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STUDY ON THE ANALYSIS OF THE CONTROLLING FACTORS OF HYPOXIA IN THE BOTTOM OF LAKE BIWA, JAPAN

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ABSTRACT: Lake Biwa in Japan is a water resource utilized by approximately 14 million people in Kansai region, and its water pollution has a significant impact not only on people but also on the ecosystem, particularly in the bottom layer, where hypoxia can cause an environmental problem. Until the 1980s, eutrophication was the main cause of hypoxia of the lake bottom, and after the measures for eutrophication, it is not clear what the main cause quantitatively is such as climate change and a regime shift in the ecosystem. In the present study, seasonal and secular variations of water quality in Lake Biwa over the past 30 years were analyzed by using vertical profile data of water temperature and dissolved oxygen concentration observed at Imazu-oki, the deepest point of observation and weather data at Hikone. The results of the analysis showed that intensity of stratification increased in the surface layer of Lake Biwa, but conversely stratification weakened in the deeper layers. These changes in the physical environment of the lake have affected the decline of dissolved oxygen in the lake bottom of Lake Biwa. The seasonal changes in dissolved oxygen over 30 years could be classified into approximately three patterns, with the dominant factors being the strengthening of stratification due to the change in air temperature and wind speed, the shortening of the period of the overturning and the vertical mixing by wind during the stratified season and cooling period.

Keywords: Dissolved Oxygen, Climate change, Overturning, Lake Biwa

1. INTRODUCTION

Water contains a variety of substances, including organic matter, minerals, and microorganisms, and physical, biological, and chemical reactions constantly occur. In rivers, there is a time span between the time the water originates at the source and the time it flows out to the sea, but that time span is only a few days. Therefore, as the water quality in the river changes, these physical, biological, and chemical reactions in rivers brought about less significant problems than in lakes and marshes. However, in lakes, once the water flows into the lake, water stays in the closed water body for a long period of time. During the residence process, physical, biological, and chemical reactions such as heat exchange with the atmosphere and elution of nutrients from the bottom sediment proceed, and hypoxia, eutrophication, and other visible changes in water quality eventually occur [1].

Lake Biwa is the largest freshwater lake in Japan. The lake has an area of approximately 674 km^2 (616 km^2 in the north and 58 km^2 in the south), a maximum depth of 103.6 m, a length of approximately 63.5 km from north to south, a maximum width of 22.8 km and a minimum width of 1.35 km (Figure 1). Lake Biwa is divided into northern part and southern part of the lake based on its shape, with an average depth of 43 m in northern part and 4 m in southern part. The total volume of Lake Biwa is approximately 27.5 billion m^3. The annual water inflow is about 5 billion m^3, and the average residence time is 5.5 years in North Lake and approximately 15 days in South Lake.

Hypoxia in the bottom layer of the northern part of Lake Biwa became pronounced around the 1960s, and it has been pointed out that the cause of the hypoxia in Lake Biwa is an increase in organic matter in the surface water layer due to eutrophication and sedimentation into the deep layer. There is concern that hypoxia of the bottom layer may affect the habitat of the ecosystem living in the bottom layer, leading to water pollution in Lake Biwa. The concentration of dissolved oxygen of 2 mg/l or less in the bottom layer (90 m) in Imazu-oki has been observed in some years since 1980. The concentration of 2 mg/l has significance as a value at which the basic metabolism of organisms declines. For example, in Lake Ikeda, the overturning (whole-layer circulation) did not occur every year, but partial circulation prevailed, and dissolved oxygen in the deep layer continued to decrease, becoming nearly hypoxic in recent years [2]. Hypoxia has been observed in temperate lakes around the world. The supply of concentration of dissolved oxygen in oceans and lakes aids to regulate biodiversity, nutrient biochemistry, greenhouse gas emissions, and water quality of drinking [3].

In the case of Lake Biwa, it is necessary to pay attention to future trends. However, even after the 1980s, when organic substances and nutrient loads from the land area were regulated, the dissolved oxygen concentration in the bottom layer of Lake Biwa remained below 2 mg/L. This is attributed to climate change around Lake Biwa in recent years ([4, 5]). Woolway [6] stated that changes in stratification due to climate change have a significant impact on the hypoxia of the bottom layer in lakes worldwide. In particular, they reported that the increase in air temperature and decrease in wind speed may weaken vertical mixing of lake water and cause a decrease in dissolved oxygen concentration.

The effect of wind speed, precipitation, and inflows on stratification in relation to warm and cold weather was significant especially when observed climate patterns were expected to have effects on thermal characteristics [7]. For example, the global warming has reduced snowfall mainly in the northern basin of Lake Biwa, and that the amount of snowmelt water, which is colder and richer in oxygen than lake water during the snowmelt season, may be flowing into the bottom layer along the lake bottom. However, no such phenomenon of snowmelt water flowing along the lake bottom was observed, and studies of the relationship between the size of snowmelt runoff and the minimum annual dissolved oxygen level showed no effect. Vertical mixing by wind causes various phenomena such as blowdown flow and destruction of stratification by vertical mixing when wind blows. Wind speed acts on the stratification of the lake, sometimes to a greater extent than changes in air temperature ([8-10]). In addition, wind causes internal waves, and the breaking of these waves results in active mixing of the lake water. Wind-driven wind, vertical mixing, and internal waves have been observed by continuously monitoring the vertical distribution of water temperature using a mooring system [11]. Internal waves have also been observed using modal analysis and numerical simulations in several lakes, including Lake Tahoe [12-14]. Vertical mixing is caused by the passage of such waves (internal surge) in Lake Biwa during summer. However, the seasonal and secular changes in dissolved oxygen at all depths due to climate change have not yet been fully investigated. In this study, water environmental changes in Lake Biwa were investigated from the physical aspect using data from a monitoring point in the northern part of Lake Biwa.

2. RESEARCH SIGNIFICANCE

Analysis of this study clarified the effects of climate change on the water stratification in Lake Biwa, and will lead to an assessment of the habitat of organisms on the lake bottom, since the relationship between the intensity of stratification and dissolved oxygen concentration in Lake Biwa is closely related. It can also contribute to the conservation of water environment due to future climate change in Lake Biwa and improvement of water quality by proper installation of aeration and cavitation devices.

3. DATA ANALYSIS

The analysis used data on water temperature and dissolved oxygen concentration obtained from periodic surveys (once or twice a month) conducted by Lake Biwa Environmental Research Institute in Shiga Prefecture at the monitoring point of Imazu-oki (Fig. 1) (water depth: approximately 90 m). This periodic survey has been conducted since 1979. This monitoring point is the deepest point among the fixed points of the periodic surveys conducted on a multidecadal scale. The water depths are 0.5 m, 5 m, 10 m, 15 m, 20 m, 30 m, 40 m, 60 m, 80 m, and 1 m just above the lake bottom (approximately 90 m). (Water temperature, dissolved oxygen concentration, and water depth were measured in the field using a HYDOROLAB water quality sensor (Quanta). Air temperature, wind speed, wind direction, and precipitation were observed at Hikone District Meteorological Observatory (every 3 hours (only precipitation is a daily average)). The height from the ground of the thermometer, which observed air temperature, is 1.5 m. The height from the ground of the anemometer, which observed wind speed and direction, is 17 m. The minimum unit of water and air temperature, wind speed and precipitation are 0.1°C, 0.1 m/s and 0.1 mm respectively. The wind direction was observed in 16 directions. The stratification strength is estimated by the difference in water temperature from the surface layer (5 m) to the bottom layer (90 m). The surface layer is not at a depth of 0.5 m, where water temperature is likely to change due to wind mixing, but at a depth of 5 m below the surface layer, while the bottom layer is at a depth of 90 m. SSI (Schmidt stability index (kgm/m^2) was estimated in order to calculate the strength of stratification as follows.

$$SSI = \frac{1}{A_0}\int_{z_0}^{z_m} A_z(z - z_g)(\rho_z - \rho_g)dz \tag{1}$$

$$z_g = \frac{1}{\int_{z_0}^{z_m} A_z\rho_z dz}\int_{z_0}^{z_m} A_z\rho_z z dz \tag{2}$$

$$VMI = \frac{WSI}{SSI} \tag{3}$$

$$WSI = \kappa \times |\tau| \tag{4}$$

$$\tau = \rho_a C_D \lfloor U_a \rfloor U_a \tag{5}$$

where A_0 is surface area of lake (m^2), z is depth (m), z_m is maximum depth (m), z_0 is water surface depth (m), A_z is area at depth z (m^2), ρ_z is density at depth z (kg/m^3), ρ_g is density at depth z_g (kg/m^3), V is lake volume (m^3), and z_g is depth to the center of gravity of stratified lake (m). In this study, the density was calculated as a function of only water temperature.

Vertical mixing index (VMI) indicates the parameter of expressing the proportion of the wind stress on the stratification. κ is the constant of 1.0. Wind stress index was calculated in order to evaluate the influence of the strong wind on the stratification. τ is the wind stress, ρ_a is the air density above the lake surface (1.2255 kg/m^3), U_a indicates the atmospheric wind speed at a height of 17 m above the lake surface, C_d represents the drag coefficient of lake surface, which performs the momentum transfer efficiency between atmosphere and lake, and is dependent on wind speed, currents, waves, lake surface roughness, and stability amongst other factors.

Frequency analysis was used to determine whether a particular period of wind prevailed.

4. RESULTS AND DISCUSSIONS

4.1 Classification of Three Patterns of DO over the past 30 years

Seasonal changes in dissolved oxygen (DO) in the bottom layer (90 m depth) in the monitoring point of Imazu-oki over the past 30 years could be approximately classified into three patterns. Fig. 2 shows the averaged seasonal changes in DO for each pattern. Firstly, in A-pattern, DO began to decrease with the onset of stratification, reached a minimum around October, and then recovered somewhat before the overturning occurred. In this case, the minimum DO was often around 2 mg/l. On the other hand, in B-pattern, DO gradually decreased and maintained a value higher than the minimum DO in A-pattern before the overturning. In C-pattern, the decrease in DO continued until around December, but the minimum DO was 2-4 mg/l at most. The rate of decrease in DO was greatest in A-pattern, and decreased in the order of C-pattern and B-pattern.

The frequency of occurrence of the three patterns is shown in Table 1 for 30 years of DO data (A-pattern 11 times, B-pattern 11 times, and C-pattern 8 times). A-pattern was most frequently observed in the late 1980s and 2000s, with only two cases in the 1990s (1996 and 1999). B-pattern was more common in the 1990s, while C-pattern was more frequently observed after 1990s.

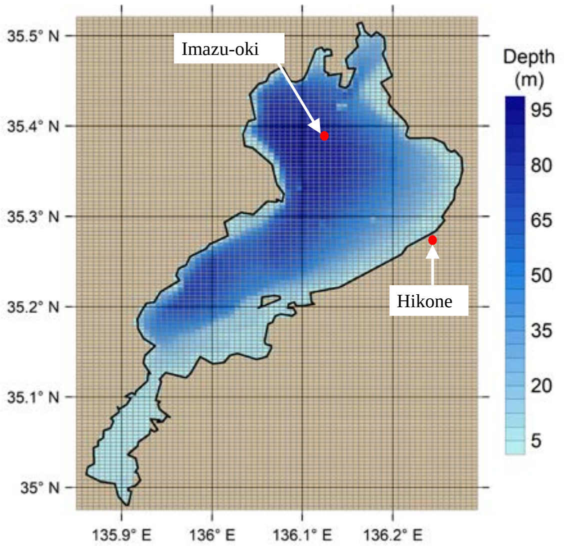


Fig.1 Monitoring point for each data in Lake Biwa

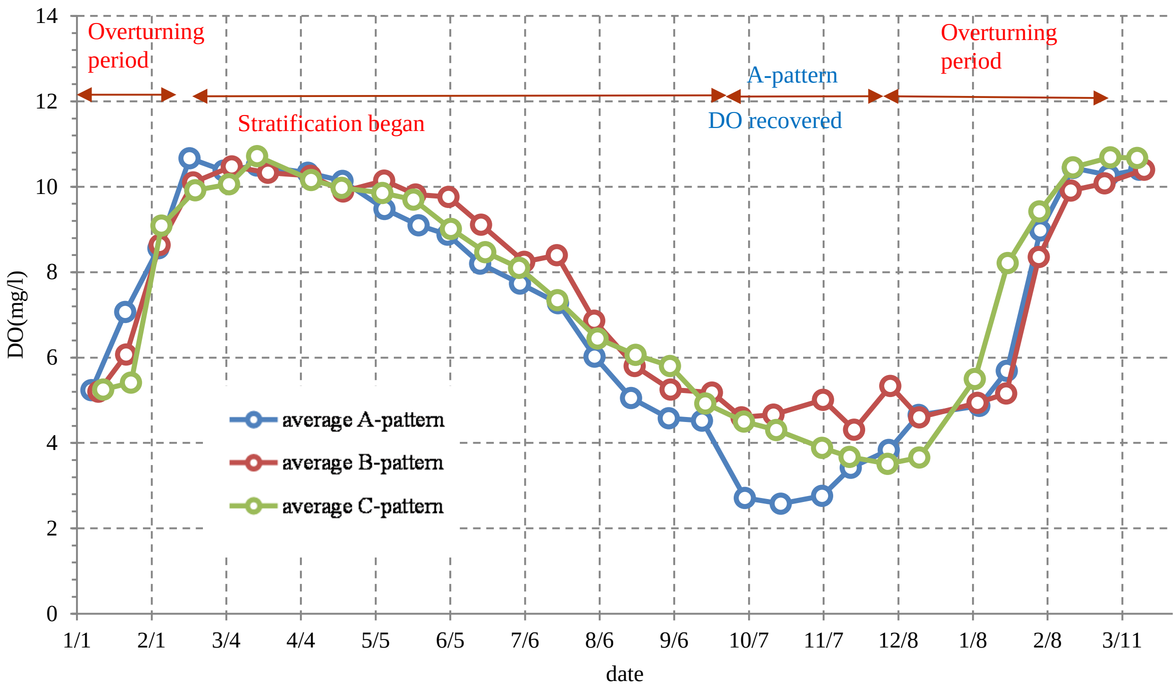
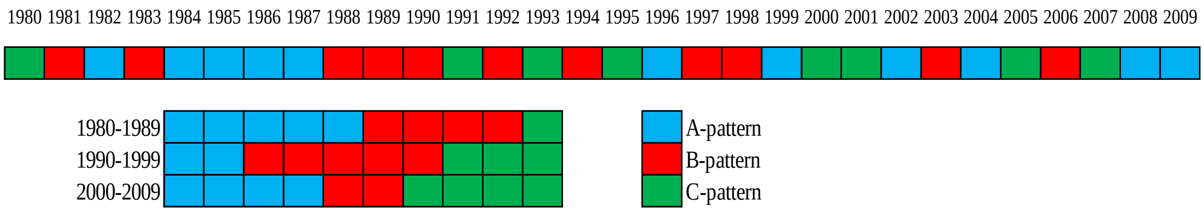


Fig.2 Average of seasonal change of DO over 30 years from 1980 to 2009

Table 1 Three types of classification based on the shape of seasonal changes in DO concentration over 30 years (A-pattern 11 times, B-pattern 11 times,C-pattern 8 times)



4.2 Factors of the Seasonal Change of DO over the past 30 years

Fig. 3 shows the secular change of SSI from 1980 to 2009. SSI indicates the Index of strength of stratification. SSI of average of A-pattern was 197.93 and 7 higher than that of B and C-pattern. The strength of stratification in A-pattern was higher than that of B and C-pattern. The decreasing rate of DO was influenced by the strength of stratification.

Fig. 4 shows the secular change of VMI from 1980 to 2009. VMI stands for the Index of strength of vertical mixing. VMI of A-pattern was 6.98×10^{-5} and 4.42×10^{-6} lower than B-pattern, and 5.67×10^{-6} lower than C-pattern. Considering the effect of the wind stress, the correlation coefficient between VMI and decreasing rate of DO was 0.54, therefore the contribution of the wind stress to the vertical mixing plays an important role in the change of DO. As for A-pattern, the vertical mixing due to the wind stress less occurred compared with B, C-pattern. DO tended to decrease during the period of stratification due to the consumption of DO by bacteria under the thermocline.

Fig.5 demonstrates the secular change of power spectrum of wind speed from April to December over 30 years. The power spectrum shows a relatively weak trend in the 1980s and 2000s and a strong trend in the 1990s. This trend was consistent with the fact that B and C-patterns were more frequent in the 1990s and A-pattern were more frequent in the 1980s and 2000s. Seasonal change of DO in 1990, 1992, 1994, and 1998 were classified as B-patterns, in those years, 24-hour period power spectra of wind speed were large. Seasonal change of DO in 1987 and 2008 were classified as A-pattern, and 1980, 1991, 1993, 2000, and 2005 as C-pattern, and their power spectra were relatively small. The periodic strong wind speed influenced seasonal change of DO over 30 years.

Fig. 6 indicates the secular change of precipitation from the starting day of overturning to the day of minimum DO for 30 years. From the perspective of the amount of precipitation, the correlation between precipitation and decreasing rate of DO was rather low.

Fig.7 shows the secular change of period of overturning from 1980 to 2009. The correlation coefficient of the period of overturning and decreasing rate of DO was 0.54, hence as the period of overturning decreased, the decreasing rate of DO increased. A-pattern with the highest DO decreasing rate and the lowest DO minimum had the shortest period of overturning, while the B-pattern with the lowest DO decreasing rate and the highest DO minimum had the longest period of overturning. The vertical mixing in winter occurred efficiently, DO in lake was enough in all layers, and hypoxia in the bottom of the layer less likely happened as in the case of B-pattern.

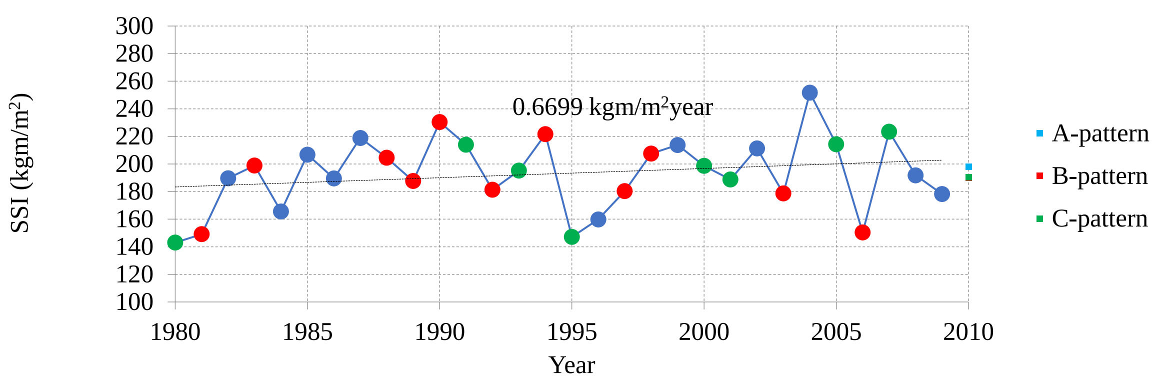


Fig. 3 Secular change of average SSI from the starting day of overturning to the day of minimum DO for 30 years (Annual rate of change 0.6699 $kgm/m^2\cdot year$)

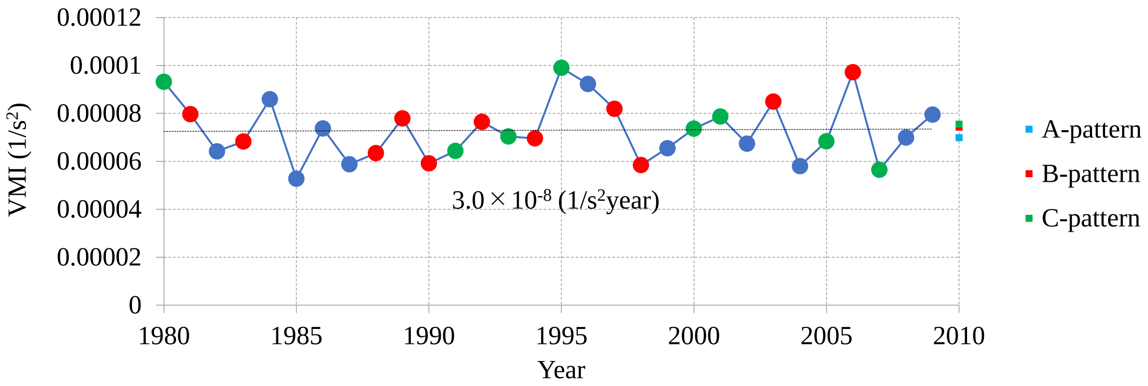


Fig. 4 Secular change of VMI from the starting day of overturning to the day of minimum DO for 30 years (Annual rate of change 3.0×10^{-8} $1/s^2 \cdot year$)

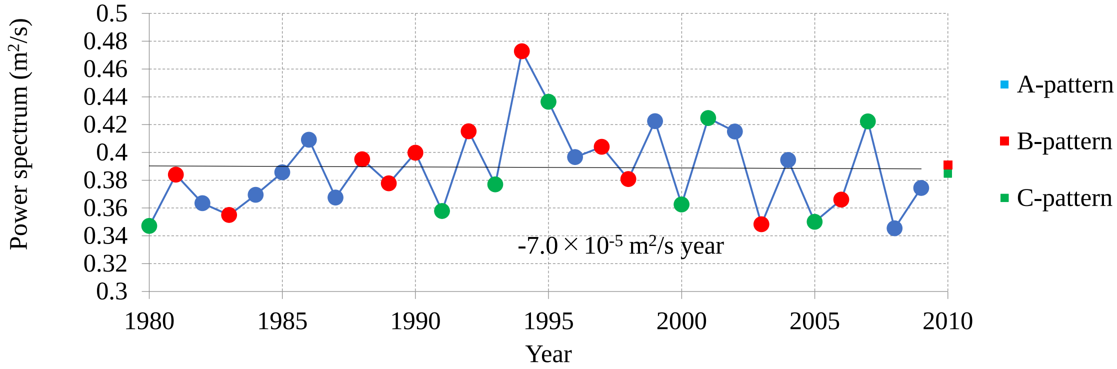


Fig.5 Secular change of power spectrum of wind speed from April to December over 30 years (Annual rate of change -7.0×10^{-5} $m^2/s \cdot year$)

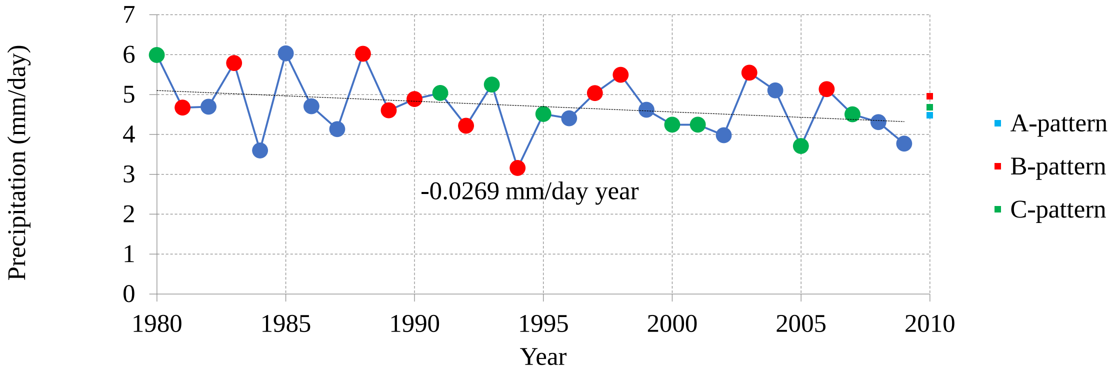


Fig.6 Secular change of precipitation from the starting day of overturning to the day of minimum DO for 30 years (Annual rate of change -0.0269 mm/day·year)

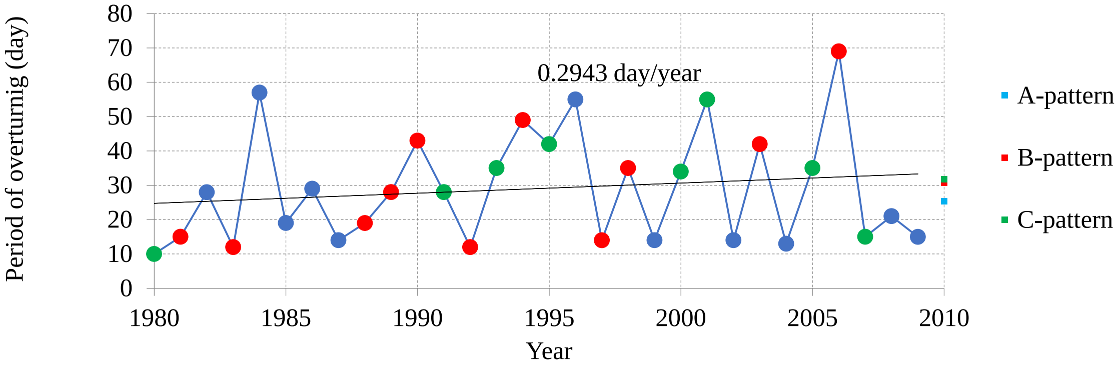


Fig. 7 Secular change of period of overturning from 1980 to 2009 (Annual rate of change 0.2943 day/year)

4.3 Recovery of DO in the Case of A-Pattern

As for the case of A and C-pattern, DO decreased more than B-pattern. Only in the case of A-pattern, DO recovered slightly right before the overturning period. Fig. 8 shows the relationship between recovery of DO and VMI in A-pattern. The correlation coefficient of VMI and the amount of average recovery value of DO in A-pattern was 0.41. The amount of recovery value of DO was calculated by the averaging the values from the day of the minimum DO to the day right before the overturning. During the period of recovery in DO, as the stratification weakened and the strong wind blew, the vertical mixing between 80 m layer and 90 m layer more likely occurred. Minimum DO remained greater for B-pattern and C-pattern than for A-pattern. Therefore, the strong wind led to the vertical mixing in the bottom layer, which supplied with the DO from the just above the bottom layer.

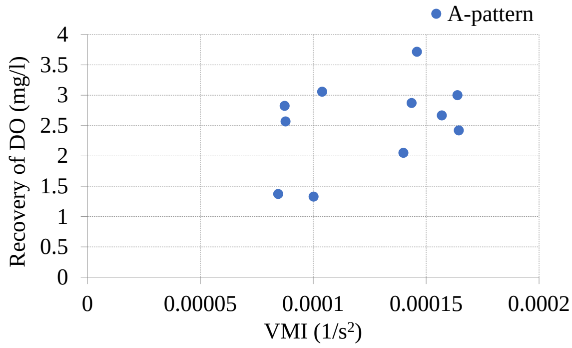


Fig. 8 The relationship between recovery of DO and VMI in A-pattern

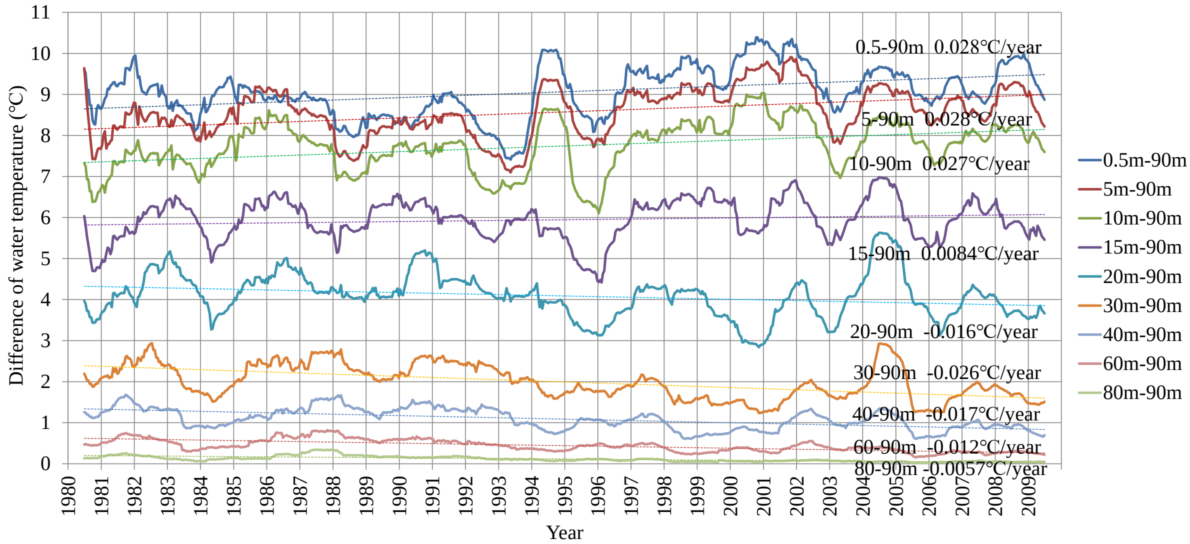


Fig. 9 Secular change of difference of DO between 90 m and each depth from 1980 to 2009

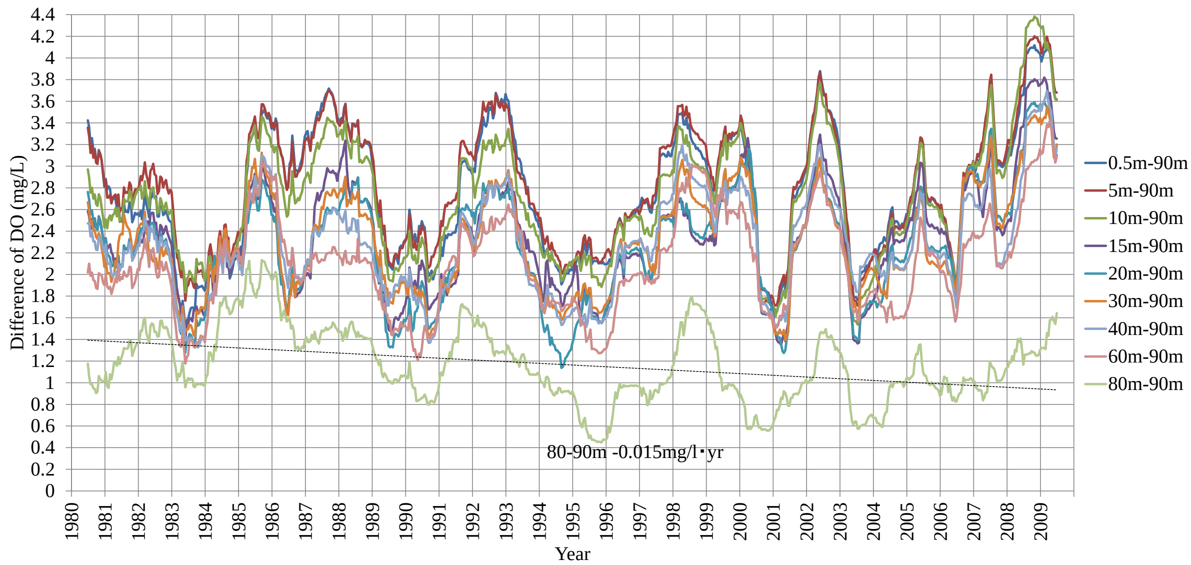


Fig. 10 Secular change of difference of water temperature between 90 m and each depth from 1980 to 2009

4.4 The Trend of Secular Change of DO and Water Temperature

Fig. 9 and 10 shows the secular change of difference of DO and water temperature between 90m and each depth from 1980 to 2009. Difference in DO and water temperature between 90m and each depth was determined by annual moving average. Difference in DO between the bottom layer and each layer (from the surface layer (0.5 m) to the deep layer (20-60 m)) became larger as time passed.

Difference in DO between 90 m and 80 m layer became less from 1980 to 2009, which means that the bottom layer from 80 m to 90 m became the homogeneous layer, taking into account that the difference of water temperature between 90 m and 80 m was not so large (From Fig.10). The increase of water temperature in the surface layer was closely related to the increase in air temperature during the stratification period. The air temperature at Hikone increased by about 1.3°C as a linear trend over the past 30 years. On the other hand, it was reported that water temperature at the lake bottom was highly correlated with the air temperature in winter when the overturning (whole-layer circulation) occurred.

The difference in the trend of the increase in water temperature by depth showed an interesting feature in the temporal variation of the difference between the water temperature in each layer and that at the bottom of the lake. The difference between the water temperature at the surface and that at the bottom of the lake increased with depth from the surface to 15 m, while the difference decreased at depths deeper than 20 m. This means that the stratification was enhanced in the entire lake, while the stratification was weakened at depths deeper than the thermocline in summer (this is irrelevant in winter, when the water temperature was uniform).

The trend of water temperature uniformity in the stratified layer is considered to be related to the increase in wind intensity. The annual mean wind speed at Hikone showed an increasing trend with time, increasing by 0.29 m/s over 30 years (10%) as a linear trend. It is possible that the mixing of the deep layer associated with enhanced winds caused the uniformity of water temperature. Another possibility is that the vertical mixing at the beginning of stratification has been enhanced in recent years. In other words, it is reasonable to assume that the conditions below the thermocline were not due to stratification period but were due to non-(weakly) stratified conditions (overturning period).

5. CONCLUSIONS

Seasonal and secular changes of water quality in Lake Biwa over the past 30 years were examined using data of water temperature and dissolved oxygen concentration observed at Imazu-oki and data of air temperature, wind speed, and precipitation from Hikone.

DO increased with time, except at depths of 80 and 90 m for 30 years. The increase in DO was inversely correlated with the increase in water temperature. The reason for the increase in DO in contrast to the increase in water temperature from 0.5 m to 15 m was unknown, but the increase in phytoplankton near the surface could have an effect.

The decreasing rate in DO at 80 m depth was larger than that at 90 m depth. Therefore, in the bottom layer the DO concentration tended to decrease over 30 years.

Seasonal changes in DO at the lake bottom varied from year to year but could be roughly classified into three patterns.

A-pattern showed an earlier decrease in DO during the period of stratification than B and C-patterns, and a further decrease than the minimum of the B and C-patterns. In B-pattern, the decrease in DO during the stratification period was slower and the minimum value remained higher than in A-pattern, and then recovered during the overturning period. In C-pattern, DO decreased more slowly than in A-pattern and recovered earlier than in B-pattern. The minimum DO was higher than in A-pattern and DO rarely recovered before the overturning.

VMI (the average of the period from the start of the overturning to the lowest DO date) showed a corresponding relationship with the three patterns. Stratification strength is stronger in the order of A, C, B. The strength of stratification mainly depends on the wind stress and air temperature.

The period of overturning was also related to the three patterns. In most cases, the short period of overturning corresponded to A-pattern, while the long period of overturning corresponded to B and C-pattern. For example, the A-pattern had a longer stratification period than the B-pattern. The overturning of A-pattern was shorter than those of B and C-pattern, while those of B-pattern tended to be longer.

Another factor controlling the pattern of seasonal changes in DO was the strong wind in the period of strong and weak stratification, and the secular variation of wind velocity over a 24-hour cycle. As for the recovery of DO in A-pattern in autumn, the strong wind such as typhoon played an important role in the vertical mixing in the bottom layer (80 m and 90 m) according to the calculation of VMI.

On the other hand, the most prominent wind system in Lake Biwa during the period of stratification is the lake breeze, which is the most dominant wind system during this period. The secular variation of the power spectrum of wind speed showed a relatively weak trend in the 1980s and 2000s and a strong trend in the 1990s.

This trend was consistent with the fact that B and C-pattern were more frequent in the 1990s, and A-pattern were more frequent in the 1980s and 2000s. In other words, the vertical mixing was relatively strong in the 1990s, when winds of this period were strong, and B-patterns were more likely to appear, while mixing was weaker in the 1980s and 2000s, when A and C-patterns were more likely to appear. the secular change of the 24-hour cycle of the lake breeze appeared to be consistent with DO pattern.

In this study, water environmental changes in Lake Biwa were investigated from the physical aspect using data from a monitoring point in the northern part of Lake Biwa. In order to examine changes of water quality in Lake Biwa as a whole in more detail, it will be necessary to study them in combination with model experiments as we developed. In addition, changes in DO could be examined from a biochemical point of view, and a complex study that includes the physical environment is a major issue for the future.

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