2

Review of Geostropic Gyres

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There are many kinds of currents in Lake Biwa, having various time scales and dynamics, including wind-driven currents, density currents, inertial oscillations, and currents associated with seiches and internal waves (e.g. Okamoto, 1984). However, the water movement most characteristic of Lake Biwa is a large, well-defined, counter-clockwise cyclonic gyre which is consistently found in the epilimnion during the season of thermal stratification (May through November). Two other gyres, one clockwise and the other counter-clockwise, have also been observed in the lake. In this section, the observational and theoretical studies which have been performed on these gyres are briefly reviewed, and the characteristics of the gyres are described on the basis of the more recent studies.

The Kobe Marine Observatory first carried out systematic observations of Lake Biwa in the summer of 1925. These observations included measurements of currents using Ekman Merz and air-bubble current meters (Suda *et al.*, 1926). This work showed the existence of three gyres in the surface layer of the North Basin and these were named respectively from north to south, the First Gyre (counter-clockwise), the Second Gyre (clockwise) and the Third Gyre (counter-clockwise).

Since World War II, a number of current measurements have been made employing various methods, including the use of Lagrangian drifters. Morikawa and Okamoto (1960, 1962) released a great number of drifter bottles on the lake surface and confirmed the existence of the First and Second Gyres. Okamoto (1968) carried out a series of buoy trackings using cross-board drogues to measure the horizontal and vertical distribution of the water movement. Okumura and Yamamoto (1978) developed a radio tracking buoy system, and Endoh *et al* (1987) used radar to trace drifters with window-shade drogues over long periods of time, including during the night and under poor

Physical Processes in a Large Lake: Lake Biwa, Japan
Coastal and Estuarine Studies, Volume 48, Pages 7–13

weather conditions. Okuda and Yokoyama (1978) and Obayashi *et al.* (1982) applied aircraft and satellite remote sensing techniques to observe the water movement. Figure 2.1 depicts the locations of the gyres in Lake Biwa obtained by radar tracking of drifters in 1983 and 1986 (Endoh *et al.*, 1987). The third gyre is not shown as it was not clearly observed by radar.

Ekman Merz current meters, operated from a boat, have also been widely deployed (Suda *et al.*, 1926; Morikawa and Okamoto 1962). Automated current meters were introduced and developed in Lake Biwa during the late 1970s (e.g., Okumura, 1977). Endoh *et al.*, (1982) detailed the seasonal variation of the First Gyre by analyzing continuous records of current meters (Aanderaa RCM-4) taken at four stations. A series of continuous current measurements using automated current meters have been carried out successively since 1981 to reveal the spatial distribution and time variations of the current field in Lake Biwa (Okumura and Endoh, 1985; Endoh and Okumura, 1989). These measurements clarified the horizontal and vertical distributions of the gyre motions, the associated periodic current fluctuations, the response of the current to the wind, the characteristics of the current in the deeper layers and the current field in winter.

Okamoto and Morikawa (1961a) analyzed current and temperature data, and found that the gyres in Lake Biwa were in geostrophic balance. More recently, a number of observations on the water temperature field were made using thermistor and bathythermographs (Okamoto and Morikawa, 1961b; Okamoto, 1962, 1968; Kunishi *et al.*, 1967; Imawaki *et al.*, 1979; Endoh *et al.*, 1979, 1981). These observations demonstrated the existence of large amplitude fluctuations in water temperature which may be attributed to internal waves. To improve the geostrophic calculations, it was necessary to obtain time series of the water temperature and then use the time-averaged temperatures. Okamoto (1968) and Endoh and Okamoto (1981) established the validity of the geostrophic balance for the gyre current using simultaneous observation of currents and water temperatures. The results show that the geostrophic approximations were poor when comparing currents observed at a specified time. However, by averaging the current over time so as to cancel the effect of the slowest internal wave signals, such methods yielded serviceable approximations for baroclinic geostrophic gyres.

Endoh (1978) developed a diagnostic model to describe the current field more accurately using the observed water temperature field, and showed the existence of a large vertical circulation in the cyclonic gyre. Using this model, Endoh (1986) evaluated the seasonal variation of the mechanical (kinetic and available potential) energies in the First Gyre and discussed the formation and maintenance mechanisms of the gyres.

Numerical calculations have been performed to evaluate the formation mechanisms of the gyres. Imasato *et al* (1975) examined the wind-induced barotropic circulation and time variation of the lake level by integrating the linear equations, and found that a geostrophic counter-clockwise circulation could be sustained by a southerly wind. They also evaluated the structure and periods of the surface seiches driven by the wind. Oonishi and Imasato (1975) calculated the time variations of the barotropic current field driven by the wind using a rigid-lid assumption. They found that a depth-integrated gyre could be set up by a steady wind with a topographic curl. They also evaluated the behavior of a topographic Rossby wave with a period of about one week.

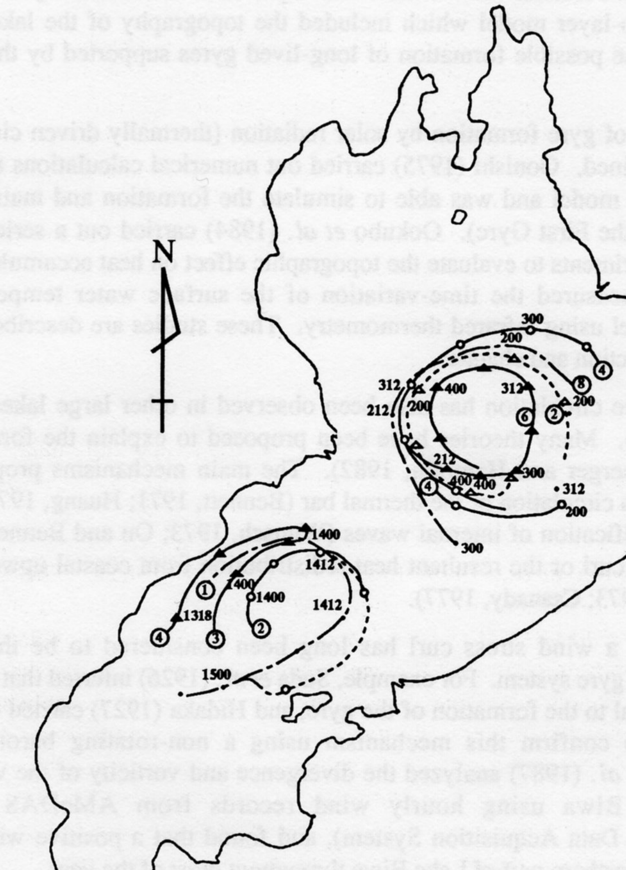

Figure 2.1. The surface gyre currents in the North Basin of Lake Biwa observed by radar tracking of drifters in 1983 and 1986 (after Endoh *et al.*, 1987). Numerals show day and hour (e.g. 312 means 1200 noon UT on 3rd September).

Two-layer models were developed to examine the wind-driven baroclinic current structure and the internal wave shear. Kanari (1974) calculated the structures of various modes of internal waves, especially the internal Kelvin wave. Kanari (1975) then carried out successive observations of the water temperature field in the summer and confirmed the structure of the internal Kelvin wave with a period of about two days. Endoh (1976) then used a two-layer model which included the topography of the lake bottom and demonstrated the possible formation of long-lived gyres supported by the wind stress curl.

The possibility of gyre formation by solar radiation (thermally driven circulation) has also been examined. Oonishi (1975) carried out numerical calculations using an axis-symmetric lake model and was able to simulate the formation and maintenance of a cyclonic gyre (the First Gyre). Ookubo *et al.* (1984) carried out a series of physical laboratory experiments to evaluate the topographic effect on heat accumulation. Itakura *et al.* (1990) measured the time-variation of the surface water temperature in the laboratory model using infrared thermometry. These studies are described in detail in the following section and chapter.

Cyclonic surface circulation has also been observed in other large lakes (Emery and Csanady, 1973). Many theories have been proposed to explain the formation of the gyres (*e.g.* Imberger and Hamblin, 1982). The main mechanisms proposed include thermally driven circulation or the thermal bar (Bennett, 1971, Huang, 1971), the Stokes drift or the rectification of internal waves (Wunsch, 1973; Ou and Bennett, 1979), and the wind stress curl or the resultant heat redistribution from coastal upwelling (Emery and Csanady, 1973; Csanady, 1977).

In Lake Biwa, a wind stress curl has long been considered to be the main force maintaining the gyre system. For example, Suda *et al* (1926) inferred that the prevailing wind was crucial to the formation of the gyre, and Hidaka (1927) carried out laboratory experiments to confirm this mechanism using a non-rotating barotropic model. Recently, Pu *et al* (1987) analyzed the divergence and vorticity of the wind over and around Lake Biwa using hourly wind records from AMeDAS (Automated Meteorological Data Acquisition System), and found that a positive wind stress curl dominates the northern part of Lake Biwa throughout most of the year.

Unequal solar heat capture (mentioned above as topographic heat accumulation leading to thermally driven currents) is considered another important force (Oonishi, 1975; Ookubo *et al.*, 1984). Endoh (1986) evaluated the energetics of the First Gyre with a diagnostic model and found the maximum energy content occurred in September. From both, the theory and experiments on thermally driven currents, it can be deduced that the maximum energy content should occur in July when the buoyancy flux is at its maximum. Thus, the gyral currents in Lake Biwa develop mainly by thermal effects in May and are maintained by the effects of both heating and wind stress curl thereafter. In autumn, when the heating effect declines, the gyral currents remain energized by the persisting wind stress curl.

The First Gyre in Lake Biwa is remarkably stable and regular, very close to a true circle when compared with the cyclonic circulation of other large lakes. It is not yet clear why this is so, but a possible explanation lies in the horizontal scale and depth of Lake Biwa. Csanady (1978) pointed out that maximum current energy is present in an area contained by the internal radius of deformation or about 5 km in Lake Biwa. This is much smaller than the lake dimensions, thus the lake boundaries are far removed from the gyre.

The currents of the gyres play an important role in the transportation and mixing of dissolved or suspended materials, i.e. the metabolism of the lake. It is well known that the electrical conductivity of the lake water is almost uniform in the offshore zone of the North Basin of Lake Biwa, due to the intense mixing and dispersion of the water by the gyral currents. Recently, very fine bottom sediment was found in the area corresponding to the center of the gyres (Kamitani, 1988). The mechanism for transporting the mud into the gyre has not yet been well explained, but the large vertical circulation associated with the gyre (Endoh, 1986) no doubt plays an important role in the transportation and selection of suspended materials.

In summary, the gyres in Lake Biwa have the following properties, based on the above observations:

1. The First Gyre exists almost continuously from May to November: i.e. during the stratification period. In winter the gyres are not observed.
2. Gyre currents develop rapidly, in parallel with the thermal stratification, in May. The maximum energy content of the First Gyre occurs in September. Thereafter, the energy of the gyre decreases gradually as winter approaches.
3. Gyre is found only in the epilimnion.
4. The time-averaged current is in geostrophic balance including the centrifugal force, but the instantaneous current is greatly complicated by the effects of internal waves, inertial oscillation, and wind-driven currents.
5. The current velocity is approximately 0.1 ms^{-1}, however, much stronger currents (> 0.3 ms^{-1}) are sometimes observed in summer.
6. The shape of the First Gyre is very close to a circle, and the maximum current speed is observed at 3 - 4 km from the gyre center.
7. The locations of the gyres differ significantly from those estimated previously from non-averaged data.

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