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Study on the circular currents in Lake Biwa

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With 5 figures and 2 tables in the text

Introduction

In the north basin of Lake Biwa, some horizontally circulating currents (gyres) exist almost stably in the surface layer during summer. OKAMOTO & MORIKAWA (1961) discovered that the circular currents are approximately on a geostrophic balance. In the last 20 years, many observations of water temperature distributions have been made in Lake Biwa to estimate the pattern and magnitude of the gyre system by means of a dynamical calculation. The validity of applying the geostrophic relation to the circular currents, however, has not been examined sufficiently up to the present. This verification is very important not only for the aspect of quantitative evaluation of the gyres by means of water temperature data but also for the clarification of the dynamics and the formation-maintenance mechanisms of the gyre system. With regard to this problem, a series of quasi-simultaneous observations of currents and water temperature were carried out on September 1978. In this article, some results of current measurements and comparisons between the directly-measured current and geostrophic current are described.

Observations of currents and water temperature

In order to examine the validity of applying geostrophic relation to the circular currents in Lake Biwa, both the vertical distributions of the current velocity and the horizontal gradients of water density (temperature) should be obtained simultaneously. Though various methods could be adopted for this purpose, we carried out the following observations: (1) the current measurements were made using the drifters with cross board placed at different depths, 1, 5, 10, 15, 20 and 40 m, respectively; (2) the vertical profiles of water temperature were measured by aid of a bathythermograph at four points about 500 m away from the current station. The arrangement of the measurement points is shown in Fig. 1, where the pressure gradient at point 0 can be obtained from the horizontal differences of the water temperature at four points around the point 0. The measurements were carried out successively at three stations in the north basin from 8 to 10 September, 1978. The locations of the stations are shown in Fig. 2. Distances and directions of the drifters from the fixed buoys, set at every station, were measured by the speed of research vessel SEIRYU and magnetic compass, respectively. It took about an hour to measure both the currents and water temperature at each station.

Results and discussion

The summary of the current measurements at three stations is shown in Table 1. It is clear that the current directions in the surface layer are considerably stable throughout at every station during the observation period. The distribution of the current directions at three stations indicates the stable existence of a counter-clockwise gyre. The current speed is rather high in the surface layer, but there exist very weak and unstable currents below the thermocline, which was at 10—15 m in depth.

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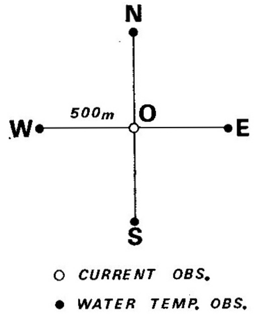

Fig. 1. Arrangement of the measurement points of current and water temperature at each station.

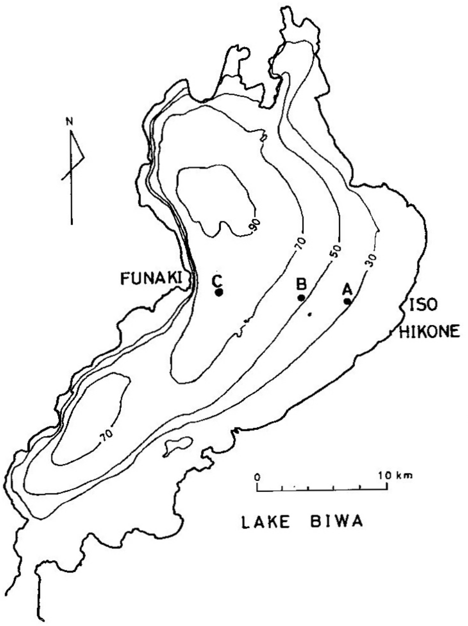

Fig. 2. Map of Lake Biwa showing the locations of current and water temperature observation stations. Depth contours are in meters.

Table 1. Directly-measured currents for five times, 8–10 September 1978. Current speed (V) is in cm/s and direction (Θ) is in degree from the north. The comparison of measured current with geostrophic current with respect to time-averaged value is shown in the right column.

Station		8 Sep.				9 Sep.				10 Sep.		Average			
		A.M.		P.M.		A.M.		P.M.		A.M.		obs.		cal.	
No.	Depth	V	Θ	V	Θ	V	Θ	V	Θ	V	Θ	V	Θ	V	Θ
Stn. A	1 m	22.0	20	21.8	44	17.5	54	13.8	50	17.4	53	18.0	43	17.9	37
	5 m	25.0	20	25.1	38	17.1	57	11.4	51	13.8	49	18.0	40	18.2	37
	10 m	24.9	17	23.0	38	10.3	53	10.6	46	12.0	19	15.8	32	18.2	36
	15 m	10.0	54	7.0	34	0.5	226	10.6	34	13.6	21	8.0	34	5.1	15
	20 m	10.6	54	3.2	3	1.3	25	4.2	76	1.8	202	3.3	52	2.2	22
Stn. B	1 m	13.6	62	11.2	127	19.4	84	14.1	50	20.5	93	14.4	82	15.5	114
	5 m	12.6	66	12.6	124	18.6	87	13.2	46	15.4	95	13.1	84	14.7	114
	10 m	4.9	91	13.2	128	13.9	71	15.0	61	12.0	85	10.7	85	10.3	116
	15 m	1.2	25	4.8	151	2.1	76	1.3	39	3.5	54	1.7	87	3.3	158
	20 m	2.2	29	3.3	138	2.1	46	3.2	106	3.4	147	2.0	108	1.9	198
	40 m	0.6	164	1.6	341	1.7	326	4.5	66	3.2	94	1.4	56	0.3	169
Stn. C	1 m	15.4	160	13.2	174	21.9	160	28.7	175	12.8	164	18.2	167	21.7	166
	5 m	16.9	168	14.6	177	20.2	164	25.7	172	13.5	152	18.0	168	20.6	166
	10 m	16.7	168	11.1	176	20.0	185	21.4	171	21.1	157	17.8	171	18.5	163
	15 m	3.4	187	10.4	162	13.3	159	14.3	198	12.8	190	10.4	179	5.6	149
	20 m	6.4	169	7.9	215	7.9	177	7.7	219	7.0	142	6.5	185	2.0	176
	40 m	0.7	207	3.9	196	2.3	182	4.0	161	3.2	177	2.7	180	0.6	180

This means that the gyre is limited to the epilimnion as pointed out by OKAMOTO (1968). The current speed in the surface layer shows the periodic time-variation, whose phase is almost inverse between Stn. A and Stn. C. This fluctuation with a period of about two days should be caused by the internal wave of the first mode in the north basin (KANARI 1975). Then, the arithmetical average of the five current measurements might represent the steady current component because the fluctuations due to internal waves should be removed. Fig. 3 shows the time-averaged current velocities in the surface layer (averaged of 1, 5 and 10 m depth) at three stations. This current pattern suggests the existence of the large counter-clockwise gyre with its center located at about 2 km north of Stn. B.

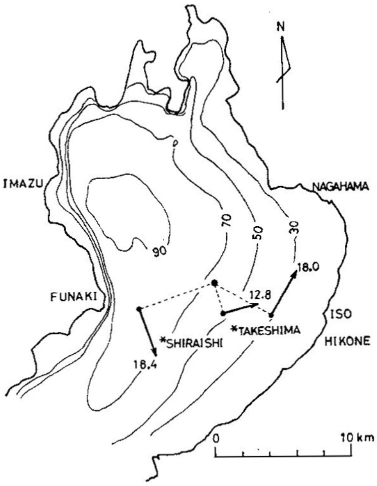

Fig. 3. Time-averaged velocity distribution in the surface layer (0—10 m), 8—10 September 1978. Numerals show the current speeds in cm/s. The estimated center of the gyre is also shown.

With regard to the validity of the geostrophic approximation, the comparisons have been made between the directly-measured current and the geostrophic current calculated from the observed water temperature distributions. For example, Fig. 4 shows the result of the comparison at Stn. B, in which the open circles indicate the directly-measured velocity components (north or east) and the solid curves represent the vertical profiles of the geostrophic velocity components obtained by means of a dynamical calculation and a least mean square method. In this figure, the measured currents appear quasi-geostrophic, but in some cases there are considerable differences between measured and geostrophic velocities. The similar results were obtained at the other two stations. This indicates that the geostrophic approximation is not so valid to the current observed at a specified place and time.

On the other hand, the time-averaged current is almost geostrophic as is shown in the right column of Table 1. It is quite interesting, however, that the current directions of the surface layer at Stn. B are deflected in about 30° to the left from those of the geostrophic currents. This means the convergence of the surface water and suggests the existence of a vertical circulation predicted by ENDOH (1978) based on the diagnostic analysis taking the vertical friction forces into consideration.

In order to evaluate the dynamics of the gyre, we calculated the magnitudes of some dynamical values (shown in Table 2) by the data of measured currents in the

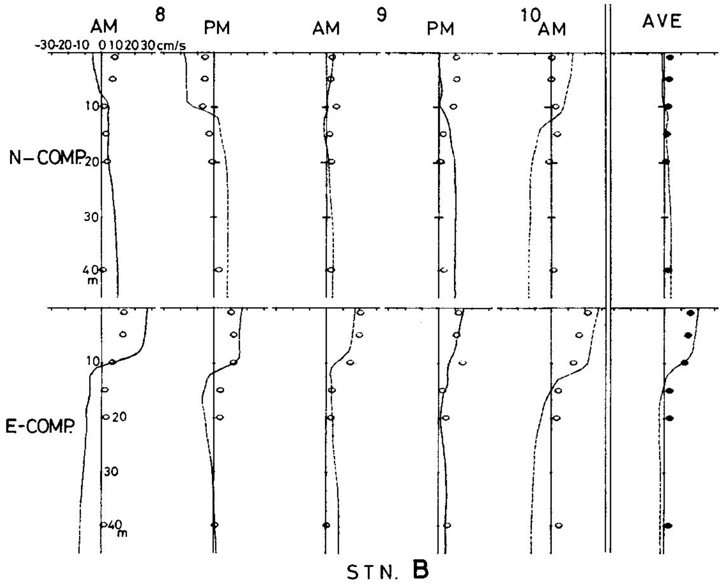

Fig. 4. Comparisons of the directly-measured velocities (open circles) with the geostrophic velocities (solid curves) with respect to the north and east components at Stn. B.

Table 2. Time-averaged current velocities in the surface layer (0–10 m), and the magnitudes of centrifugal and Coriolis forces ($f = 8.4 \times 10^{-5}\,s^{-1}$).

Station	Water depth (m)	Radius R (km)	Current Dir. (°)	Current Speed V	V/R $\times 10^{-5}s^{-1}$	V^2/R $\times 10^{-4}$ cm/s^2	fV $\times 10^{-4}$ cm/s^2
A	32	4.8	38	18.0	3.8	6.8	15.2
B	53	2.2	84	12.8	5.8	7.5	10.8
C	82	5.8	169	18.4	3.2	5.8	15.5

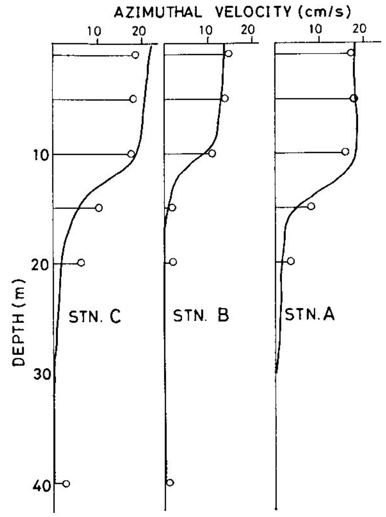

Fig. 5. Comparisons of the time-averaged azimuthal velocities between the directly measured and geostrophic currents including centrifugal effects.

surface layer. The angular speed (V/R) is high near the center of the gyre, whereas the centrifugal acceleration (V^2/R) is almost the same at three stations. It must be noticed that the centrifugal term is comparatively same order of magnitude with CORIOLIS term (fV) especially at Stn. B. This yields that the dynamical calculation must be done including the centrifugal forces. Fig. 5 shows the comparisons of the azimuthal velocity component of the measured current with the geostrophic current including the centrifugal forces. The values are time-averaged as mentioned above, and the depth of a level of no-motion was chosen at the depth of 50 m. In this figure, the considerable agreement can be seen between the measured and calculated currents. This suggests that the current, averaged with respect to time long enough to cancel the effect of the longest internal wave, can be dealt as the baroclinic geostrophic current including the centrifugal force.

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