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EFFECTS OF STRONG WINDS ON THE BOTTOM LAYER DURING THE WEAK STRATIFICATION PERIOD IN LAKE BIWA, JAPAN

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ABSTRACT: In recent years, a decrease in dissolved oxygen in the lake bottom has been observed in the northern part of Lake Biwa, the largest freshwater lake in Japan. The main physical controlling factor is considered to be changes in stratification, which are influenced by weather and climatic conditions. As atmospheric temperature increases, lake surface temperature rises, and stratification is formed. The strength of stratification has a significant impact on the transport of various material cycles, such as dissolved oxygen and nutrients, from the lake surface to the bottom layer. Therefore, in this study, the analysis of the effect of strong winds during the stratification collapse period (autumn) on the stratification structure of Lake Biwa was performed. Baseline simulations using actual meteorological data and experimental simulations using meteorological data with modified wind speed and direction were conducted. The numerical experiments showed that collapse of stratification was more likely to occur in autumn than in summer, and vertical mixing was enhanced. When strong winds blew more in one direction, vertical mixing was further enhanced when the duration of strong winds was longer during periods of weak stratification, as well as the results during the stratification period. When winds of the same magnitude as during the stratification period blew during periods of decreasing water temperature, a decrease in bottom water temperature was observed prior to the full-layer circulation in the following year. This suggested that strong winds during the decreasing temperature period had a strong influence on the water temperature environment next year.

Keywords: Strong Wind, Decreasing air temperature period, Vertical Mixing, Hydrodynamic Model, Lake Biwa

1. INTRODUCTION

In the northern part of Lake Biwa, the surface water temperature rises to approximately 27°C in summer, while the water temperature in the bottom layer of the lake is approximately 7°C. Because of the vertical difference in water temperature, the stratification is formed. The stratification prevents oxygen supply from the lake surface, and oxygen is consumed by decomposition of dead plankton in the layer below the thermocline. However, as the lake surface cools during the autumn and winter, the stratification weakens and disappears. Vertical mixing then takes place in all layers, and water temperatures in the upper and lower layers become the same. When oxygen-rich water masses are supplied to the bottom layer, the dissolved oxygen concentration near the lake bottom recovers to saturation.

In recent years, the increase in lake surface temperatures of 0.01-0.1°C/year has been observed due to rising air temperatures caused by global warming ([1-3]). Climate changes such as frequent tropical cyclones with heavy rainfall and gusty winds have also been observed ([4-8]). Storms, in particular, change in frequency and intensity of wind speed ([9,10]) and precipitation ([11,12]). These changes in meteorological conditions are considered to significantly affect dissolved oxygen concentrations in closed water bodies such as lakes ([13-15]). Rising lake surface temperatures strengthen the stratification by increasing the temperature difference with the bottom layer, which weakens vertical mixing and contributes to lower dissolved oxygen concentrations. On the other hand, when strong winds blow, the wind pressure on the surface layer causes significant mixing, weakening the stratification and contributing to the recovery of dissolved oxygen concentration. When the wind blows strongly in one direction, wind-driven flow occurs in the surface layer and the water in the lower layers moves in the opposite direction. Depending on the direction of the wind toward the coast, upward or downward water flow occurs. In the thermocline, this movement causes the stratification layer to oscillate, which causes internal waves in stratified lakes. Observations of wind-induced flow and internal waves were made by continuously measuring vertical water temperature and velocity using thermistor chains and acoustic anemometers ([16,17]). These observations confirmed that the flow and internal waves were caused by wind. Wind is a major source of momentum and energy and affects the general circulation of lakes at various scales. However, how strong winds affect the deeper layers of lakes and marshes has not yet been elucidated.

The effect of strong winds on dissolved oxygen concentration in the bottom layer of Lake Biwa in summer was investigated by Koue et al. [18]. The destruction to the structure of stratification by continuous strong winds caused differences in vertical mixing due to the inclination angle of the lake bottom [19], but the effect of strong winds on the weak stratification of Lake Biwa in autumn and winter was not enough clarified yet. In this study, a three-dimensional hydrodynamic model was used to analyze the effects of strong winds on the weak stratification of Lake Biwa in autumn when air temperatures decrease. Numerical simulations were performed for a baseline case using actual meteorological data and an experimental case using meteorological data with modified wind speed and direction.

2. RESEARCH SIGNIFICANCE

In Lake Biwa, the decrease in dissolved oxygen concentration in the bottom layer due to climate change is a problem. Among the climate changes, the rise in temperature and decrease in average wind speed have a significant effect on the decrease in dissolved oxygen concentration by weakening the vertical mixing that delivers oxygen-rich water masses to the bottom of the lake. Since the effect of strong winds on the hypoxia of the bottom layer of Lake Biwa is important, this study can contribute to the prediction and improvement of the aquatic environment of Lake Biwa.

3. FLOW FIELD MODEL IN LAKE BIWA

3.1 Calculation domain

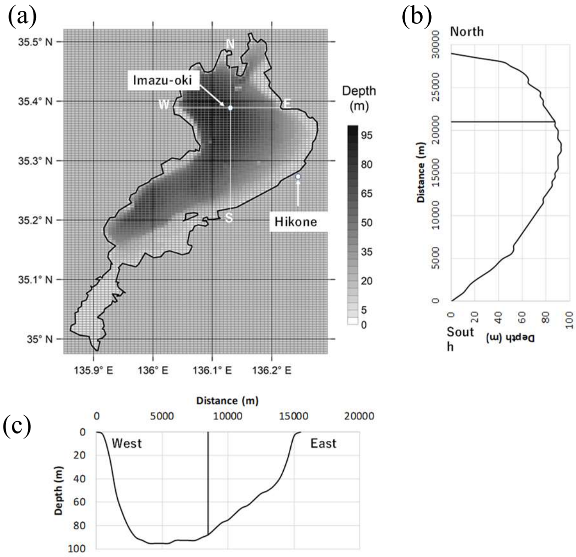


Fig. 1 Calculation domain with topography of Lake Biwa: (a) horizontal domain, (b) south-north and (c) west-east vertical cross sections through Imazu-oki.

The horizontal computational domain of the flow field model is 36 km x 65.5 km, including the entire Lake Biwa area, with a horizontal grid of 500 m x 500 m and a grid size of 72 x 131 cells. The grid width in the vertical direction is set at intervals of 0.5 m from the water surface to a depth of 20 m. The grid width is increased to intervals of 0.1 m for depths greater than 20 m, with a maximum grid width of 2.5 m. This is to represent the temperature dynamic layer in detail in summer. The maximum grid width is set to 2.5 m. This is to represent the temperature dynamic layer in summer in detail, and the number of the grid is 86. The x- and y-axes of the coordinate system are set at the origin at the southwest end of the area on the horizontal plane, and the z-axis is set vertically upward from the bottom of the lake.

3.2 Governing Equations

The basic equations of the flow field model assume the Boussinesq approximation and the hydrostatic approximation in the vertical direction and consist of the equation of motion of the fluid, the equation of continuity, and the advection-diffusion equation for the water temperature [23]. The governing equations are described in the Cartesian coordinate system as follows.

Momentum equations (*x*, *y* direction) are written by

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv=-\frac{1\partial p}{\rho_0\partial x}+\nu_h\frac{\partial^2 u}{\partial x^2}+\nu_h\frac{\partial^2 u}{\partial y^2}+\nu_z\frac{\partial^2 u}{\partial z^2}-\frac{g}{\rho_0}\int_z^0\frac{\partial\rho}{\partial x}dz \quad (1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu=-\frac{1\partial p}{\rho_0\partial x}+\nu_h\frac{\partial^2 v}{\partial x^2}+\nu_h\frac{\partial^2 v}{\partial y^2}+\nu_z\frac{\partial^2 v}{\partial z^2}-\frac{g}{\rho_0}\int_z^0\frac{\partial\rho}{\partial y}dz \quad (2)$$

Hydrostatic equation is given by

$$0=-\frac{1\partial p}{\rho_0\partial z}-\frac{\rho}{\rho_0}g \quad (3)$$

Continuity Equation is written by

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

Conservation equation for temperature is written by

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\kappa_h\frac{\partial^2 T}{\partial x^2}+\kappa_h\frac{\partial^2 T}{\partial y^2}+\kappa_z\frac{\partial^2 T}{\partial z^2} \quad (5)$$

where $\boldsymbol{u}$, $\boldsymbol{v}$, and $\boldsymbol{w}$ are the $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$ components of current velocity (m s^{-1}) , $\boldsymbol{T}$ is the water temperature (K), $\boldsymbol{p}$ is the pressure (N m^{-2}),$\boldsymbol{\rho}$ is the density of water (kg m^{-3}), $\boldsymbol{\rho_0}$ is the reference density of water (= 10^3 kg m^{-3}), $\boldsymbol{g}$ is the acceleration due to gravity (= 9.8 m s^{-2}), $\boldsymbol{f}$ is the Coriolis parameter (= 8.34 × 10^{-5} s^{-1} corresponding to 35 ° N), $\boldsymbol{\nu_h}$ is the horizontal eddy viscosity for momentum equations (= 1.0 m^2 s^{-1} [20]), $\boldsymbol{\kappa_h}$ is the horizontal eddy diffusivity (= 1.0 m^2 s^{-1} [20]), $\boldsymbol{\nu_z}$ is the vertical eddy viscosity (m^2 s^{-1}) for momentum equations, $\boldsymbol{\kappa_z}$ is the vertical eddy diffusivity (m^2 s^{-1}).

During the summer, a thermocline forms at depths ranging from 10 to 30 meters. This thermocline prevents the vertical transport of momentum and heat. To account for this effect, the vertical eddy viscosity and diffusivity parameter values are estimated using the Richardson number. The Richardson number is a dimensionless number that expresses the ratio of the buoyancy term to the flow gradient term [21] and is denoted by

$$\boldsymbol{Ri} = -\frac{g}{\rho_0}\frac{\frac{\partial \rho}{\partial z}}{\left(\frac{\partial U_w}{\partial z}\right)^2} \tag{6}$$

where $\boldsymbol{U_w} = \sqrt{\boldsymbol{u^2} + \boldsymbol{v^2}}$ is the horizontal current velocity (m s^{-1}). Vertical eddy viscosity and diffusivity are respectively given by

$$\boldsymbol{\nu_z} = \frac{0.0001}{1.0 + 5.2\boldsymbol{Ri}} \tag{7}$$

and

$$\boldsymbol{\kappa_z} = \frac{0.0001}{(1.0 + \frac{10}{3} \times \boldsymbol{Ri})^{\frac{3}{2}}} \tag{8}$$

3.2.1 Initial conditions

The initial condition was set to 0 m s^{-1} for the current velocity. The initial water temperature on April 1st, 2006 was calculated using linear interpolation of data collected on March 20th and April 10th, 2006. The Lake Biwa Environmental Research Institute conducted the observations twice a month at the Imazu-oki monitoring station (35°23’41” N., 136°07’57” E.), the depth of which was 0.5 m, 5 m, 10 m, 15 m, 20 m, 30 m, 40 m, 60 m, 80 m, and approximately 90 m.

3.2.2 Boundary Conditions

The following formula gives the boundary conditions for the current velocity at the lake's surface, taking wind stress into account.

$$\boldsymbol{\nu_z}\frac{\partial u}{\partial z} = \frac{\tau_x}{\rho_0}$$
$$\boldsymbol{\nu_z}\frac{\partial v}{\partial z} = \frac{\tau_y}{\rho_0} \tag{9}$$

where $\boldsymbol{\tau_x}$ and $\boldsymbol{\tau_y}$ are the surface wind frictional stresses calculated by

$$\boldsymbol{\tau_x} = \boldsymbol{\rho_a C_f} U_{ax} \boldsymbol{U_a}$$
$$\boldsymbol{\tau_y} = \boldsymbol{\rho_a C_f} U_{ay} \boldsymbol{U_a} \tag{10}$$

$$\boldsymbol{C_f} = (\mathbf{1.0} + \mathbf{0.07}\boldsymbol{U_a}) \times \mathbf{10^{-3}} \tag{11}$$

where $\boldsymbol{\rho_a}$ is the density of air (kg m^{-3}), $\boldsymbol{C_f}$ is the wind frictional constant , $\boldsymbol{U_{ax}}$ and $\boldsymbol{U_{ay}}$ are respectively the $\boldsymbol{x}$ and $\boldsymbol{y}$ components of wind velocity (m s^{-1}), $\boldsymbol{U_a}$ is the wind speed from a height of 10 m above the surface (m s^{-1}).

The heat flux through the water surface consists of short-wave solar radiation ($\boldsymbol{S}\downarrow$), latent heat flux (Q_l), sensible heat flux (Q_s) and net long-wave radiation (L_{net}). The heat balance equation on the water surface is given by

$$\rho C_p \boldsymbol{\kappa_z}\frac{\partial T}{\partial z} = S\downarrow + Q_l + Q_s + L_{net} \tag{12}$$

At the bottom and side walls, no-slip condition is imposed. Normal gradients of water temperature are also set to zero to provide thermal insulation.

The Grid Point Value derived from Japan Meteorological Agency's Meso-Scale Model (GPV MSM) was used to calculate air temperature, atmospheric pressure, wind direction and speed, and relative humidity over Lake Biwa. GPV MSM data have a spatial resolution of 0.0625° (longitude) × 0.05° (latitude) (approximately 5 km) and a temporal resolution of an hour. The data were horizontally interpolated into the hydrodynamic model's surface meshes.

Hourly observations at the Hikone local meteorological observatory (35°16'30" N., 136°14'36" E.) were used to calculate solar radiation. The lake's solar radiation was assumed to be horizontally uniform.

The hydrological model calculated the boundary conditions for the water volume and temperature associated with inflow from each river and outflow from the lake [22].

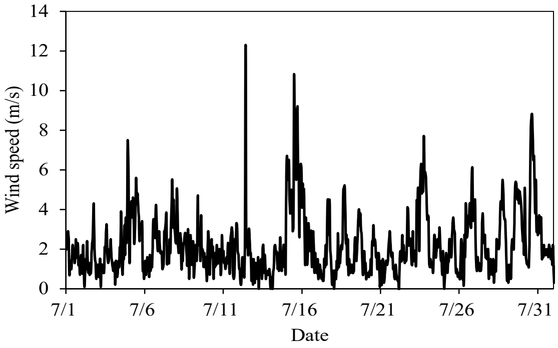
3.3 Simulation Cases

The baseline simulation was conducted using actual meteorological data for a period from April 1st, 2006 to March 31st, 2008 including a spin-up period from April 1st, 2006 to March 31st, 2007. Another simulation was also conducted for the week from October 26th to November 1st, 2007, using meteorological data with the same wind direction and wind speed doubled from July 15th to 21st to investigate the effect of strong winds on stratification changes for the period when temperatures were decreasing. As for the strong stratification period, the date was chosen due to strongly developed stratification, and in addition, strong wind associated with a typhoon and cyclone shown in Fig. 2. As for the air temperature decreasing period, the date was chosen during the weak stratification.

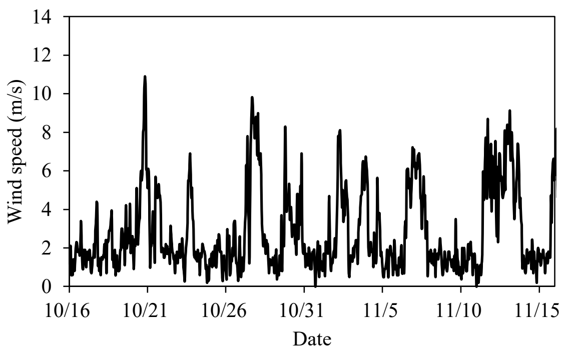
In the numerical experiments, the wind speed was fixed to 10 m/s. The wind direction was fixed to four different directions: northward, southward, eastward and westward. The duration of strong wind ranged from 1 day to 3 days. Another simulation, in which the wind speed was twice as strong as the baseline case and the wind direction was the same as the baseline case, was carried out to analyze the more realistic situation. As shown in Table 1, each case was named for speed, direction, date, and duration of strong wind.

Table 1 Wind conditions in numerical experiments

Case name	Wind speed (m /s)	Wind direction	Strong wind duration (day)
s10dS_date_duration	10	Southerly	0715_1, 1026_1, 0715-0717_3, 1026-1028_3
s10dN_date_duration	10	Northerly	1,3
s10dW_date_duration	10	Westerly	1,3
s10dE_date_duration	10	Easterly	1,3
sX2dO_date_duration	twice (0715-0721)	Original	0715-0721_7
sX2dO_date_duration	twice (0715-0721)	Original	1026-1101_7



(a) Wind speed (from July 1st to August 1st, 2007)



(b) Wind speed (from October 16th to November 16th, 2007)

Fig. 2 Hourly wind speed and direction used in the baseline simulation at Hikone local meteorological observatory from July 1st to July 31st, 2007, and from October 16th to November 16th, 2007.

4. RESULTS AND DISCUSSIONS

As a premise, the simulated water temperature from the surface to the bottom layer agreed well with the observed one according to Koue et al. [23]. In addition, the stratification was also reproduced well in the simulation.

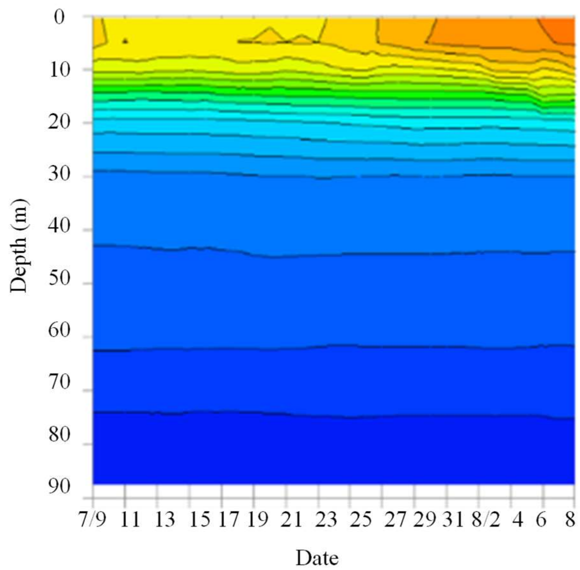
Next, the effect of the strong wind on the bottom water in the lake when the air temperature decreased in autumn was investigated. Fig. 3 shows time series of vertical water distribution in Baseline case and some cases at the monitoring point, Imazu-oki from 9th of July to 8th of August [19] and from October 20th to November 19th. Fig. 4 shows time series of water temperature at a depth of 87.5m in each case.

As for the case of s10dS, N, W, E_0715_1, and s10dS, N, W, E_1026_1, comparing the change of the vertical water temperature, the strong wind could influence the water temperature of the bottom layer in each case right after the wind blew as shown in Fig. 3b, 3d, and Fig. 4a, 4b.

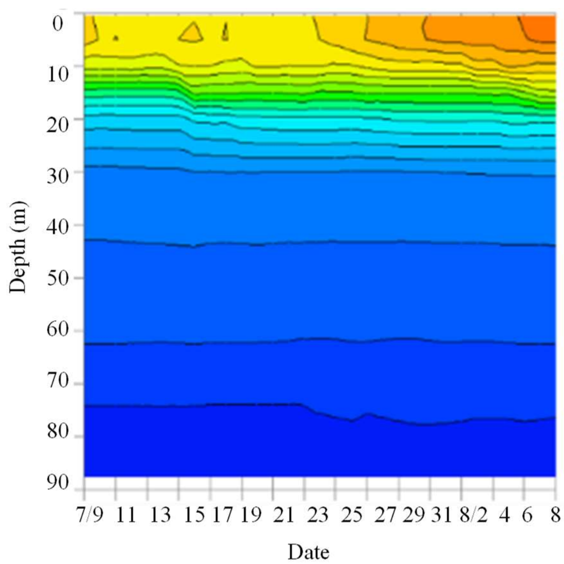
As for the difference between s10dS, N, W, E_0715_1 and s10dS, N, W, E_1026_1, the bottom water temperature after the overturning was higher or lower than that of Baseline case. This is because the vertical mixing occurred after the strong wind blew, and all layers was partially mixed in summer in case of s10dS, N, W, E_0715_1,3, and more mixed in autumn in case of s10dS, N, W, E_1026_1,3. The warm water parcels have more heat energy than cool water parcels, therefore the cooling effect was larger in autumn dure to the strong wind than in summer.

The period of the strong wind influencing the water in the bottom layer was investigated. As the period extended from 1 day to 3 days, the duration of the change in water temperature was longer. Fig. 4 shows that the period of strong wind could affect the movement of the water parcel in the bottom layer. From Fig. 4a-d, the strong westerly wind could increase the water temperature more than other wind directions in both summer and autumn. The rate of the vertical mixing depended on the position of the monitoring point and the topography. The monitoring point was located at the bottom of the eastern coast (Fig. 1c), thus the water descended down along the coast and reached that point. In each direction, water temperature of the bottom layer increased after the strong wind blew in summer and autumn. After the overturning occurred, the water temperatures were warmer than the original one when the strong wind blew in summer, and the water temperatures were cooler than the original one when the strong wind blew in autumn.

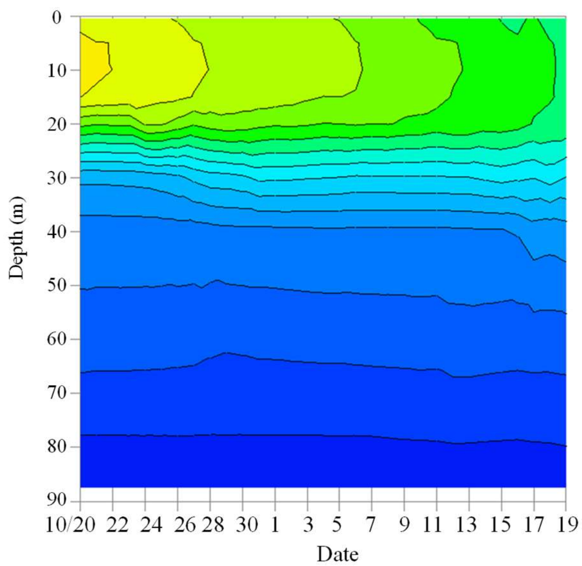
On the other hand, in sX2dO_0715-0721_7, the stratification collapsed right after the wind blew, and the vertical mixing occurred, as shown in Fig. 3e. In addition, in sX2dO_1026-1101_7, the stratification also collapsed, and the water was more mixed between the bottom layer and the layer above the bottom one (Fig. 3f). Once the stratification collapsed, water temperature at the bottom rose and didn't return to the original water temperature. The destratification depends on the strength of the wind and the stratification.



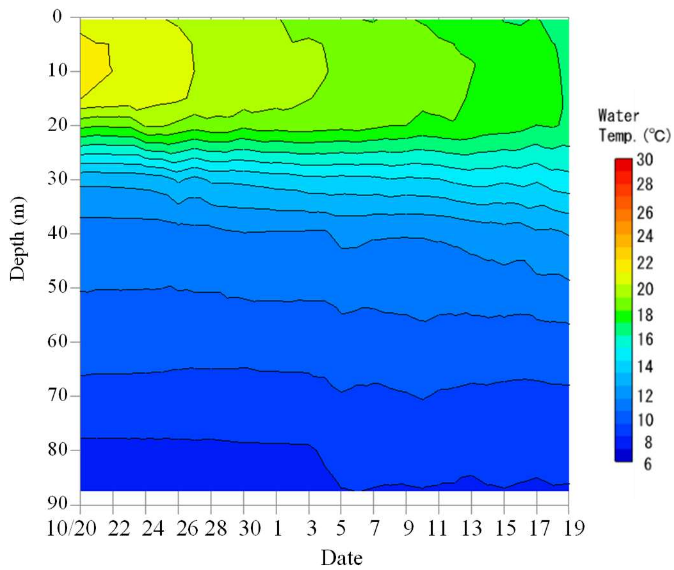
(a) Baseline case



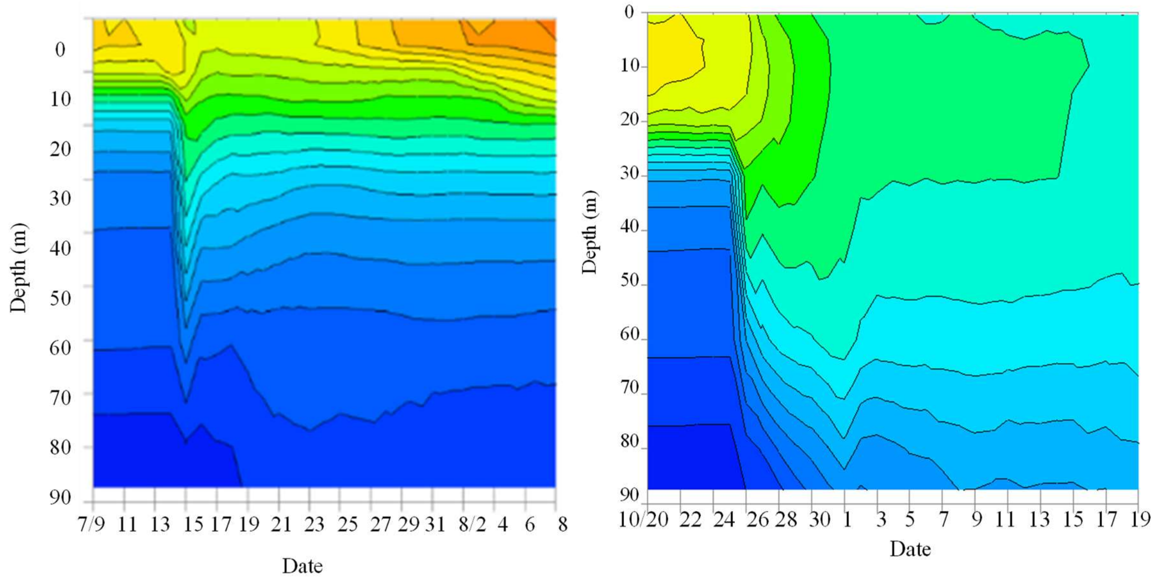
(b) s10dS_0715_1



(c) Baseline case

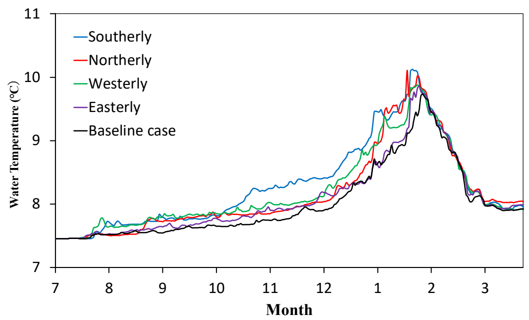


(d) s10dS_1026_1

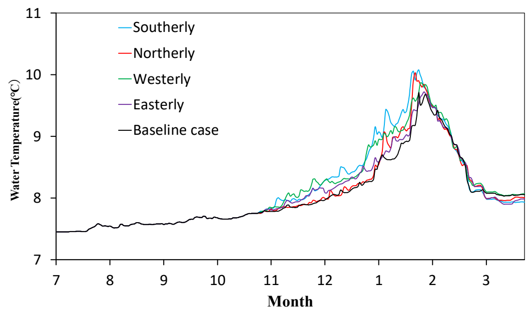


(e) sX2dO_0715-0721_7 (f) sX2dO_1026-1101_7

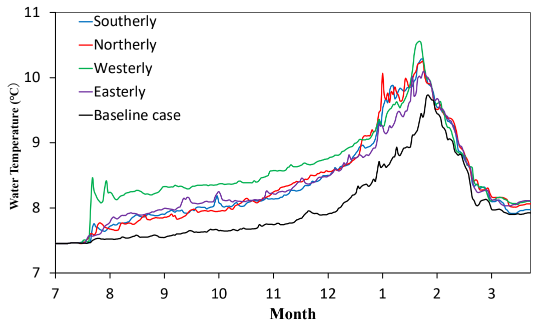
Fig. 3 Time-vertical cross sections of water temperature at Imazu-oki.



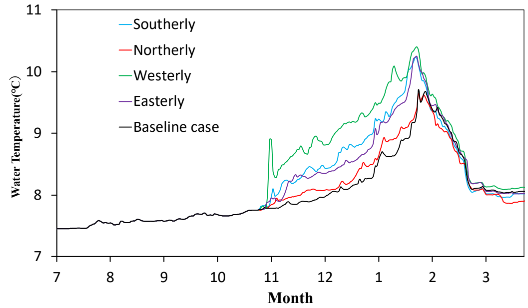
(a) s10dS, N, W, E_0715_1



(b) s10dS, N, W, E_1026_1



(c) s10dS, N, W, E_0715-0717_3



(d) s10dS, N, W, E_1026-1028_3

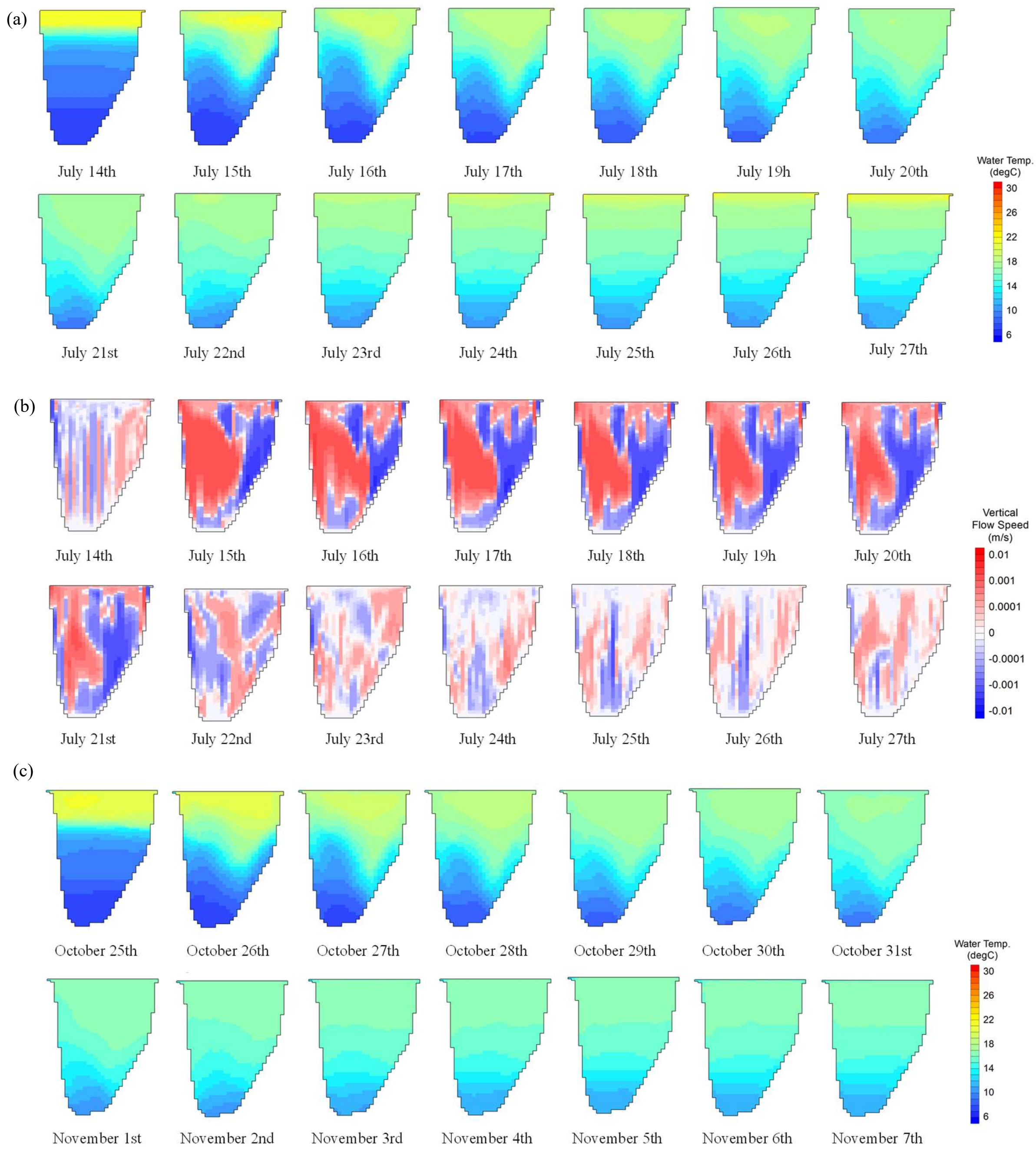
Fig. 4 Time series of water temperature at a depth of 87.5m from July 2007 to March 2008.

Fig. 5 and Fig.6 shows the vertical distribution of simulated water temperature and vertical flow speed when the strong wind blew for the week from July 15th to 21st, 2007, using meteorological data with wind speed doubled from July 15th to 21st (sX2dO_0715-0721_7) and the week from October 26th to November 1st, 2007, using meteorological data with wind speed doubled from July 15th to 21st (sX2dO_1026-1101_7) to investigate the effect of strong winds on the change in stratification between the period when temperatures increased in summer and decreased in autumn.

When strong winds started to blow, the surface water was driven to the coast. Then, the water in the lower layer moved against the wind, and the thermocline tilted (Fig. 5a). As shown in Fig. 5b, when the thermocline tilted toward the coast, the water flew downward in the coast. After winds ceased, the thermocline returned to its original position and tilted in the opposite direction. The effect of the wave reached the bottom as the amplitude of the internal wave increased, and the stratification collapsed. Finally, vertical mixing was enhanced in the bottom layer on July 19th-27th.

This phenomenon was also shown in the case of sX2dO_1026-1101_7. When severe winds associated with the passage of cyclones blew such as the meteorological data with wind speed doubled from July 15th to 21st, the depth of the thermocline rose deeply in the case of the weak stratification due to the decrease in air temperature. After the wind ceased, it declined abruptly and caused waves to form, which impacted the deep layer (Fig. 5c). Vertical mixing was caused by the passage of this wave (internal surge). The internal wave generated by strong wind had a larger amplitude than usual, and as the gratitude of the wave suddenly became steep and nonlinear, the amplitude of the wave was so large (Fig. 5d). Internal waves broke at the boundaries, increasing turbulence in the bottom layer and causing mixing events.

Compared with the sX2dO_0715-0721_7 and sX2dO_1026-1101_7, in weaker stratification period, when the air temperature decreased in autumn, the vertical mixing was more enhanced, and the temperature of all layers decreased in December as shown in Fig.6. Therefore, the strong wind in autumn and winter decreased the water temperature of all layers next year before and after the overturning. The water temperature of bottom layer influenced the dissolved oxygen saturation, which lead to the dissolved oxygen concentration next year.



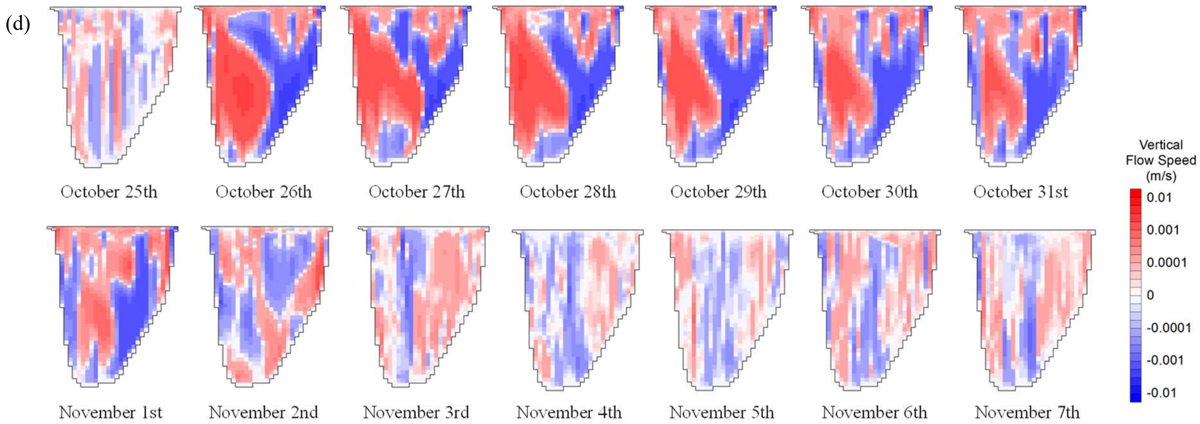


Fig. 5 West-east vertical cross sections through Imazu-oki for (a) water temperature and (b) vertical flow speed in sX2dO_0715-0721_7 and (c) water temperature and (d) vertical flow speed in sX2dO_1026-1101_7 from July 14th to 27th in 2007.

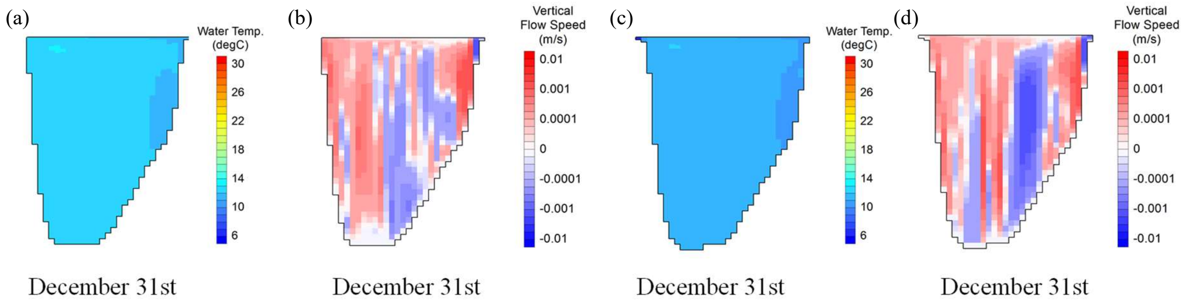


Fig. 6 West-east vertical cross sections through Imazu-oki for (a) water temperature and (b) vertical flow speed in sX2dO_0715-0721_7 and (c) water temperature and (d) vertical flow speed in sX2dO_1026-1101_7 on December 31st in 2007.

5. CONCLUSION

In the present study, the effect of strong wind on the bottom layer in the weak stratification during autumn by using a three-dimensional hydrodynamics model in Lake Biwa was investigated.

When the wind is strong enough in magnitude, stratification can collapse, and wind stress promotes more vertical mixing in the bottom layer in autumn when the stratification decreases than in summer when thermal stratification is strong. When strong winds blow in only one direction during both strong and weak stratification season, the vertical mixing rate varies with the wind direction. Vertical mixing velocity also vary with the topography of the lake bottom more largely in autumn than in summer. When the stratification collapses, the water temperature in the bottom layer is higher than the original water temperature even after the overturning both in summer and autumn. However, Severe strong winds blow when the air temperature decreases in autumn during the weaker stratification period, vertical mixing is more enhanced than in summer, and the temperature of all layers decreases in winter. As a result, the strong wind in autumn and winter next year decreases the water temperature in all layers before and after the overturning. The water temperature of the bottom layer influences dissolved oxygen saturation, which causes the dissolved oxygen concentration the following year. This suggests that strong winds could change the water environment near the bottom layer next year.

Thus, strong winds, such as cyclones, in autumn have enough energy to tilt the thermocline from its original position. After the wind stops, the thermocline oscillates with a certain periodicity. Internal waves redistribute this energy over different scales of time and length. Wind-driven currents and waves play an important role in weakening lake stratification and in vertical mixing. These phenomena can affect the transport of substances such as dissolved oxygen and the resuspension of bottom sediment.

Numerical calculations have revealed that strong winds blowing more frequently in autumn than in summer can contribute to the restoration of hypoxia in the bottom layer of Lake Biwa, even though the frequency of typhoons and cyclones has increased recently due to climate change. These results will contribute to the habitat of organisms living in the bottom layer of Lake Biwa and will enable us to make new proposals for measures to protect the water quality environment of Lake Biwa.

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