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NOTE

Yasuhiro Satoh · Michio Kumagai · Kotaro Sugawara
Yasushi Miyamori

Winter anoxic layer in Lake Hibara

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Abstract The concentration of dissolved oxygen in waters 0.5–0.6 m above the bottom of Lake Hibara, a dimictic lake, was zero in early spring of 1994 and 1997. The concentrations in early spring of 1992, 1993, 1995, 1996, and 1998 ranged from 3.75 to 10.1 $mg\,l^{-1}$. The depth profiles of water temperature suggest that water had not circulated prior to the sample collections of 1994 and 1997, but it had done so in the cases of the other years, suggesting that winter conditions were well preserved in the former years. On the other hand, the dissolved oxygen in the same strata decreased severely in summer. However, more or less titratable amounts of dissolved oxygen still remained (0.01–0.73 $mg\,l^{-1}$) at the final stages of summer stratification from 1992 to 1998. These facts show that a completely anoxic condition is not formed in this lake in summer but is sometimes formed in winter. It is interesting to note that in spite of unfavorable winter conditions for oxygen consumption, i.e., shorter duration and lower water temperature, oxygen is exhausted. These facts suggest that ventilation to the depths is much greater in summer than in winter.

Key words Dissolved oxygen · Ventilation · Oxygen consumption

Introduction

Lake Hibara in Fukushima Prefecture, Japan (37°41′N, 140°03′E) is a dimictic lake formed at the time of the volcanic eruption of Mt. Bandai in 1888. The summit of Mt. Bandai, 1.7 km^3, was blown away by the eruption (Murayama 1973), resulting in large-scale mudflows, which dammed many river valleys and formed three moderately sized lakes: Hibara, Onogawa, and Akimoto. Many other small lakes were also formed in the depressions of the mudflows. Lake Hibara lies 819 m above mean sea level. Its maximum depth is 31 m, with a mean depth of 12 m. The lake covers 10.83 km^2 and contains 0.13 km^3 of water (Horie 1961). The trophic status of Lake Hibara is on the boundary between oligo- and mesotrophic (Satoh et al. 1993). Though the dissolved oxygen in the hypolimnion decreases to a very low level during the summer stratification period, it is not exhausted (Satoh et al. 1993 and unpublished data). However, we now have evidence of the presence of a winter anoxic layer in this lake, as will be shown below.

Y. Satoh (✉) · K. Sugawara · Y. Miyamori
Faculty of Science, Yamagata University, Yamagata 990-8560, Japan
Tel. +81-23-628-4589; Fax +81-23-628-4510
e-mail: hirosato@sci.kj.yamagata-u.ac.jp

M. Kumagai
Lake Biwa Research Institute, Otsu, Japan

Contribution No. 23 from the Urabandai Limnological Station, Yamagata University

Materials and methods

Water samples were collected from a station shown in Fig. 1, which is the same station described in Satoh et al. (1993). The water samples from 1992 to 1994 were processed in the same way as described in Satoh et al. (1993), i.e., water samples for chemical analyses were transported in heat-insulating boxes to a laboratory in Yamagata University and filtered through pre-ignited (at 410°C for 4 h) Whatman GF/F glass fiber filters (nominal mean porosity, 0.7 μm) within 4 to 7 h after sample collection. The filtrates were stored frozen until the chemical analyses. The duplicate samples for dissolved oxygen by the Winkler method were fixed on the boat and titrated at the laboratory on the same day as the sample collection. The water samples from 1995 to 1998 were processed at a field laboratory near the lake. The filtration and titration were started within 1 to 3 h after sample collection. The filtrates were frozen at the field laboratory, transported to Yamagata University, and kept frozen until the time of chemical analyses. The methods used are shown in Table 1.

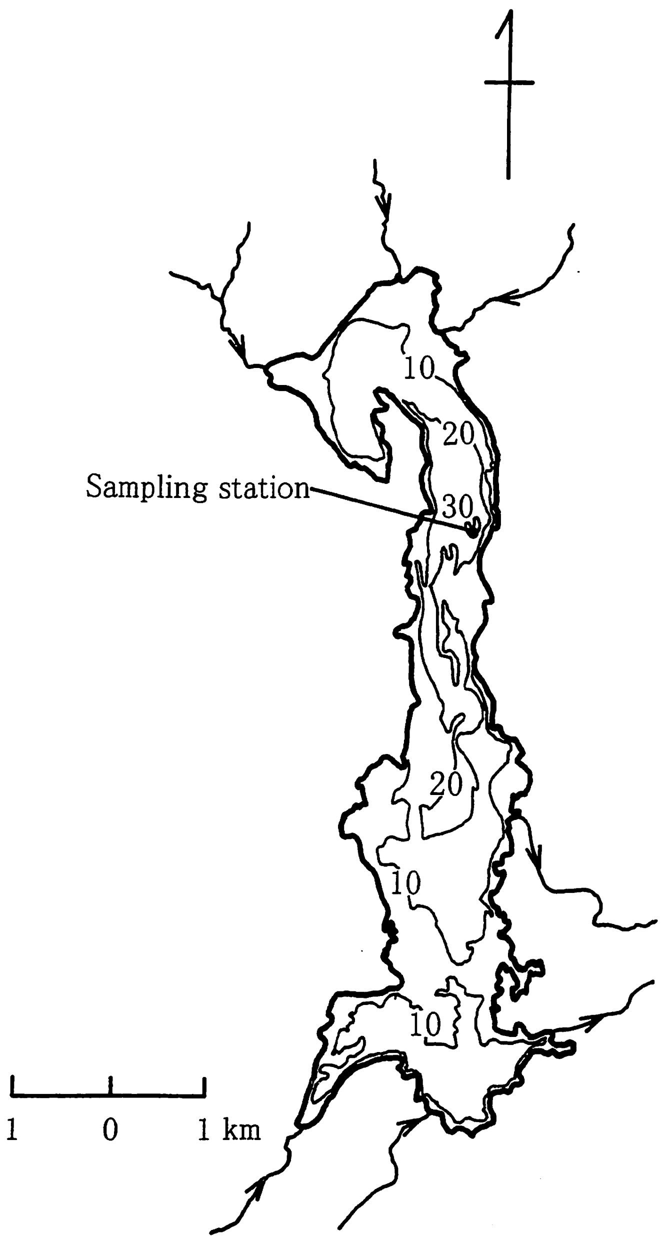

Fig. 1. Map showing the location of the station on Lake Hibara. *Numerals* show water depths in meters

Table 1. Methods used for measurement of water temperature and chemical analyses

Parameter	Methods
Water temperature	Thermistor thermometer
Dissolved oxygen	Winkler method
Ammonia	Phenol hypochlorite method (Solōrzano, 1969)
Nitrate	Cadmium reduction with subtraction of nitrite (Strickland and Parsons, 1972)
Total nitrogen	UV measurement after persulfate digestion (Otsuki, 1981)
Total phosphorus	Molybdate blue method after persulfate digestion (Menzel and Corwin, 1965)
Inorganic carbon	Satake et al. (1972) for 1992–1993 Shimazu TOC 5000 for 1994–1998
Dissolved organic carbon	Menzel and Vaccaro (1964) for 1992–1993 Shimazu TOC 5000 for 1994–1998

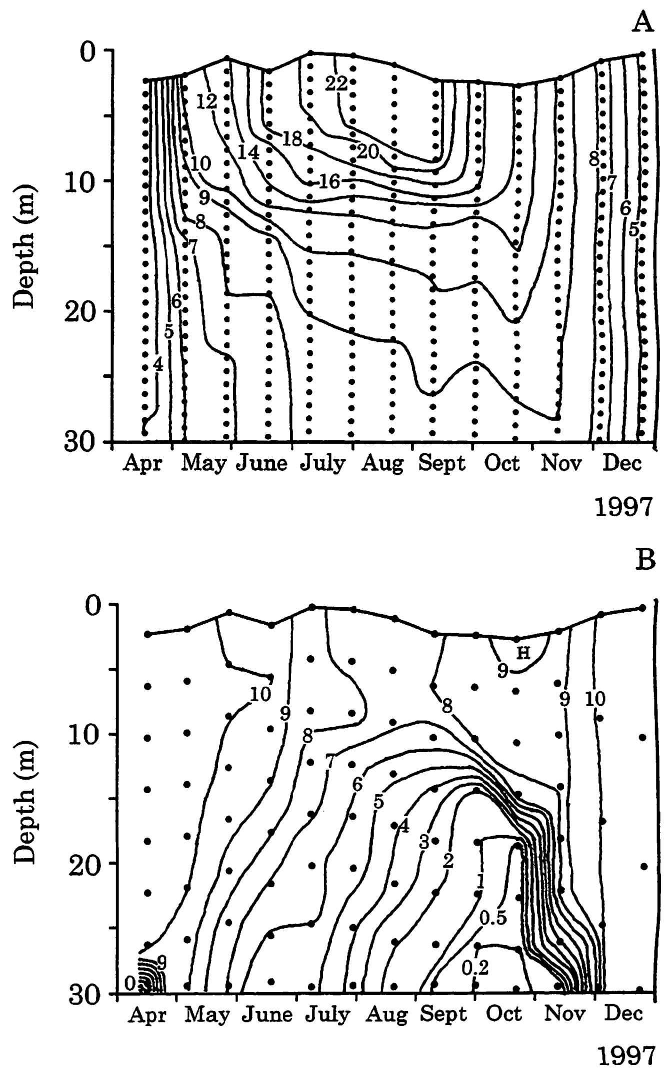

Fig. 2. Depth-time diagrams for (**A**) water temperature (°C) and (**B**) concentration of dissolved oxygen ($mg l^{-1}$) in 1997

Results and discussion

The concentrations of dissolved oxygen 0.5–0.6 m above the sediment-water interface were $0.0 mg l^{-1}$ on 21 April 1994 (Table 2) and 16 April 1997 (Table 2, Fig. 2). Both dates are the first sampling date of each year after the melting of the lake's ice cover. The concentrations of ammonia, total nitrogen, inorganic carbon, and dissolved organic carbon are significantly high, and total phosphorus is moderately high at this depth as compared with the upper strata (Table 2). On the other hand, nitrate concentration was significantly low in both cases. A similar increase and decrease in these parameters are usual in the anoxic hypolimnia of summer stratified conditions in many lakes (e.g., Lake Onogawa in

Table 2. Water temperature (WT), dissolved oxygen (DO), ammonia, nitrate, total nitrogen (TN), total phosphorus (TP), inorganic carbon (IC), and dissolved organic carbon (DOC) in Lake Hibara on the first sampling dates of 1994 and 1997

Date	Water depth (m)	Depth (m)	WT (°C)	DO (mg l^{-1})	NH_3 (μM)	NO_3^- (μM)	TN (μM)	TP (μM)	IC (mM)	DOC (μM)
21 April 1994	27.3	0.0	2.2	9.82	4.5	7.8	10.3	0.24	0.26	55
		4.1	2.0	9.16	4.4	7.6	12.5	0.26	0.27	68
		8.1	1.9	9.27	4.5	7.4	14.1	0.22	0.27	63
		12.1	1.9	9.26	4.4	7.2	13.1	0.21	0.27	59
		16.2	1.9	9.02	4.9	7.6	12.8	0.21	0.27	68
		20.2	1.9	8.93	4.8	7.0	14.1	0.21	0.28	69
		24.2	1.8	7.13	9.0	5.2	21.9	0.21	0.38	67
		26.8	2.7	0.00	60.1	0.1	139	0.45	1.03	223
16 April 1997	27.7	0.0	3.5	10.2	2.2	9.5	14.9	0.25	0.21	56
		4.1	3.5	10.2	1.8	10.0	16.4	0.27	0.21	53
		8.2	3.3	10.2	2.2	9.1	19.0	0.33	0.21	47
		12.4	3.2	10.6	1.9	6.9	17.4	0.25	0.21	57
		16.5	3.1	10.2	1.9	6.3	16.0	0.23	0.21	66
		20.6	3.1	10.2	2.0	8.3	19.2	0.27	0.22	62
		24.7	3.0	10.1	1.9	8.2	19.6	0.27	0.22	54
		27.3	4.0	0.0	37.7	2.0	233	0.43	1.20	228

Table 3. Water temperature (WT) (°C) and dissolved oxygen (DO) (mg l^{-1}) in Lake Hibara on the first sampling dates in 1992, 1993, 1995, 1996, and 1998

Depth (m)	17 April 1992		27 April 1993		27 April 1995		8 May 1996		23 April 1998	
	WT	DO	WT	DO	WT	DO	WT	DO	WT	DO
0	4.2	9.50	4.5	9.53	6.3	10.5	6.2	10.1	9.4	10.5
4	4.1	9.26	4.5	9.61	6.2	10.6	6.0	9.89	7.8	11.1
8	4.0	9.37	4.3	9.71	5.5	10.6	5.9	10.0	6.0	10.6
12	3.9	9.62	4.2	9.66	5.2	10.4	5.9	9.91	5.2	10.1
16	3.9	9.30	4.1	9.16	5.0	10.4	5.9	9.97	4.5	9.92
20	3.9	9.56	3.8	8.46	5.0	10.4	5.5	9.81	4.3	9.78
24	3.9	9.56	3.8	7.83	4.9	10.3	5.0	9.55	4.2	9.43
28–29	3.9	9.15	4.1	3.75	4.8	10.1	4.9	9.44	4.2	9.34

Satoh et al. 1996). The temperature in the water columns of both dates was below 4°C (Table 2 for 1994, Table 2 and Fig. 2 for 1997), indicating that the lake water had not yet been mixed from the surface to the bottom, and suggesting that winter conditions were well preserved.

On the other hand, the total water columns were well oxygenated on the first sampling dates in 1992, 1995, 1996, and 1998. The concentrations of dissolved oxygen even in the lowermost strata ranged from 9.15 to 10.1 mg l^{-1} for these years (Table 3). The vertical profiles of water temperature on these dates show slight thermal stratification (Table 3), indicating that the lake water had been mixed prior to collection of the water samples. The concentration of dissolved oxygen in the sample from the deepest layer (3.75 mg l^{-1}) in 1993 was significantly lower than those of the overlying layers. The concentrations in the second (7.83 mg l^{-1}) and third (8.46 mg l^{-1}) deepest layers were moderately lower than those in the overlying layers. Water temperature showed a slight stratification at that time (Table 3). Before the depths were well aerated, stratification seemed to have already started in this case. Whether or not winter anoxia developed in these years is unknown. Even if winter anoxic layers developed, spring water circulation would supply oxygen to the depths, resulting in more or less oxygenated water columns like those in Table 3. However, the present results show that a hypolimnetic anoxic layer could sometimes develop in winter.

We tried to track dissolved oxygen under the ice-covered water column. Two automatic dissolved oxygen meters (Sea-Bird Electronics, Model SBE 16 DO) were set 50 cm and 2 m above the lake bottom at the station in early December 1997. However, the records show that they drifted towards a shallower part (18 m) of the lake in early January 1998. Anoxic water was not recorded there.

Hypolimnetic dissolved oxygen decreases severely in summer. Summer minima of dissolved oxygen ranging from 0.01 to 0.73 mg l^{-1} were recorded at the lowermost strata just before the complete autumnal circulation (Table 4). The concentrations of dissolved oxygen were almost zero in 1992 and 1998. However, a more or less titratable amount of dissolved oxygen still remained at the final stages of sum-

Table 4. Minimum concentrations of dissolved oxygen (DO) at the final stages of summer stratification from 1992 to 1998 in Lake Hibara

Date	DO (mg l^{-1})	Depth above bottom (m)
20 Nov 1992	0.02 ± 0.02	0.8
9 Nov 1993	0.08 ± 0.01	0.9
8 Nov 1994	0.13 ± 0.01	0.2
1 Nov 1995	0.09 ± 0.00	0.4
31 Oct 1996	0.73 ± 0.06	0.7
22 Oct 1997	0.08[a]	0.3
5 Nov 1998	0.01 ± 0.02	0.8

[a] One replicate analysis

mer stratification. The duration of the summer stratification period is more than 5 months, from mid-May to October, and the hypolimnetic water temperature during this period is about 8–10°C (Fig. 2 and Satoh et al. 1993). On the other hand, the duration of the ice cover is 2–3 months from January or February to March or April, and the water temperature is less than 4°C. It is worthy of note that the shorter duration and lower water temperature of the winter stratification are much more unfavorable for microbial oxygen consumption than the condition during the summer. In spite of these unfavorable conditions, dissolved oxygen in the depths of Lake Hibara is sometimes completely exhausted in winter, but not in summer.

The phenomena reported here are not easy to understand. However, it can be pointed out that the ventilation to the depths is much greater in summer than in winter. The density barrier of the metalimnion in summer will prevent efficient water mixing, resulting in a limited supply of oxygen from the overlying strata to the hypolimnion. However, the limitation of the oxygen supply to the depths of the lake would be much more complete in winter than in summer, for the following reasons. First, the ice cover of the lake in the winter would prevent the water of the whole lake from supplying atmospheric oxygen. Second, the ice cover would also prevent wind-caused vertical water mixing, resulting in more complete isolation of the depths from the overlying strata. Both conditions would greatly limit ventilation to the depths of the lake in winter.

Inflowing water would affect the oxygen in the depths of the lake in both summer and winter. However, the influence of this dissolved oxygen source is not yet clear.

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