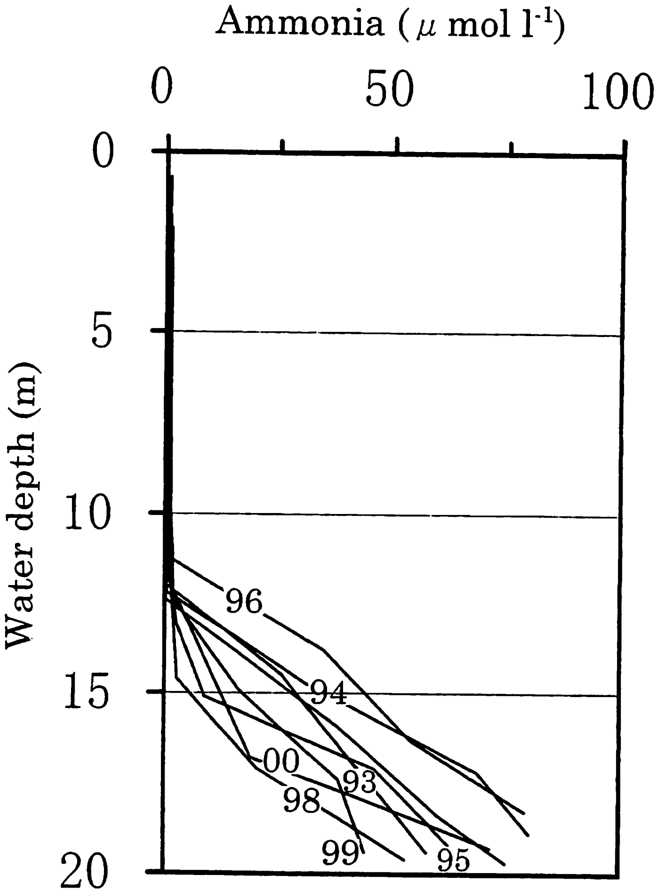

Fig. 3. Vertical profiles for ammonia ($\mu mol\,l^{-1}$) at the time of annual maximum concentration in Lake Onogawa from 1993 to 2000

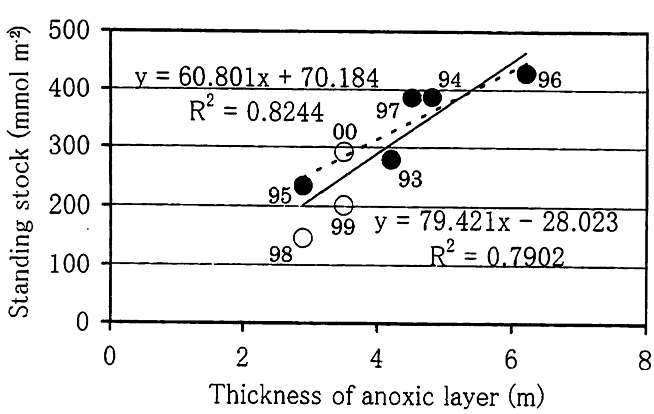

Fig. 4. Scatter diagram for annual maximum standing stock of ammonia vs. annual maximum thickness of anoxic layer. (—) Linear regression for all data from 1993 to 2000; (----) linear regression without the data in 1998 and 1999. (●) Before the local heavy rainfalls; (○) after the local heavy rainfalls (see text for details)

standing stock of ammonia. Because 1993 and 2000 also show a similar relationship, these deviations from the general trend may be considered within the range of fluctuation. However, there is another possible reason for the deviation in 1999, as described below.

A vast quantity of minerals apparently was deposited on the sediment surface of Lake Onogawa from the watershed by way of the inflowing streams at the time of the local heavy rainfalls in 1998. During the local heavy rainfalls in 1998, the organic carbon content in the trapped deposits at 15 m depth was 2.0% (data not shown). The organic carbon contents in another 10 samples from April to December 1998 ranged from 8.4% to 14%, averaging 10.2 ± 1.6%, showing that the deposits during the local heavy rainfalls were rich in minerals and poor in organic substances as compared with those in the normal months. Freshly deposited organic matter, an effective source of the hypolimnetic ammonia and ammonia in interstitial water, would have been capped by these mineral deposits poor in organic substances and might have resulted in a low level of hypolimnetic ammonia in the next year. We collected some core samples of the sediment on 6 December 2000 and found a dark-brown sediment 10 to 15 mm in thickness at the topmost layer, which could easily be distinguished visually from its underlying layer. Because the cores were collected 2 years after the perturbation, the lake sediment experienced summer anoxic conditions three times until the time of the sample collection. Anoxia might have given the sediment its dark-brown color. Assuming that this topmost 10- to 15-mm layer was formed at the time of the local heavy rainfalls in 1998, this layer might act as a cap enclosing the underlying freshly deposited organic matter and ammonia in the interstitial water. After the local heavy rainfalls, organic matter would also have been deposited. However, the quantity of the organic matter on the surface sediment in the stratification period of 1999 would be significantly lower than in the case without the perturbation. This condition might result in a low level of hypolimnetic ammonia accumulation in 1999. The position of the data point of 2000 in Fig. 4 suggests the recovery from the perturbation. If these speculations are true, the major part of the hypolimnetic ammonia should be derived from the fresh organic matter deposited within a year.

Kamiyama (1978, 1979) and Kamiyama et al. (1976, 1977a,b; 1978, 1979) intensively studied the release of ammonia from the bottom sediments of lakes. They used the vertical profiles for ammonia and organic matter in the sediments for their model. The model suggests that in the North Basin of Lake Biwa, almost half of the particulate organic nitrogen deposited on the bottom sediment returned to the overlying water as ammonia (Kamiyama 1978). They also estimated the rate constant of the decomposition of organic matter in the sediment of the North Basin of Lake Biwa to be 10^{-4} day^{-1}, a value that scarcely changed over several centimeters' depth of the bottom sediment (Kamiyama et al. 1977a). A decomposition rate constant of 10^{-4} day^{-1} means that the turnover time of the organic matter in the sediment is $1/10^{-4}\ day^{-1} = 10^4$ days = 27 years. As discussed above, we have speculated that the major part of the hypolimnetic ammonia could have been derived from the fresh organic matter deposited within a year. The decomposition rate reported by Kamiyama et al. (1977a) is much slower than the one speculated in the present study.

Matsunaga (1981) found that the decomposition of phytoplanktonic organic nitrogen obeys two-step first-order reactions. One is a fast step with a rate constant of 0.062 day^{-1} in the first 14 days. Another is a slow step with a rate constant of 0.018 day^{-1} for the next 35 days. The turnover times of organic nitrogen are calculated to be 16 and 55 days, respectively. Even Matsunaga's slow step is quite fast as compared with the results of Kamiyama et al. (1977a). Although phytoplankton and the freshly deposited organic matter are not necessarily the same, we may adopt the results of Matsunaga (1981), since there is no question that phytoplankton is one of the major sources of the freshly deposited organic matter. Probably the decomposition rate of a part of the freshly deposited organic matter, a labile fraction, is very fast, similar to the results of Matsunaga (1981). The rest of the organic matter, a refractory fraction, may be subjected to extremely slow decomposition processes, as suggested by Kamiyama et al. (1977a), after it was buried in the sediment.

Conclusions

The degree of the development of the summer anoxic layer is confirmed to be the primary factor controlling the extent of the hypolimnetic ammonia accumulation. To make clear the regulating factors on the development of the anoxic layer will be the next step of the study.

Perturbation of the water column by sporadic local heavy rainfalls in August 1998 affected the extent of the hypolimnetic ammonia accumulation in the same year (Satoh et al. 2001).

A kind of aftereffect of the local heavy rainfalls is conceivable in 1999. A thick allochthonous mineral deposit apparently was formed on the topmost layer of the lake sediment during the local heavy rainfalls in 1998. This layer is considered to enclose freshly deposited organic matter, an effective source of hypolimnetic ammonia and ammonia in interstitial water, resulting in a low level of hypolimnetic ammonia accumulation in 1999.

By 2000, the lake seems to have recovered from the aftereffect of the local heavy rainfalls, suggesting that the major part of the hypolimnetic ammonia is derived from the fresh organic matter deposited within a year. To confirm the speculations above, regeneration experiments of ammonia from the trapped freshly deposited organic matter together with in situ observation of ammonia accumulation will be conducted.

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