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Diagnostic Study on the Vertical Circulation and the Maintenance Mechanisms of the Cyclonic Gyre in Lake Biwa

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Lake Biwa in Japan has a stable cyclonic gyre during seasons of thermal stratification. A vertical circulation consisting of downwelling in the central area and upwelling near the rim of the gyre is calculated by the diagnostic model. The energetics in the model indicate that this vertical circulation corresponds to the decay process of the gyre. Tracking of drifters in summer supports the presence of a vertical circulation, though its magnitude is about 50% less than that estimated by the diagnostic model. This is explained from the ratio of kinetic energy and available potential energy of the gyre. The realistic value of the vertical eddy viscosity is estimated to be 0.8–2.1 $cm^2\ s^{-1}$ in summer. Monthly variations of the horizontal and vertical circulations are calculated by the diagnostic model using the monthly mean density fields. The gyre and the vertical circulation are maximal in September. The characteristic decay time scale of the gyre is estimated to be about 10 days. The effect of topographic differential heating is considered to be one of the maintenance mechanisms of the gyre in early summer, and the wind stress curl to be the important maintenance force for the gyre from late summer to late fall.

1. INTRODUCTION

The mean circulation in a lake is one of the most fundamental and important problems not only in physical limnology but also of chemical, biological, and environmental sciences on a lake. It is quite interesting to note that a counterclockwise (cyclonic) surface circulation is common to most large lakes in the northern hemisphere [*Emery and Csanady*, 1973]. Various theories have been proposed to explain the formation and maintenance mechanisms of the cyclonic surface circulation [see, e.g., *Csanady*, 1977].

Lake Biwa (Figure 1), the largest lake in Japan, also has a large cyclonic circular current (gyre), which is quite stable during seasons of thermal stratification [*Endoh et al.*, 1981]. This gyre is on a quasi-geostrophic balance and exists only in the epilimnion, or the layer above the thermocline [*Okamoto and Morikawa*, 1961*a*; *Endoh*, 1984]. A number of dynamical calculations have been done to estimate the pattern and magnitude of the gyre from the observed water temperature distributions [*Okamoto and Morikawa*, 1961*b*; *Kunishi et al.*, 1967; *Imawaki et al.*, 1979; *Endoh et al.*, 1981].

Endoh [1978] developed a diagnostic model to obtain a more reliable velocity field from the observed density field. This model involved the effect of the vertical shearing stress, to estimate the deviation from geostrophic velocity. Though the calculated velocity field was not so different from the geostrophic one, a large vertical circulation consisting of a downwelling in the central region and an upwelling near the rim of the gyre was calculated to accompany the gyre. The magnitude of the vertical circulation was almost proportional to the vertical eddy viscosity. This result may be questionable because the "steady" vertical circulation should destroy the horizontal density gradient associated with the gyre. This question arises from the basic idea of the usual diagnostic calculation itself, which does not require the density (heat) balance equation, and from the assumption of no external forces such as wind stress.

In this paper the physical significance of vertical circulation and evidence for its existence in Lake Biwa are shown, and some maintenance mechanisms of the gyre are discussed on the basis of the diagnostic model and observed water temperature distributions.

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2. VERTICAL CIRCULATION

2.1. *Diagnostic Model*

A number of methods of diagnostic calculation using observed density fields have been developed to estimate ocean circulation [e.g., *Sarkisyan*, 1977; *Holland and Hirschman*, 1972; *Sarmiento and Bryan*, 1982], but few have been developed to estimate lake circulation, perhaps because the steady state assumption does not apply to many lakes [*Kielmann and Simons*, 1984], there being time variations in velocity and density fields in lakes, such as seiches, internal waves, topographic waves, and wind-driven currents [e.g., *Csanady*, 1978]. On the other hand, *Emery and Csanady* [1973] pointed out the presence of mean circulation in large lakes. If a mean circulation is quite obvious, diagnostic calculations should be useful to estimate the mean velocity field from a time-averaged density field in a lake.

The equations governing the diagnostic model applied to Lake Biwa are as follows [*Endoh*, 1978].

$$-fv = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}\left(\nu\frac{\partial u}{\partial z}\right) \tag{1}$$

$$fu = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + \frac{\partial}{\partial z}\left(\nu\frac{\partial v}{\partial z}\right) \tag{2}$$

$$\frac{\partial P}{\partial z} = -\rho g \tag{3}$$

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

where x, y, and z are the eastward, northward, and upward coordinates, respectively, with the origin at the lake surface; u, v, and w are the corresponding velocity components; P is pressure; ρ is water density; ρ_0 is mean water density; g is acceleration due to gravity; ν is vertical eddy viscosity; and f is the Coriolis parameter, which is assumed to be constant ($8.4 \times 10^{-5}\ s^{-1}$).

Boundary conditions at the lake surface and the bottom are

$$\rho_0\nu\left(\frac{\partial u}{\partial z}, \frac{\partial v}{\partial z}\right) = (\tau_x, \tau_y) \qquad w = 0 \qquad z = 0 \tag{5}$$

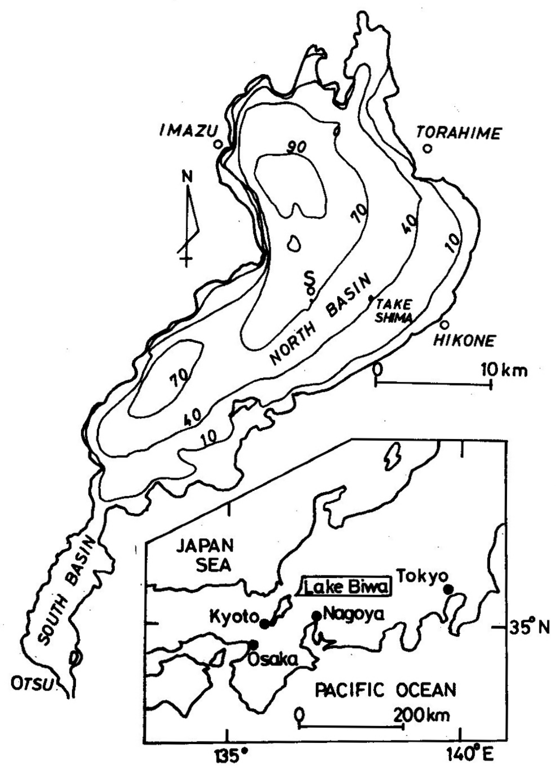

Fig. 1. Bathymetry map of Lake Biwa showing locations of the observation stations. Some depth contours are shown in meters.

$$u = 0 \quad v = 0 \quad w = 0 \quad z = -h(x, y) \tag{6}$$

where τ_x, τ_y are wind stress in the x, y direction and $h(x, y)$ is water depth.

This diagnostic model is similar to the "D_1 Model" of *Sarkisyan* [1977]. The major differences are that the vertical eddy viscosity is effective in the whole depth and the procedure of calculation is fairly easy. Though the centrifugal force is important in the momentum balance of the gyre [*Endoh*, 1984], the current pattern can be well estimated by linear momentum equations except for the central area of the gyre, where only weak currents exist. Equations (1)–(6) can be solved numerically using the observed distribution of density $\rho(x, y, z)$. *Endoh* [1978] applied this model to the 4-day mean density field of Lake Biwa observed in summer, assuming $\nu = 5$ cm^2 s^{-1} and no wind stress, i.e., $\tau_x = \tau_y = 0$. The numerical techniques and procedure have been presented in detail by *Endoh* [1978].

Endoh [1978] calculated a large cyclonic gyre with the maximum current speed of 35 cm s^{-1} in the surface layer of Lake Biwa. In the hypolimnion (the layer below the thermocline), however, weak currents (<5 cm s^{-1}) with various directions were calculated, and no gyre could be detected. The most interesting finding of *Endoh* [1978] was the large vertical circulation associated with the gyre, i.e., horizontal convergence in the surface layer and divergence near the thermocline depth. The physical meaning of this calculated vertical circulation is clarified by considering the energy balance in the model.

2.2. *Energetics*

The kinetic energy balance in the present model can be easily derived from (1)–(6) as follows.

$$u\frac{\partial P}{\partial x} + v\frac{\partial P}{\partial y} = \frac{\partial}{\partial z}\left[\rho_0\nu\left(u\frac{\partial u}{\partial z} + v\frac{\partial v}{\partial z}\right)\right] - \rho_0\nu\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right] \tag{7}$$

for any fixed point (x, y, z), and

$$0 = Bs + W - D \tag{8}$$

for the total water volume V, where

$$Bs = -\int_V \rho g w \, dV$$
$$W = \int_S (\tau_x u_0 + \tau_y v_0)\, dS \tag{9}$$
$$D = \int_V \rho_0 \nu\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right] dV$$

Here (u_0, v_0) is the horizontal velocity at the lake surface, and S the area of the lake surface. Three terms in (8) represent the buoyancy work Bs, the energy input by the wind stress W, and the energy dissipation rate due to the vertical shearing stress (D).

If $W = 0$, which is the case in *Endoh* [1978], the energy balance for the volume V is reduced to be $Bs = D$. Since the dissipation rate D is always positive, the buoyancy work Bs must also be positive. This means the sinking of more dense water and upwelling of less dense water, or positive conversion from potential energy to kinetic energy. Therefore the potential energy should decrease if this "steady" energy conversion continues without energy supply. In this context, the system of the diagnostic model without external forces is not closed in energetics. This, however, does not mean that the vertical circulation calculated by the model is not true, as is described below.

If there is no energy supply, the mechanical energy budget equation in the total water volume V can be written as

$$\frac{\partial K}{\partial t} = B - D \tag{10}$$

$$\frac{\partial A}{\partial t} = -B \tag{11}$$

where K and A denote total kinetic energy and available potential energy, respectively, in the water volume V, and t is time. The buoyancy work B for an unsteady solution may differ from the buoyancy work Bs for the steady solution, but the dissipation rate D should be almost the same as that in the steady state solution.

The ratio A/K of the available potential energy to the kinetic energy of the quasi-geostrophic current in the two-layer fluid under an isostasy assumption has an order of magnitude of $(L/\lambda_i)^2$, where L is the horizontal scale of the current and λ_i is the internal radius of deformation [*Gill et al.*, 1974]. The ratio A/K in Lake Biwa in summer is estimated to be 0.5–1.0 from the observed water temperature data during 1973–1983. This value satisfies the above relationship, provided that λ_i is 5 km and L (radius to maximum current of the gyre) is 3–5 km, the typical values in summer.

The quasi-geostrophic current changes slowly with time, maintaining the ratio A/K by mutual adjustment of the velocity and density fields. Substituting the relationship of $A/K = c$

(c is the constant value) into (11), the buoyancy work B in the unsteady case can be expressed in terms of D or Bs as follows.

$$B = DA/(A + K) = BsA/(A + K) \quad (12)$$

Equation (12) shows that the magnitude of the buoyancy work, and hence the vertical circulation in the decay process of the gyre, is less than that calculated by the steady diagnostic model by the factor of $A/(A + K)$. In large lakes and oceans the value of A/K is very large, and B is almost equal to Bs. In such a case, the diagnostic model is quite useful for estimating the decay process of the gyre, eddy, or ring.

In Lake Biwa the ratio B/Bs is 0.3–0.5 because the ratio A/K is 0.5–1.0. Therefore the vertical circulation in the lake can be determined during a calm period, though its magnitude is 30–50% of that estimated by the diagnostic model. Because the magnitude of Bs is almost proportional to the value of the vertical eddy viscosity ν, the realistic value of ν can be evaluated inversely if the magnitude of the vertical circulation is determined from observations.

2.3. *Observational Results*

Observations were carried out on September 1–4, 1983, in order to detect the vertical circulation associated with the cyclonic gyre in Lake Biwa.

Thirteen drifters with window-shade drogues and reflectors (Figure 2) were released at nine points and were tracked for 60 hours continuously by radar at the top of Take-shima (an islet in the lake). Nine window shades were placed at 5-m depth, and four were at 10-m depth. Positions of drifters displayed on the radar CRT were photographed at 30-min intervals. The accuracy of the reading of the position of the drifters is estimated to be 1%, that is, about 100 m in the case of a 6-mile range on the radar CRT.

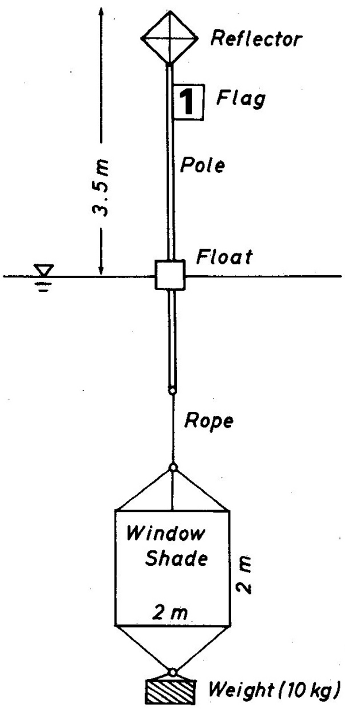

Fig. 2. Schematic picture of the drifter with window shade tracked by radar.

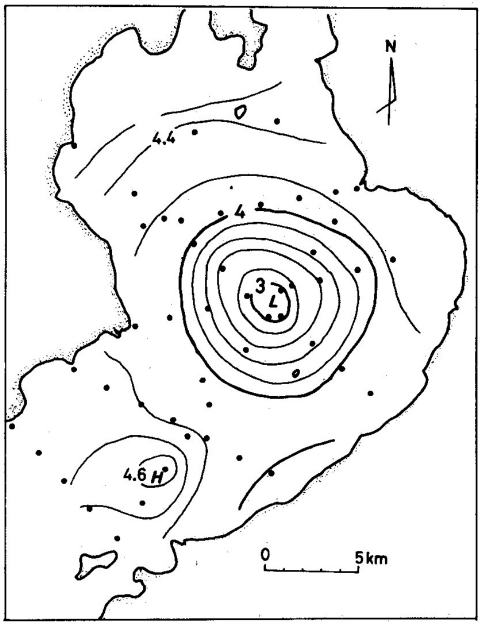

Fig. 3. Dynamic height topography (in dynamic centimeters) at 5-dbar surface referred to 30-dbar surface averaged over September 1–3, 1983. Contours are in 10^{-3} dyn cm.

Water temperature surveys by bathythermograph were also made at intervals of 2 km on eight lines by two vessels, which covered the northern half of the lake once a day. In addition, continuous current measurements by Aanderaa RCM-4 current meters were carried out at three depths (8, 18, and 73 m) at station S, the southwestern part of the gyre (Figure 1).

Figure 3 shows the dynamic height topography at a 5-dbar surface referred to a 30-dbar surface calculated from the water temperature data averaged over September 1–3. This shows clearly that a large cyclonic gyre exists in the middle area of the lake. The maximum current speed is estimated to be 30 cm s^{-1} at the region 3–4 km away from the gyre center.

Figure 4 shows some trajectories of the drifters placed at 5-m depth. All these drifters moved in a counterclockwise direction, but some of them moved away from the gyre area. Because no strong wind blew during the observation, these departures of the drifters are considered to be caused by internal waves. In fact, the record of the upper current meter at station S showed a large amplitude of velocity fluctuation with a period of 43 hours, which overlapped on the southeastward mean flow at this station. This current fluctuation indicates the development of the slowest internal Kelvin wave during this period [*Kanari*, 1975].

Figure 5 shows details of the trajectories of four drifters at a 10-m depth. All four drifters shifted toward the gyre center, though the trajectories are almost circular. The radial velocity component estimated from these spiral trajectories is 0.3–0.5 cm s^{-1}. The horizontal convergence calculated from the temporal change of the triangle or quadrilateral area composed of drifters is $3\text{–}5 \times 10^{-6}$ s^{-1}. These values correspond to the results of the diagnostic calculation based on the water temperature data, provided that the constant vertical eddy viscosity ν is 0.3–0.8 cm^2 s^{-1}. The ratio of available potential energy to kinetic energy (A/K) is estimated to be 0.6 from the observed currents and density fields. Therefore the realistic value of ν is 0.8–2.1 cm^2 s^{-1} according to the discussion in the previous section.

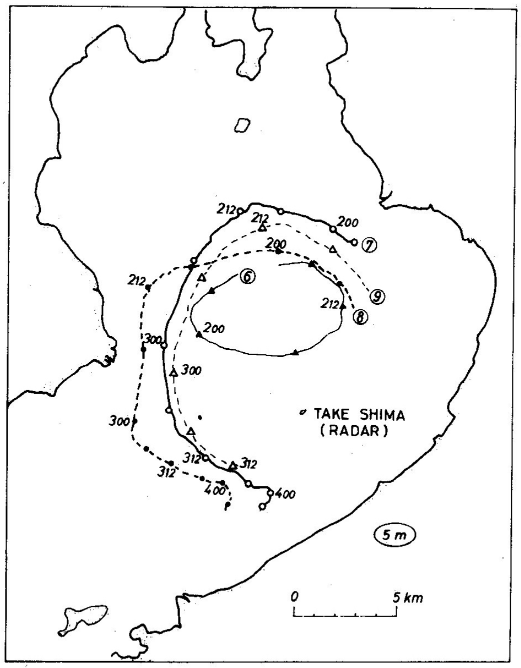

Fig. 4. Trajectories of four drifters at 5-m depth on September 1–4, 1983. Numerals show the day and hour, e.g., 312 means 1200 UT on September 3.

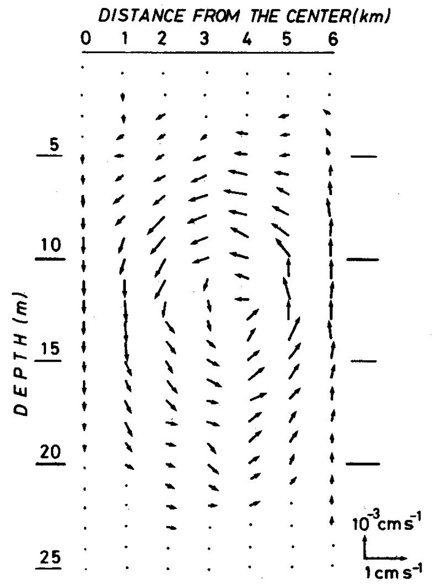

Fig. 6. Vertical circulation in the east side of the gyre calculated by the diagnostic model using $\nu = 0.5$ cm^2 s^{-1}.

Figure 6 shows the vertical circulation in the eastern half of the vertical cross section of the gyre calculated by the diagnostic model with $\nu = 0.5$ cm^2 s^{-1}. The negative radial velocity (toward the gyre center) can be seen especially in the layer between 6- and 12-m depths, and the vertical velocity component has an order of magnitude of 10^{-3} cm s^{-1} near the gyre center.

3. MAINTENANCE MECHANISMS OF THE GYRE

The cyclonic gyre in Lake Biwa is quite stable in summer but has a characteristic seasonal variation in intensity [*Endoh et al.*, 1981]. In this section, some maintenance mechanisms are examined on the basis of the water temperature data taken each month during the stratified season.

Successive surveys of water temperature by a bathythermograph were carried out in the north basin of Lake Biwa from June to November in 1977 [*Endoh et al.*, 1981]. Each month the observation was made for five successive days to obtain a time-averaged density field. Figure 7 shows the dynamic height topographies at the lake surface referred to a 30-dbar

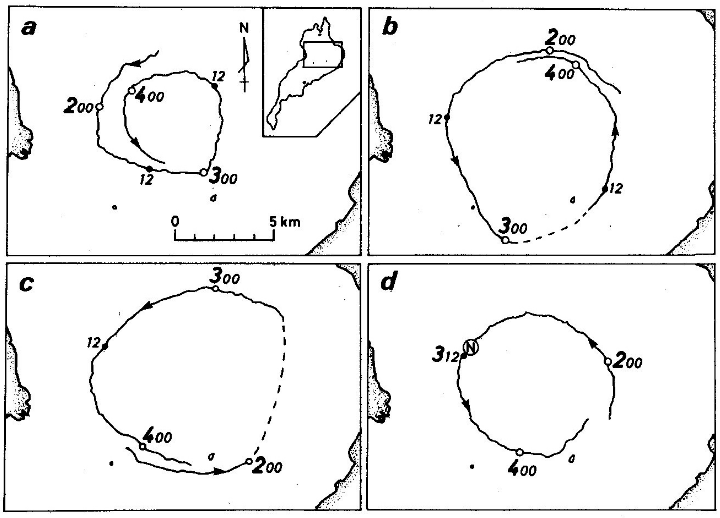

Fig. 5. Trajectories of all four drifters at 10-m depth. The drifter in Figure 5*d* was caught in a fishing net at point N from 1200 UT on September 2 to 1000 UT on September 3.

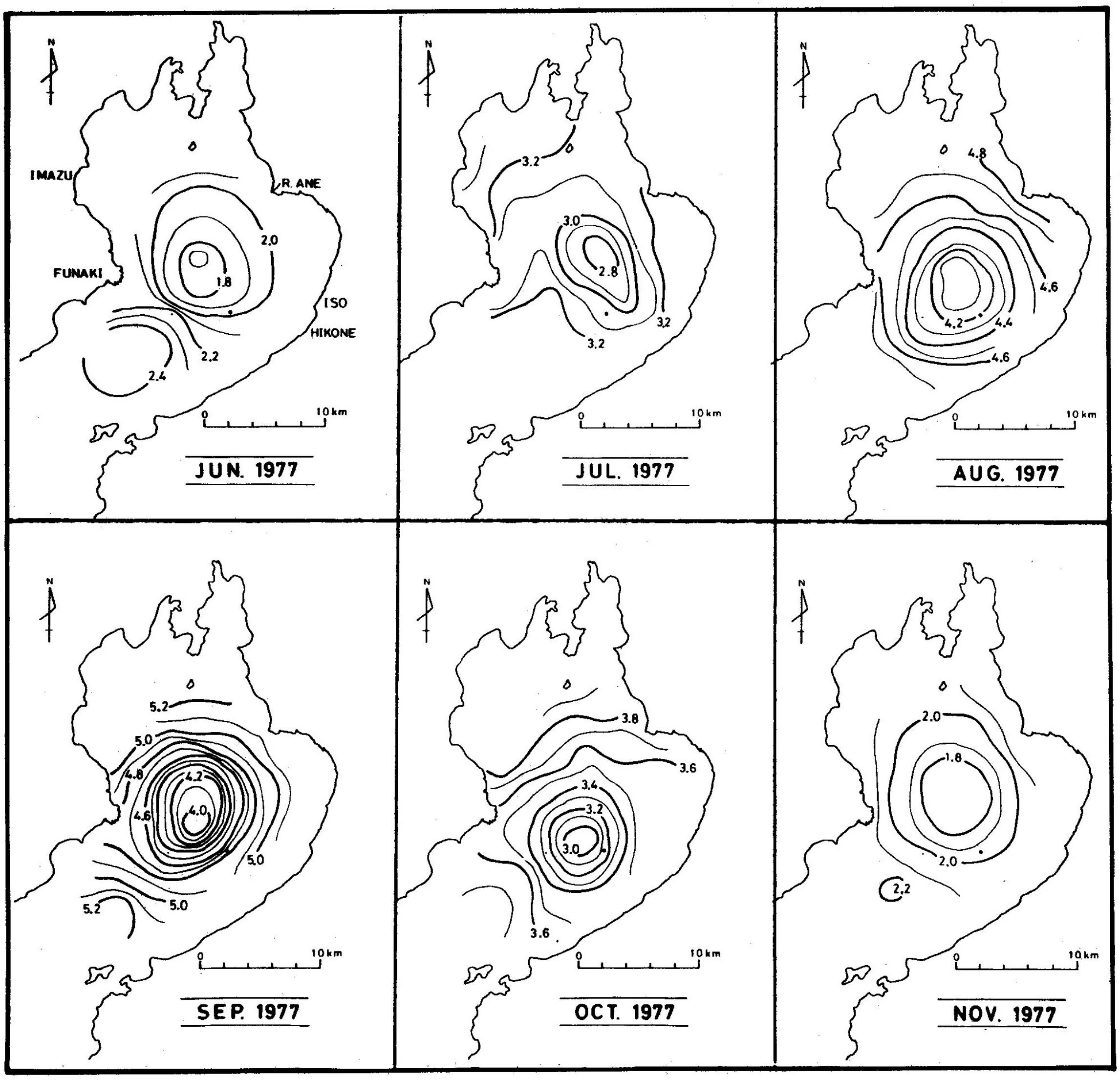

Fig. 7. Monthly variation of dynamic height topography (in 10^{-3} dyn cm) at the lake surface referred to 30-dbar surface from June to November 1977 [after *Endoh et al.*, 1981].

surface calculated from the density field averaged over 5 days. The cyclonic gyre is stable throughout this period and has a maximum intensity in September.

Using these monthly density fields, the diagnostic calculations were made for two cases. In case 1 the vertical eddy viscosity ν is assumed to be a constant 0.5 $cm^2\ s^{-1}$ both in space and time according to the analysis described in the previous section. In case 2, ν is assumed to be variable with depth as well as month and is set almost equal to the vertical eddy diffusivity Kz (Y. Oonishi et al., unpublished data, 1981). The values of ν used in case 2 are 1–10 $cm^2\ s^{-1}$ for the surface layer, $\sim$0.1 $cm^2\ s^{-1}$ for the thermocline, and $\sim$1 $cm^2\ s^{-1}$ for the deep layer.

The results of the diagnostic calculations and available potential energy in each month are summarized in Table 1 for two cases of ν. The kinetic energy K of the gyre increases gradually from June to September and decreases thereafter. The energy dissipation rate D shows a similar monthly variation to K. The ratio K/D, which gives a characteristic decay time scale of the gyre, takes the same magnitude of 10–20 days each month. This indicates tha the cyclonic gyre in Lake Biwa should disappear in this time scale if no energy source exists.

In case 2 the magnitude of kinetic energy is of the same order as that in case 1. Therefore the basic velocity field is not sensitive to variation of ν. The magnitude of the viscous dissipation, however, is somewhat less than that in case 1. This is due to the smaller ν values ($\sim$0.1 $cm^2\ s^{-1}$) specified at the thermocline depth, where the vertical gradient of the horizontal velocity is also large. Consequently, the ratio K/D is 15–30 days, which is about 50% larger than that in case 1.

Using these results, two maintenance mechanisms of the gyre will be examined. The first is the thermally driven circulation due to the effect of topographic heat accumulation [*Oonishi*, 1975; *Ookubo et al.*, 1984]. This mechanism has also been studied for circulation in the Great Lakes [*Huang*, 1971; *Bennet*, 1971]. The second is the traditional idea of a wind

TABLE 1. Summary of the Results of the Diagnostic Calculation in Case 1 ($\nu = 0.5$ cm^2 s^{-1}) and Case 2 ($\nu \simeq K_z$) on the Basis of the Monthly Mean Temperature Field Observed in 1977 [*Endoh et al.*, 1981]

Month in 1977	K, 10^{16} ergs	D, 10^{10} ergs s^{-1}	K/D, days	A, 10^{16} ergs	A/K	Q	$\rho_0 c_p$ $\langle\lvert\mathrm{HAD}\rvert\rangle$, 10^{-3} cal cm^{-2} s^{-1}	τ_x, 10^{-2} dyn cm^{-2}	w_x, m s^{-1}
June	3.5	1.9	20	5.2	1.5	3.0	3.8	0.6	0.8
	(3.9)	(1.1)	(41)		(1.3)		(2.0)	(0.3)	(0.5)
July	6.0	5.7	13	6.9	1.2	3.1	5.0	1.1	1.0
	(6.3)	(2.5)	(29)		(1.1)		(4.4)	(0.5)	(0.7)
August	8.4	9.4	10	6.0	0.7	1.5	9.8	1.6	1.3
	(8.4)	(3.9)	(25)		(0.7)		(6.8)	(0.7)	(0.8)
September	14.6	13.8	13	6.8	0.5	0.2	15.0	2.0	1.4
	(14.8)	(9.3)	(18)		(0.5)		(10.3)	(1.3)	(1.1)
October	10.7	7.7	16	4.7	0.4	−2.0	3.4	1.7	1.3
	(10.5)	(5.5)	(22)		(0.4)		(2.5)	(1.2)	(1.1)
November	1.6	1.4	13	2.1	1.3	−2.2	0.9	0.6	0.8
	(2.3)	(1.6)	(17)		(0.9)		(0.5)	(0.7)	(0.8)

Numbers in parentheses are case 2 calculations. Here K is the kinetic energy, D the dissipation rate, A the available potential energy, Q the net surface heating rate, $\rho_0 c_p\langle\lvert\mathrm{HAD}\rvert\rangle$ the horizontal heat advection (see text), and τ_x and w_x the wind stress and wind speed necessary to maintain the gyre (see text).

stress over the lake. Some numerical experiments have been carried out to examine the wind-driven circulation in Lake Biwa [*Imasato et al.*, 1975; *Oonishi and Imasato*, 1975; *Kanari*, 1974; *Endoh*, 1976]. These studies clarified that a uniform wind produces only a topographic circulation that should decrease rapidly after the wind is stopped, while the wind with curl can produce a long-life circulation in the stratified lake.

Now, we will examine the first mechanism of the topographic differential heating, using the heat balance equation, i.e.,

$$\frac{\partial T}{\partial t} + \frac{\partial}{\partial x}(uT) + \frac{\partial}{\partial y}(vT) + \frac{\partial}{\partial z}(wT) = \frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right) \quad (13)$$

where T is water temperature and K_z is vertical eddy diffusivity. The horizontal diffusion term is neglected because this effect is not essential to the following discussion. The equation for temperature averaged over the whole volume can be derived by integrating (13) over the water volume V such that

$$\frac{\partial[T]}{\partial t} = \frac{Q}{\rho_0 c_p h_m} \quad (14)$$

where

$$[T] = V^{-1}\int_V T\, dV$$

and Q is the net heating rate at the lake surface, c_p is the specific heat at constant pressure, and h_m is the mean depth. Subtracting (14) from (13), the equation for the temperature deviation from $[T]$ can be obtained. The depth-integrated form of this equation is written as

$$\frac{\partial}{\partial t}\int_{-h}^{0} T'\, dz + \int_{-h}^{0}\left[\frac{\partial}{\partial x}(uT') + \frac{\partial}{\partial y}(vT')\right]dz = \frac{Q}{\rho_0 c_p}\left(1 - \frac{h}{h_m}\right) \quad (15)$$

where $T' = T - [T]$. This heat balance equation indicates that the depth integral of horizontal heat advection (HAD), the second term in the left-hand side of (15), should be balanced with the effect of topographic heat accumulation (TAC), the right-hand side of (15), in the steady state solution. HAD can be evaluated from an observed temperature field and a velocity field calculated by the diagnostic model. TAC can be estimated by the bottom topography and the temporal change of heat accumulation in the lake.

The calculated vertical circulation for each month has the same pattern as that in Figure 6, i.e., a horizontal convergence at the top of the thermocline and divergence at the bottom of the thermocline. Consequently, HAD is always negative near the gyre center and positive near the lake shore due to the existence of vertical circulation. The sign of TAC is almost the same as that of HAD when the heating rate Q is positive. Because integrals of HAD and TAC with respect to the whole area of the gyre must be zero, the heating rate Q and $\rho_0 c_p\langle\lvert\mathrm{HAD}\rvert\rangle$ are compared, where $\langle\lvert\mathrm{HAD}\rvert\rangle$ is the horizontal average of the absolute value of HAD. These values calculated for each month are shown in Table 1, where Q is calculated from observed water temperature by means of (14). The magnitude of $\rho_0 c_p\langle\lvert\mathrm{HAD}\rvert\rangle$ is nearly equal to that of Q only in June in case 1, and June and July in case 2. In the other month, $\rho_0 c_p\langle\lvert\mathrm{HAD}\rvert\rangle$ is much larger than Q or is of the opposite sign of Q during the cooling season. This indicates that the gyre in early summer might be formed and maintained only by topographic differential heating, but another mechanism must be considered to explain the stable existence of the gyre from summer to late fall.

As described above, the diagnostic model without wind stress is not closed in energetics. However, the magnitude of the wind stress that is necessary to maintain the gyre can be estimated from the energy dissipation rate D. In the steady state for kinetic energy as well as for the available potential energy, the energy balance must be $W = D$ from (8).

In order to estimate the magnitude of wind stress that is necessary to maintain the gyre, the horizontal distribution of wind must be given explicitly; from the definition of W in (9), only the wind with a positive curl can be the energy source because the current is cyclonic and circular. Unfortunately, little is known about the wind field over Lake Biwa, as is the case for many lakes. To obtain a rough estimate of the wind stress, we assume that the uniform wind blows only over half the gyre area and τ_x is set to be constant there and $\tau_y = 0$. In such case, the wind stress can be estimated as follows.

$$\tau_x = D\Big/\int_{S/2} u_0\, dS \quad (16)$$

It is convenient to transform wind stress τ_x to wind speed w_x

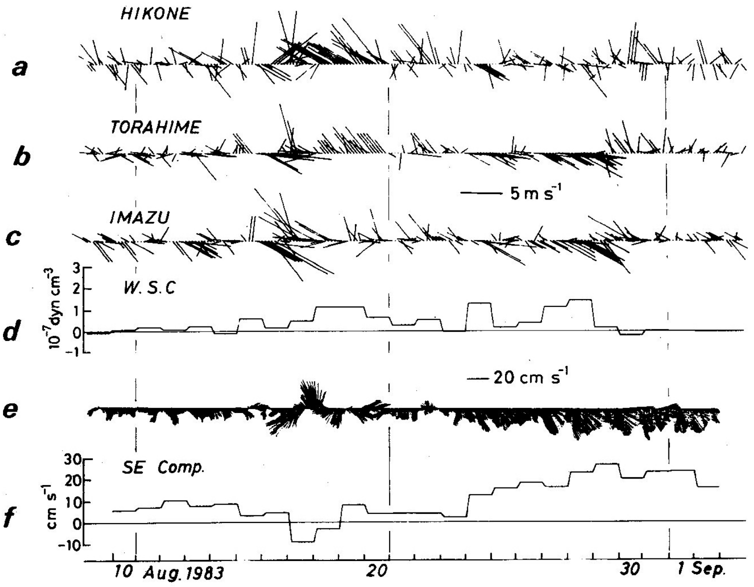

Fig. 8. (*a–c*) Stick diagrams of wind at three AMeDAS stations from August 9 to September 3, 1983, (*d*) daily averaged wind stress curl, (*e*) a stick diagram of the current at 8-m depth of station S, and (*f*) daily averaged current speed in the southeast direction.

in the direction x using the following relationship:

$$\tau_x = \rho_a \gamma_a^2 w_x^2 \tag{17}$$

where ρ_a is air density and the drag coefficient γ_a^2 is taken to be 1.3×10^{-3} after *Kunishi* [1963].

The estimated values of τ_x and w_x in the two cases listed in Table 1 suggest that a very weak wind of the order of 1 m s^{-1} is needed to maintain the gyre each month. The wind stress curl has not been well accepted as the main maintenance force of the mean circulation in a lake because the scales of many lakes are not larger than the scale of the weather system [*Emery and Csanady*, 1973]. The topography around Lake Biwa is quite complicated and makes some characteristic wind fields [*Kodama*, 1966; *Nakajima et al.*, 1977]. It is well known that northwest and southeast winds prevail in the northern half of Lake Biwa. There is some observational evidence on the intensification of the gyre by strong winds. One example, given in Figure 8, shows the stick diagrams of wind vectors at three stations with automated meteorological data acquisition systems (AMeDAS) by the Japanese Meteorological Agency, wind stress curl calculated by these wind data, and time variation of the surface current at station S. The locations of these stations are shown in Figure 1. Figure 8 shows that both wind and current were fairly weak in the first half of this observation period, and the current speed doubled thereafter, probably due to an intermittent strong wind with a positive curl of the order of 10^{-7} dyn cm^{-3}. This wind stress curl, which lasted for 10 days (August 20–29), produced a positive vorticity in the upper layer (0–10 m) of the order of 10^{-4} s^{-1}, which is almost the same order as the typical value of the observed vorticity in summer. The main direction of the intensified current at station S agrees with that of the cyclonic gyre. This evidence suggests that the winds over Lake Biwa have a positive curl and intensify the cyclonic gyre intermittently.

4. CONCLUSION

Diagnostic calculation is a powerful method of estimating the mean velocity and pressure field of a lake as well an ocean. A number of diagnostic calculations have been made for ocean circulation, including mean wind stress, to estimate the annual or seasonal mean circulation. On the other hand, the velocity field during the fairly short period of a weak wind can be estimated without considering the wind stress. In that case a diagnostic model is not closed in energetics, and the resulting velocity field relates to a decay process of mean circulation.

In the case of Lake Biwa [*Endoh*, 1978], a large vertical circulation is calculated from the energy dissipation by the vertical shearing stress. The realistic magnitude of vertical circulation is evaluated by estimating the ratio of available potential energy to kinetic energy. The vertical circulation in Lake Biwa has a magnitude of 0.3–0.5 of that calculated by the diagnostic model. In large lakes and oceans, the vertical circulation can be detected to be the same as that estimated by the diagnostic model.

The results of buoy tracking made in September 1983 support the presence of a vertical circulation. This observation was carried out under the condition of no energy supply because there was no strong wind and no net heating. The realistic value of the vertical eddy viscosity is estimated to be 0.8–2.1 cm^2 s^{-1} from comparisons of observations and the diagnostic model.

Two maintenance mechanisms of the gyre in Lake Biwa were examined using the energy dissipation rate estimated by the diagnostic model on the basis of monthly density field. The effect of differential heating due to variable water depth could have produced the cyclonic surface circulation in early summer. This is in accordance with the results obtained in the numerical and hydraulic experiments [*Oonishi*, 1975; *Ookubo et al.*, 1984].

Some observational evidence indicates that the wind field over Lake Biwa should have a positive curl and such wind intermittently intensifies the gyre. The wind with a curl works as energy input and makes a vertical circulation inverse of that calculated by the steady diagnostic model. This is the intensification of horizontal density gradient, i.e., the conversion of kinetic energy to available potential energy. In order to evaluate the energetics of the gyre in detail, the wind field over the lake must be examined.

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