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NUMERICAL ASSESSMENT OF THE IMPACT OF STRONG WIND ON THERMAL STRATIFICATION IN LAKE BIWA, JAPAN

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ABSTRACT: Water temperature near the surface of a lake increases with increasing air temperature, which results in stratification. The strength of stratification substantially influences the transport of dissolved oxygen from the surface to the bottom water of a lake. In recent years, the decrease in dissolved oxygen at the bottom of the northern part of the Lake Biwa, the largest freshwater lake in Japan, has been observed. The main cause of this is considered to be the change in stratification, which depends on weather and climate conditions. In the present study, numerical simulations were carried out to investigate the effect of strong wind on the structure of stratification in Lake Biwa. The baseline simulation was conducted using actual meteorological data, and experimental simulations were conducted using meteorological data with modified wind speed and direction. The numerical experiments showed that if the magnitude of the wind is strong enough, the stratification collapses and the wind can enhance the vertical mixing in the bottom layer even in the summer season with strong thermal stratification. In a stratified season, when the strong wind blows predominantly in one direction, the rate of the vertical mixing changes by the wind direction. Moreover, as the duration of the strong wind extends, vertical mixing easily occurs.

Keywords: Strong Wind, Structure of Stratification, Vertical Mixing, Hydrodynamic Model, Lake Biwa

1. INTRODUCTION

In a warm season, water temperature near the surface of a lake increases with increasing air temperature, which results in lake stratification. The thermocline disrupts the transport of substances such as dissolved oxygen between the surface layer and the layer under the thermocline.

In some lakes, a lack of oxygen occurred in the deep layer during a stratified period because of the thermocline [1]. In recent years, the decrease in dissolved oxygen at the bottom of the northern part of Lake Biwa, the largest freshwater lake in Japan, has also been observed. The strength of stratification plays an important role in the varying amounts of dissolved oxygen in the lake. The main cause of the change in the stratification is weather and climate conditions such as air temperature, wind strength, and the precipitation.

Climate change leads to prolonged periods of stratification in lakes [2]. In Lake Zurich, in Switzerland, a continual long-term increase in thermal stability resulted in an increase of about 2-3 weeks in the duration of the summer stratification from the 1960s to the 1990s [3]. This impact directly affected the stratification characteristics and mixing processes.

On the other hand, strong typhoons will occur more frequently due to climate change [4], [5]. When the strong wind blows, wind stress on the surface layer provokes significant mixing, leading to the weakening of the stratification. Vertical mixing occurs by strong wind according to the observation.

When the wind blows predominantly in one direction, wind-driven currents develop in the surface layer and the water in the lower layer proceeds to the opposite direction. Upwelling or downwelling of the water occurs depending on the wind direction toward the coast. In a stratified season, the thermocline oscillates by this movement. This generates internal waves in a stratified lake. Wind-driven currents and internal waves were observed by measuring the vertical water temperature and the velocity continuously with using a thermistor chain and an acoustic current profiler [6], [7]. Wind forcing carries the major source of momentum and energy and affects the general circulation in lakes at various scales. However, the processes and the effects of the strong wind on the deep layer remains unclear. Therefore, it is important to understand the effect of the strong wind on the bottom layer in the lake.

In the present study, we investigated the effect of strong wind on stratification in Lake Biwa by using a three-dimensional hydrodynamic model. Numerical simulations were carried out for a baseline case using actual meteorological data and experimental cases using meteorological data with modified wind speed and direction.

2. Hydrodynamic Model in Lake Biwa

2.1 Calculation domain

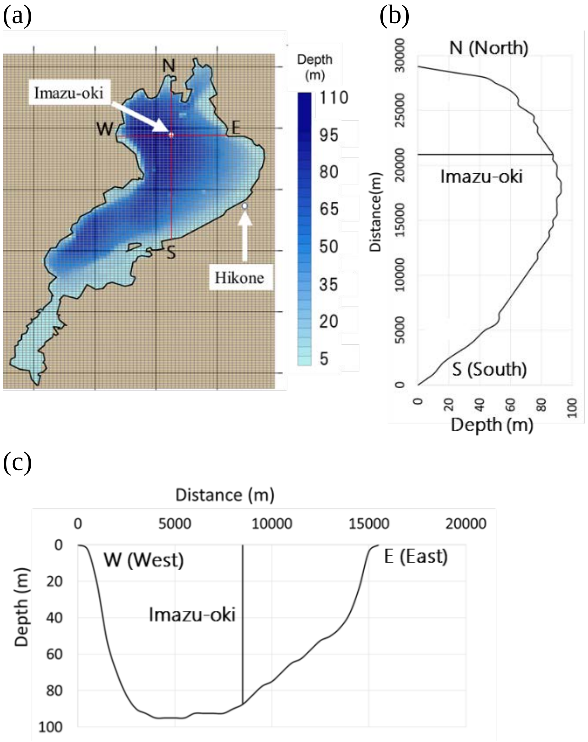


Fig. 1 Calculation domain with the topography of Lake Biwa: (a) horizontal domain, (b) south-north and (c) west-east vertical cross sections through Imazu-oki.

This study focused on Lake Biwa, which is the largest freshwater lake in Japan. Fig. 1 shows the calculation domain and water depth in the hydrodynamic model of Lake Biwa. The horizontal domain is 36 km × 65.5 km with a horizontal resolution of 500 m. The vertical domain consists of 86 layers from the lake surface to the depth of 107.5 m. The vertical grid size is 0.5 m from the surface to the depth of 20 m and gradually increases up to 2.5 m.

2.2 Governing equations

The governing equations consist of the momentum equation with Boussinesq approximation, the hydrostatic equation, continuity equation and the conservation equation for temperature. The governing equations are described in the Cartesian coordinate system as follows. The origin of the coordinate axes is in the southwestern edge of the domain on the horizontal plane. The *x* and *y*-axes are set to west-east and south-north directions, respectively, and the *z*-axis directs upward. Momentum equations (*x*, *y*-direction) are written by

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

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

Hydrostatic equation is given by

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

Continuity equation is written by

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

Conservation equation for temperature is written by

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

where u, v, and w are the x, y, and z components of current velocity (m s^{-1}), T is the water temperature (K), p is the pressure (N m^{-2}), ρ is the density of water (kg m^{-3}), ρ_0 is the reference density of water (= 10^3 kg m^{-3}), g is the acceleration due to gravity (= 9.8 m s^{-2}), f is the Coriolis parameter (= 8.34×10^{-5} s^{-1} corresponding to 35 ° N), ν_h is the horizontal eddy viscosity for momentum equations (= 1.0 m^2 s^{-1} [8]), κ_h is the horizontal eddy diffusivity (= 1.0 m^2 s^{-1} [8]), ν_z is the vertical eddy viscosity (m^2 s^{-1}) for momentum equations, κ_z is the vertical eddy diffusivity (m^2 s^{-1}).

In summer, a thermocline is typically formed at the depth from 10 m to 30 m. This thermocline suppresses the vertical transport of momentum and heat. To take this effect into account, the parameter values of vertical eddy viscosity and diffusivity are estimated by using Richardson number. Richardson number is a dimensionless number that expresses the ratio of the buoyancy term to the flow gradient term [9] and written by

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

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

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

and

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

2.3 Initial conditions

As for the initial condition, the current velocity was set to be 0 m s^{-1}. The initial water temperature on April 1st, 2006 was derived from linear interpolation of observed data on March 20th and April 10th, 2006. The observations were conducted by the Lake Biwa Environmental Research Institute twice a month at the monitoring point Imazu-oki (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, about 90 m.

2.4 Boundary Conditions

The boundary conditions for the current velocity at the surface of the lake are given by the following formula, taking the wind stress into account.

$$\upsilon_z \frac{\partial u}{\partial z} = \frac{\tau_x}{\rho_0}$$

$$\upsilon_z \frac{\partial v}{\partial z} = \frac{\tau_y}{\rho_0} \tag{9}$$

where τ_x and τ_y are the surface wind frictional stresses calculated by

$$\tau_x = \rho_a C_f U_{ax} U_a$$

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

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

where ρ_a is the density of air (kg m^{-3}), C_f is the wind frictional constant , U_{ax} and U_{ay} are respectively the x and y components of wind velocity (m s^{-1}), 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 ($S\downarrow$), 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

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

The no-slip condition is imposed at the bottom. On the side walls, the no-slip condition is imposed. The normal gradients of water temperature are also zero so that there is thermal insulation.

Air temperature, atmospheric pressure, wind direction and speed, and relative humidity over Lake Biwa were derived from the Grid Point Value derived from Meso-Scale Model of Japan Meteorological Agency (GPV MSM). 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 each surface mesh of the hydrodynamic model.

Solar radiation was derived from hourly observation data at Hikone local meteorological observatory (35°16’30” N., 136°14’36” E.). Solar radiation was assumed to be horizontally uniform over the lake.

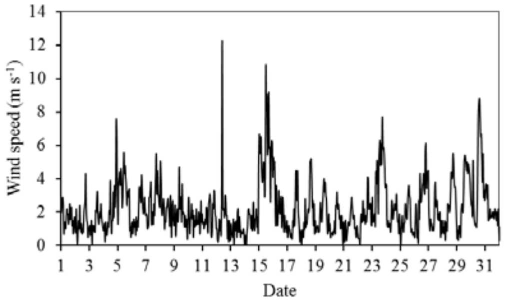
The boundary conditions for the water volume and temperature associated with inflow from each river and outflow from the lake were calculated by the hydrological model [10].

2.5 Simulation cases

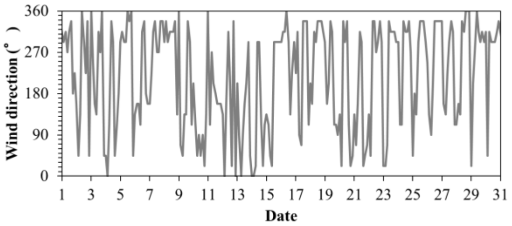
The baseline simulation was conducted using actual meteorological data for a period from April 1st, 2006 to March 31st, 2008 including a spin-up period from April 1st, 2006 to March 31st, 2007. In addition, experimental simulations were conducted for the same period using meteorological data with modified wind speed and direction on and after July 15th, 2007 in order to investigate the effect of the strong wind on the change of the stratification. The date was chosen due to strongly developed stratification, and in addition, strong wind associated with a typhoon as shown in Fig. 2. In the numerical experiments, the wind speed was fixed to 10 m s^{-1} or 20 m s^{-1}. The wind direction was fixed in four different directions: northward, southward, eastward and westward. The duration of strong wind ranged from 1 day to 7 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 Table1, each case was named for speed, direction, and duration of strong wind.

Table 1 Wind conditions in numerical experiments

Case name	Wind speed (m s^{-1})	Wind direction	Strong wind duration (day)
s10dS_day	10	Southerly	1,3,5,7
s10dN_day	10	Northerly	1,3,5,7
s10dW_day	10	Westerly	1,3,5,7
s10dE_day	10	Easterly	1,3,5,7
s20dS_day	20	Southerly	1
s20dN_day	20	Northerly	1
sX2dO_day	twice	Original	1,3,5,7



(a) Wind speed



(b) Wind direction

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

3. RESULTS AND DISCUSSIONS

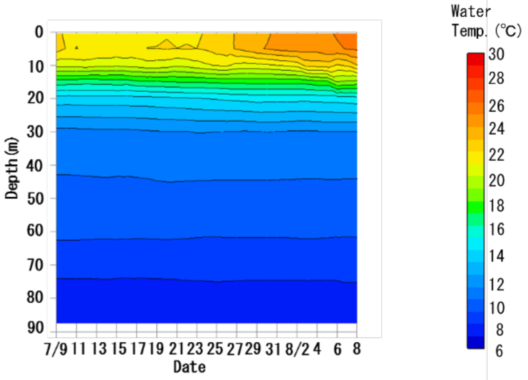
At first, we examined the effect of the strong wind on the bottom water in the lake. Fig. 3 shows time series of vertical water distribution in Baseline case and some cases at the monitoring point, Imazu-oki from 9th of July to 8th of August. Fig. 4 shows time series of water temperature at a depth of 87.5m in each case.

In s10dS_1, s10dN_1, s10dW_1, and s10dE_1, comparing the change of the vertical water temperature, the wind could not influence the water temperature of the bottom layer in each case right after the wind blew as shown in Fig. 3b and Fig. 4a. Although, in November, the difference between the original data and strong southerly winds blowing (northward) with the speed of 10 m s^{-1} appeared, after the overturning in the middle of winter, the water temperature in all conditions became the same.

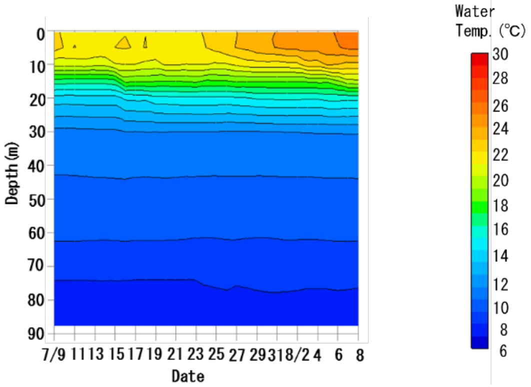
On the other hand, in s20dS_1, the stratification collapsed right after the wind blew, and the vertical mixing occurred, as shown in Fig. 3c. In addition, in sX2dO_1, the stratification also collapsed and the water was mixed between the bottom layer and the layer above the bottom one (Fig. 3d). Once the stratification collapsed, water temperature at the bottom rose because it mixed well with the water parcel above the bottom layer. The destratification depends on the strength of the wind.

Next, the period of the strong wind influencing the water in the bottom layer was investigated. As the period extended from 1 day to 7 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. And, we could also find the difference in each direction. From Fig. 4b-d, the strong westerly wind would affect the water temperature more than other wind directions. It was because of 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 proceeded down along the coast and reached that point.

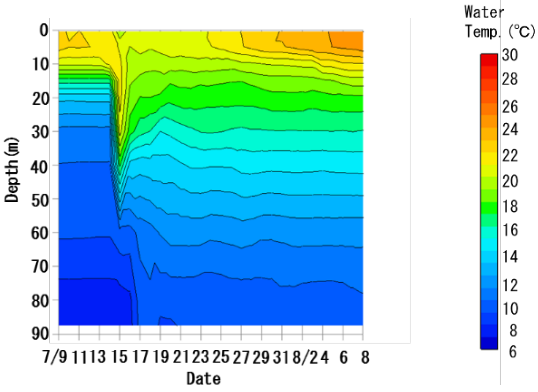
In each direction, the water temperature of the bottom layer increased after the strong wind blew. Even if after the overturning occurred, the water temperatures were warmer than the original one, therefore, the bottom water was completely mixed with the water in the upper layer.



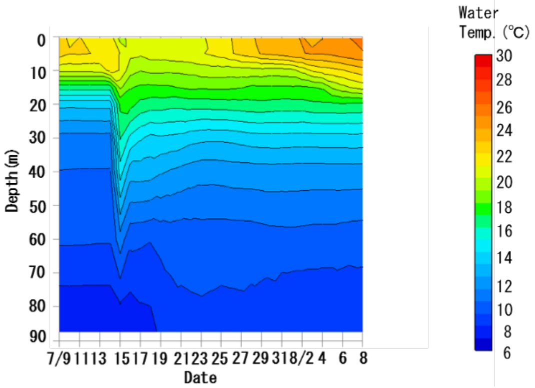
(a) Baseline case



(b) s10dS_1

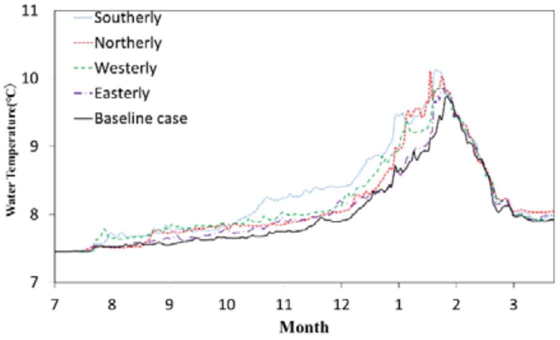


(c) s20dS_1

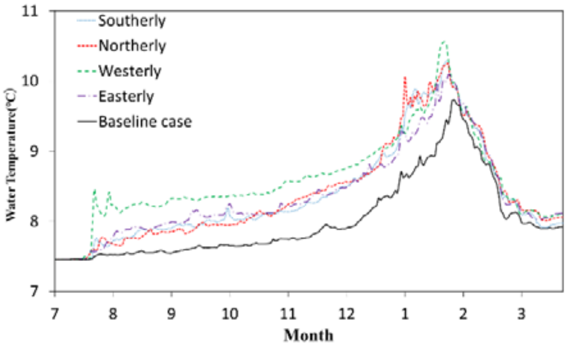


(d) sX2dO_1

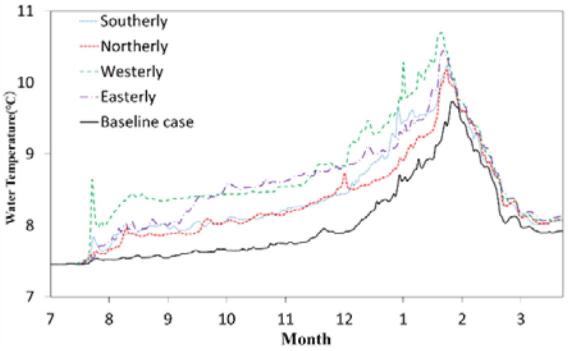
Fig. 3 Time-vertical cross sections of water temperature at Imazu-oki from July 9th to August 8th, 2007.



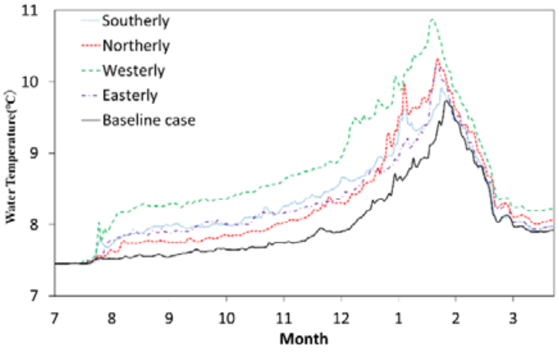
(a) s10dS,N,W,E_1



(b) s10dS,N,W,E_3



(c) s10dS,N,W,E_5



(d) s10dS,N,W,E_7

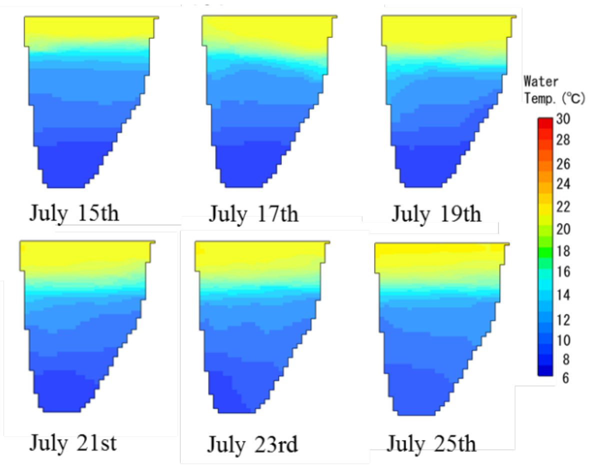
Fig. 4 Time series of water temperature at a depth of 87.5m from July 2007 to March 2008.

Fig. 5 shows the vertical distribution of simulated water temperature and vertical flow speed when the strong westerly winds blew from 15th to 17th of July for 3 days. When strong westerly winds started to blow (eastward), 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 the original position and tilted toward the opposite position on the 19th of July as shown in Fig. 5a. With the amplitude of the internal wave being larger, the effect of the wave reached the bottom, and the stratification collapsed. Finally, vertical mixing was enhanced in the bottom layer on July 23rd-25th. This similar phenomenon was shown in the observation. When severe winds associated with the passage of three typhoons blew in 1993, the depth of the thermocline rose deeply. After the wind ceased, it declined suddenly. This movement generated waves that affected the deep layer. The observation showed that the passage of this wave (It is called internal surge) lead to the vertical mixing [7]. The internal wave whose amplitude was larger than usual generated by strong wind became larger during moving, and as the gratitude of the wave suddenly became steep and nonlinear, the amplitude of the wave was such a large one. The internal waves broke at the boundaries, and enhanced the turbulence in the bottom layer, which resulted in mixing events.

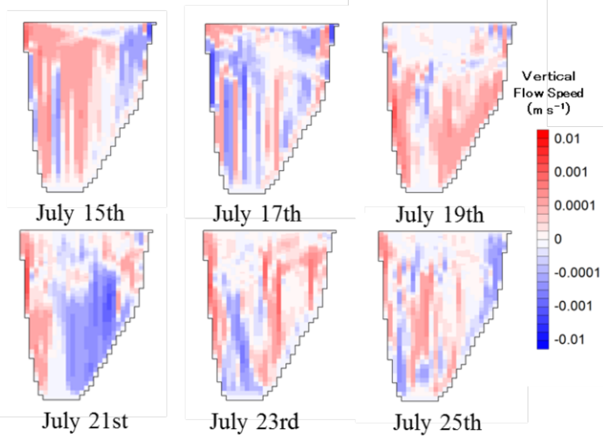
4. CONCLUSION

In the present study, we examined the effect of strong wind on the bottom layer by using a three-dimensional hydrodynamic model in Lake Biwa.

If the magnitude of the wind is strong enough, the stratification collapses and the wind can enhance the vertical mixing in the bottom layer even in the summer season with strong thermal stratification.



(a) Water temperature



(b) Vertical flow speed

Fig. 5 West-east vertical cross sections through Imazu-oki for (a) water temperature and (b) vertical velocity from July 15th to 25th in 2007 in the s10dE_3 case.

In a stratified season, when the strong wind blows predominantly in one direction, the rate of the vertical mixing changes by the wind direction. Especially, if the strong westerly wind blows continuously, it excites the vertical mixing more than in other directions. It is possible that the internal mixing may be affected by characteristics of the topography at the bottom of the lake. After the overturning, the water temperature at the bottom layer increases more than the original temperature. It implies that strong winds can change the water environment surrounding the bottom next year. Furthermore, as the duration of the wind extends from 1 day to 7 days, vertical mixing easily occurs.

Strong winds such as typhoons are energetic enough to tilt the thermocline from its original position. After the wind ceases blowing, the thermocline oscillates at a certain period of time. Internal waves redistribute this energy over different time and length scales. If the amplitude of the internal wave is too large, the wave will break and internal mixing can be generated.

In this way, wind-driven currents and waves play an important role in the weakening of stratification and vertical mixing in the lake. These phenomena can influence the transport of substances such as dissolved oxygen and the resuspension of bottom sediments.

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