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Gyre generation after a typhoon-induced upwelling in a stratified lake.

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1) Introduction

Since its discovery by Soda 1924, the largest gyre in Lake Biwa, known as the “first gyre”, has been the topic of many studies over the years to clarify the processes that create the basin-scale cyclonic current system during the stratified period. Several study results of the ecosystem of Lake Biwa highlight the correlation between the biology of the lake and the first gyre. For instance Ishikawa et al. (2002) observed a patch of high concentration of microcystis at the centre of the expected location of the first gyre. Despite its ecological importance and their role on the large-scale dynamics of the lake, the energetics of the first gyre remain unclear.

Several hypotheses about the generation of the first gyre derive from these studies. Based on a laboratory experiment with a reduced model of Lake Biwa and heating lamps to model the solar heating, Ookubo et al. (1984) suggested the generation of a cyclonic gyre due to differential heating. Using a two-layer model Endoh et al 1995 concluded that the cyclonic gyre results from a positive wind stress curl during the stratified period. Akitomo et al. (2009) continued the investigation of the first gyre being generated by positive wind stress curl. They performed a six-year long three-dimensional numerical model of the lake's hydrodynamics, using observed meteorological forcings. By forcing the model with the wind stress curl component only, the outputs of the model are closer to observations than the other cases. Their results reinforce the hypothesis that positive wind stress curl on the lake generates the first gyre. They also suggest that the energy of the gyre reaches its peak during September and October. One should note that their results are based on monthly average spanning four years, and in general impulsive wind effects has not been investigated.

In addition to being the season of peak energy gyre strength, September and October are the months when typhoons most frequently strike the lake. However, in Lake Biwa, the hypothesis that a typhoon can generate a gyre has not been investigated. A typhoon-generated gyre need not be consistent with the hypothesis of the role of positive wind stress curl, as a wind field of uniform direction with varying magnitude can generate wind stress curl.

To investigate the assumption of a typhoon-generated gyre in Lake Biwa, we employ a three-dimensional numerical simulation of the response of the lake to a typhoon. We first describe the setup of the model and confirm the consistency with in-situ observations. We then analyze the outputs of the simulation to extract information about the generation of the first gyre. We chose to simulate the response of the lake to the typhoon Manyi, September 16th 2013, because the weather was clear enough to recover satellite image of the lake surface after the typhoon for qualitative check of the simulation.

2) Method and Results

Lake Biwa’s bathymetry (Figure 1a) exhibits steep slopes on the West side, and more gentle slopes on the East side. This bathymetry associated with the strong stratification during summer precludes the use of a sigma-level numerical model. Therefore, we use the three-dimensional z-level ocean model SUNTANS (Fringer et al. 2006) that solves the Navier-Stokes equations, using the approximation of hydrostatic pressure. Our unstructured grid resolves the lake with a horizontal resolution of about 180 meters (Figure 1b). We refined the grid at the rivers to a resolution lower than 100 meters (Figure 1c). We chose a non-uniform vertical resolution that concentrates grid points in the epilimnion. The water column is better resolved close to the surface with $\Delta z = 0.3$ meters, and increases to approximately 2 meters at the deepest parts of the lake.

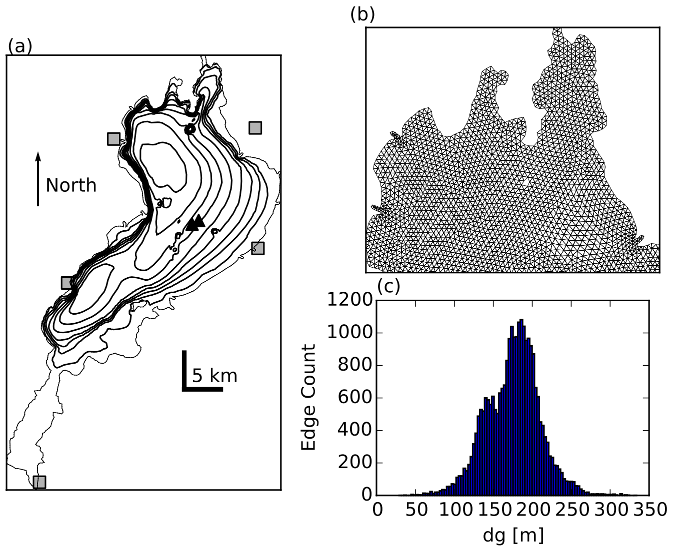

Figure 1: (a) Bathymetry of Lake Biwa with the isobaths (black lines), plotted every 10 meters. The black triangles at the centre of the lake indicate the location of water temperature observations from the Japanese Water Agency. The grey-filled squares indicate the location of JMA's meteorological stations.
(b): A zoomed-in version of the unstructured grid used in simulation of the lake's response to the typhoon Manyi.
(c): Distribution of the distance between neighbouring cells.

In the vicinity of the lake, five weather stations operated by the Japanese Meteorological Agency record hourly wind speed, wind direction and air temperature. These parameters have been interpolated using the Inverse Distance Weighting method. Other meteorological parameters needed for the estimation of heat fluxes are recorded hourly at only one station, hence we assume these parameters to be constant all over the lake. The wind stress and heat fluxes are computed using the COARE3.0 library implemented in SUNTANS.

At the centre of the lake, the Japanese Water Agency operates a profiling CTD, whence water

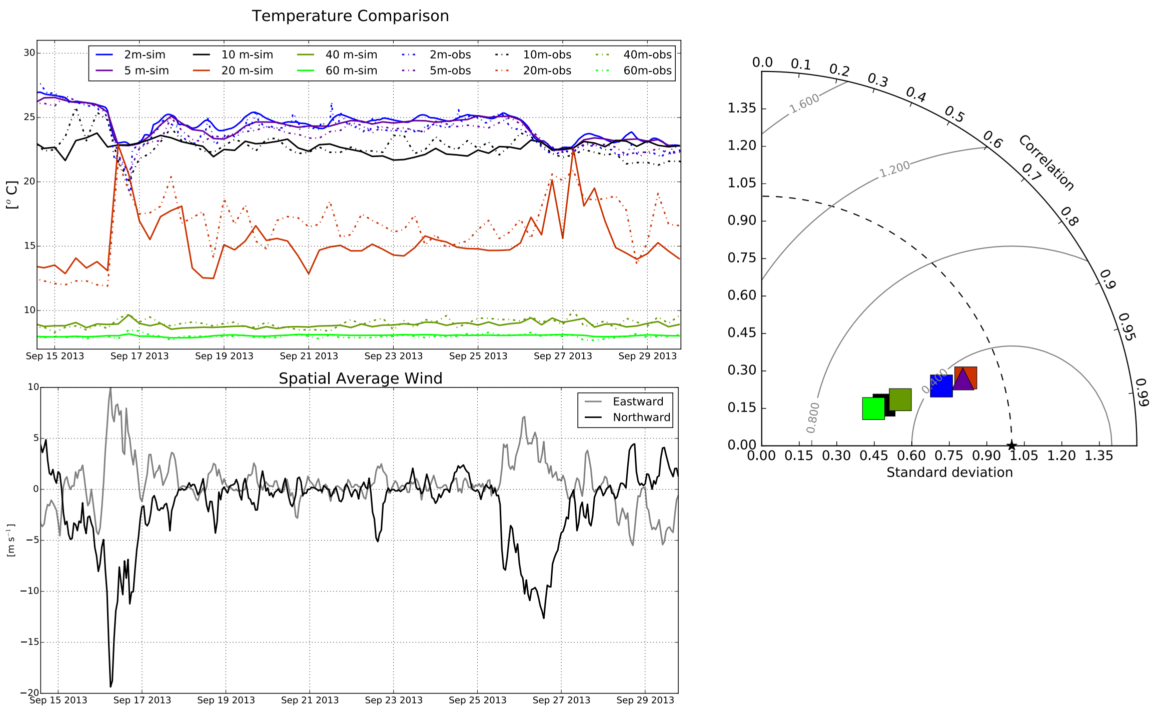

Figure 2: (a) Comparison of temperature between Simulation (solid lines) and observation (chain-dotted lines). Temperature was linearly interpolated vertically to match the depth of observed values. Simulated data points were taken at the same time as the observed data. (b) Taylor diagram describing our model. The colors of the the markers are consistent with the corresponding layer. The standard deviation values were normalised. The grey lines indicate the normalised root-mean-square difference between observed and simulated temperature. (c) Spatial average of the eastward (grey line) and northward (black line) components of the wind speed used as wind forcing to Lake Biwa.

temperature is logged hourly at 2m below the surface and every six hours at 5m, 10m, 20m, 40m and 60m below the surface. We start the simulation from a state of rest on September 1st 2013, which provides enough spin up time the typhoon arrival on September 16th 2013. We set the initial temperature profile as a piecewise linear interpolation between the one-week average water temperatures entered on September 1st, from the monitoring stations in the centre of the lake (Figure 1b).

We assess the consistency of the simulation by comparing the time series of simulated temperature with the observed temperatures at the centre of the lake, as shown in Figure 2a. Qualitatively, the simulation appears to consistently simulate the lakes's response to the wind forcing associated with typhoon Manyi. During the typhoon event on September 16th 2013, simulated and observed temperature decrease by about 3ºC within 10 meters of the surface, whereas the water temperature at 20 meters depth increases by about 10ºC. However after the cessation of the wind, the water temperatures return to values approaching those prior to the typhoon. This feature of the temperature time series suggests the occurrence of an upwelling caused by the typhoon. After the typhoon, from September 17th, the water temperature at 20 meters, which is considered to be within the thermocline, exhibits oscillations. Oscillations of the thermocline has been ascribed to large scale internal waves in Lake Biwa (Kanari 1974).

To quantitatively evaluate the consistency of our model, we display the Taylor diagram (Taylor 2001) of our water temperature results. In order to plot the assessment of each layer on the same graph, we normalised the standard deviation of simulated temperature at each depth by the standard deviation of the observed temperature at the corresponding depth. The obtained ratio is plotted as the radial distance in a cylindrical coordinate system, with angle corresponding to the correlation coefficient. Consequently a perfectly simulated water temperature would be located on the x-axis with a normalised standard deviation of 1. Although the correlation between observation and simulation appear substantial (greater than 0.9), the amplitude of the variations is underestimated in the lowest layers as the normalised standard deviation is lower than 0.6 for the water temperature at 40m and 60m depth.

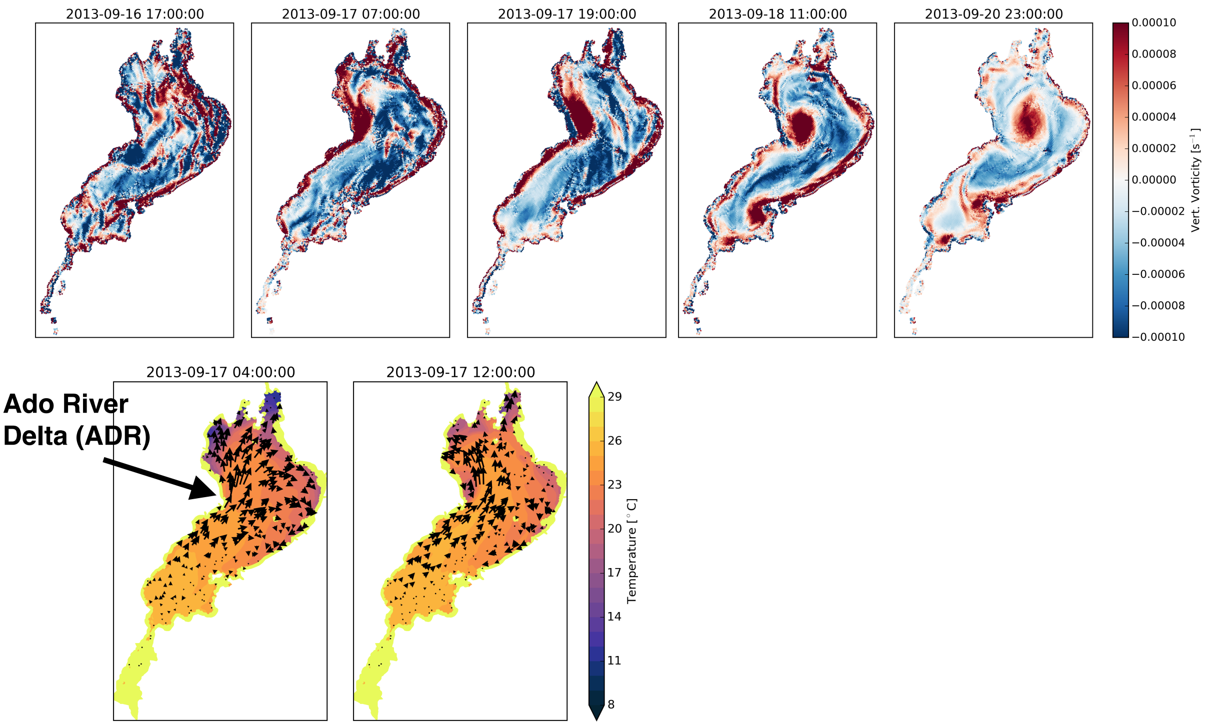

Figure 3: Vertical vorticity distributions at 5 m depth at several times. The first four snapshots indicate the distribution within two days after the typhoon Manyi. The last snapshot represents the distribution of vertical vorticity several days after the typhoon. (Second row): Temperature distribution at 5 m depth, in colorscale, with horizontal velocity current overlaid with black vectors.

3) Discussion

The "first gyre" in Lake Biwa is defined to be a cyclonic horizontal-velocity field in the surface layer in the northern part of the lake. Instead of analysing the velocity field, we have plotted the distribution of vertical vorticity at 5 meters depth (Figure 3). A couple of days after the typhoon, an elliptical patch of positive ,i.e. cyclonic, vorticity is seen in the northern part of the lake. Assuming the first gyre to be a circle with a diameter of 15 km, and current velocity reaching 20 cm/s (Akitomo et al 2009), one obtains a vorticity of the order 2.5 10^{-5} s^{-1}. This estimate is consistent with the average vorticity on the patch observed in our simulation.

Following the formation of the vorticity patch frame-by-frame (Figure 3), it originates from the western side of the lake, right after the cessation of the wind. The patch of positive vorticity appears close to the shore north of the Ado River Delta (ARD), and remains at this location for a couple of days. We also observe between the patch of positive vorticity and the boundary a strip of negative vorticity. The absolute value of the negative vorticity appears to increase over time, before the patch of positive vorticity is moves away from the boundary toward the centre of the lake.

The process responsible of the positive vorticity appearing north of the delta in the first place appears to be the separation and rollup of a boundary layer due to relaxation of the typhoon-generated upwelling. The upwelling was identified, in both simulation and MODIS sea surface temperature (not shown), by the presence of cold water in the northern part of the lake (Figure 3, September 17th 0400). When the upwelling re-equilibrates, the surface water returns northward and generates positive vorticity in a boundary layer south of the ARD (Figure 3, September 17th 1200).

In the oceanographic literature, the detachment of a patch of anticyclonic vorticity has been often associated with centrifugal instability (Dong et al 2007). Centrifugal instability occurs when the magnitude of anticyclonic vertical vorticity exceeds the Coriolis frequency. We test the hypothesis of centrifugal instability in computing the spatial average of vertical vorticity north of the delta (Figure 4), where the strip of negative vorticity is seen between the future gyre and the shore (Figure 3), as normalised by the Coriolis frequency (8.4 10^{-5} rad s^{-1} at the latitude of Lake Biwa). While the patch of positive vorticity remains bounded to the shore, until September 18th mid morning, the absolute value of the spatially averaged negative vorticity increases to value about six times larger than the Coriolis frequency. Several hour after this threshold the cyclonic starts moving away from the shore and is advected to the centre of the lake.

On several occasions, we note a filament of positive vorticity stretching toward the centre of the lake from the west shore, south of the delta (Figure 4, last two plan view of the vorticity distribution). We have

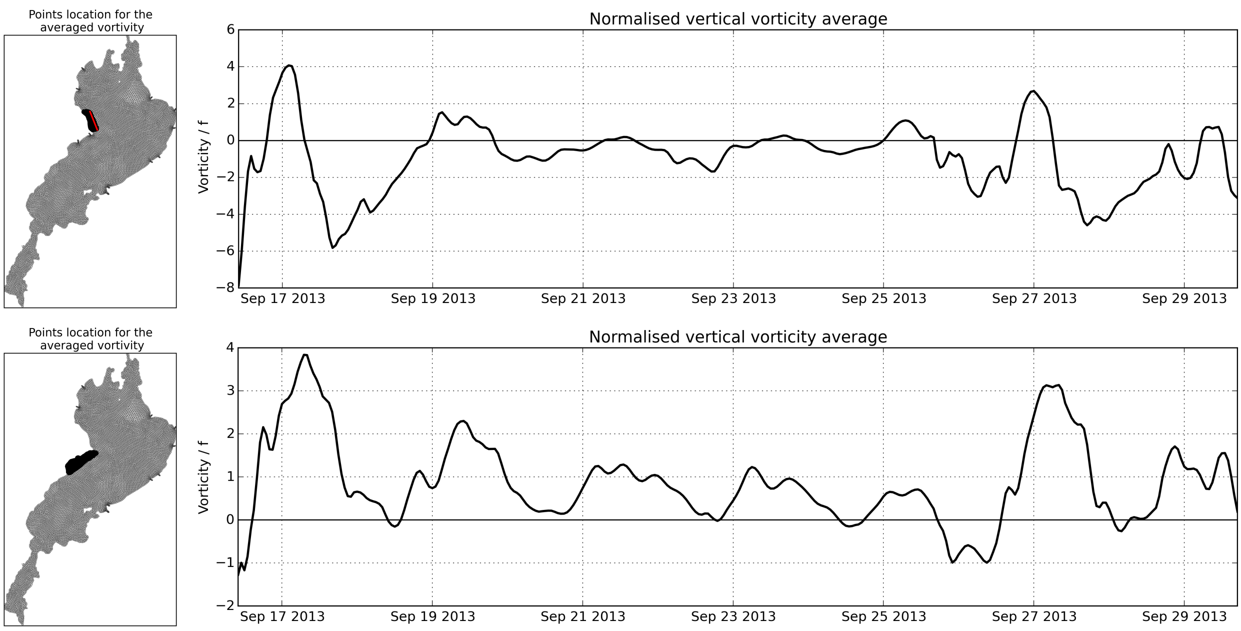

Figure 4: Time series of area-averaged vorticity at five meters depth, normalised by the Coriolis frequency, from two locations on the western shoreline. Location of the areas are blackened in the panels on the left.

computed the normalised spatial average of vorticity in a longshore strip south of the delta's tip. The time series of this normalised vorticity shows oscillations, with values greater than unity on several occasions, and with a period of about 48 hours, which is similar to the period of the internal Kelvin wave first mode that has been observed and simulated in past studies of Lake Biwa. We have checked the presence of a first mode internal Kelvin wave by performing an Empirical Orthogonal Functions analysis on the temperature distribution at 20 meters depth, e.g. within the thermocline. The first mode of the EOF analysis contains a substantial percentage of the total variance (45%), the principal component (temporal coefficient) of the first mode highlights the 48 hours oscillation (Figure 5). The spatial component of the EOF first mode shows negative values to the south and positive values to the north, which is consistent with an internal wave first mode. Similarly, the second mode of the EOF decomposition also detains a substantial fraction of the variance and a 48 hours oscillation. The eigenvector of the EOF, which by definition is orthogonal to the first eigenfunction, tilts roughly East to West.

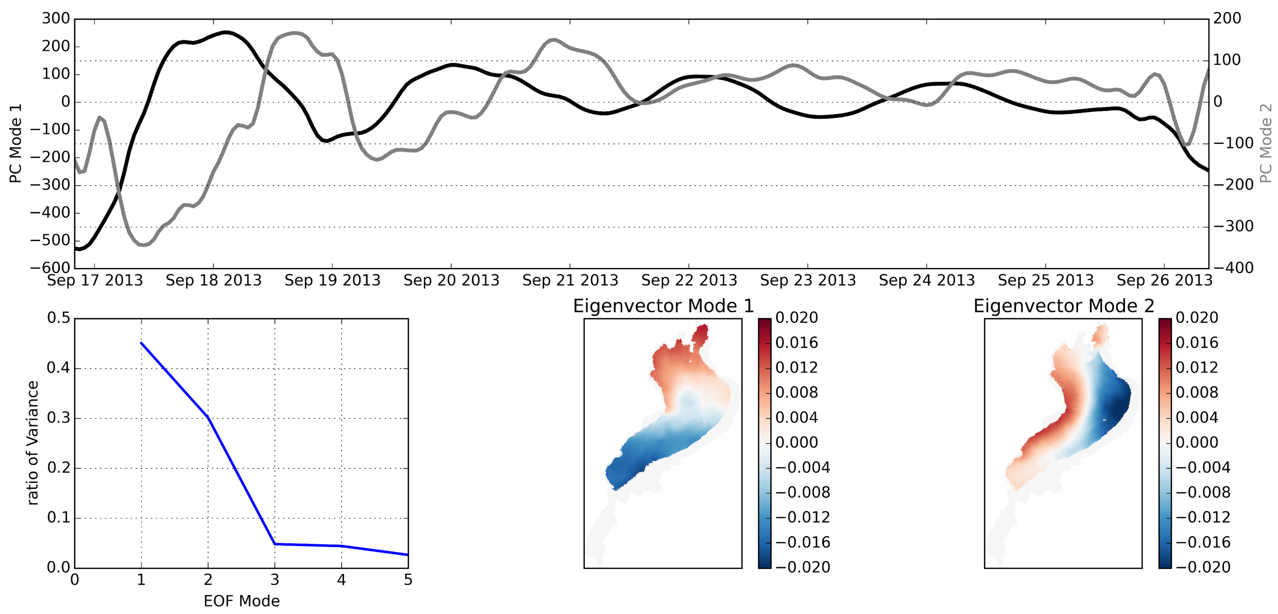

Figure 5: EOF decomposition of the temperature distribution at 20 m depth. Top panel: Principal Component of the Mode 1 (black line) an Mode 2 (in grey). Lower panel on the left: Ratio of the total variance detained by the Mode. Lower panel in the middle: Eigen vector (spatial coefficient) of the Mode 1. Lower panel on the right: Eigen vector of the Mode 2.

The internal wave field in Lake Biwa is dominated by internal Kelvin and Poincare waves. The internal Kelvin waves rotate cyclonically, with a period greater than the Coriolis frequency (about 1.2 10^{-5} Hz at Lake Biwa), whereas Poincaré waves rotate clockwisedly with a frequency greater than the Coriolis frequency. We compute the rotary spectrum of the 2D vector whose components are the first two principal components (Figure 6). The counter-clockwise part of the rotary spectrum confirms the presence of 48 hours oscillations, with a diffuse peak at 5.8 10^{-6} Hz. Moreover, we also note a peak at around 2.4 10^{-5} Hz, corresponding to a period of 12 hours, in the clockwise component. The 12 hours internal wave has been observed in previous studies of Lake Biwa and has been identified as an internal Poincare waves (Saggio and Imberger 1998).

The linkage between the positive vorticity south of the delta and the internal Kelvin wave first mode suggests a generation process dependant on the phase of the internal wave. Since horizontal currents associated with a Kelvin wave are stronger close to shore between the trough and the crest phases of the wave, the increase of vorticity should occur during the period between the extrema of the waves. The local maxima of the normalised vorticity (for example September 17th noon, and September 19th noon) in the lower panel in Figure 4 correspond the minima of the EOF mode 2 (Figure 5) at the same time. This correspondence alludes to a positive-vorticity patch building up during the crest-to-trough period south of the delta, and a decreasing vorticity after the trough of the wave.

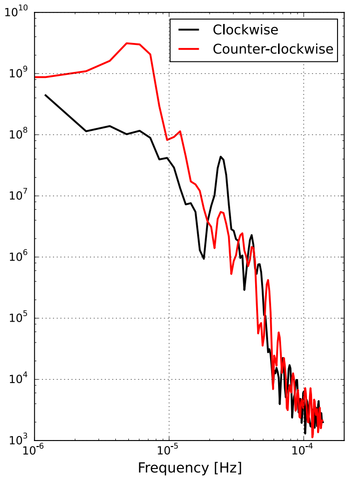

Figure 6: Rotary spectrum using the principal components of the EOF decomposition. The clockwise component of the spectrum is displayed in black and the anti-clockwise component of the spectrum is displayed in red

III) Conclusion

Using results from a three-dimensional numerical simulation, which consistency has been check against observation, we provide an explanation about the generation of a gyre-structure in Lake Biwa in September 2013. Previous studies on the generating process of Lake Biwa's first gyre suggest that either differential heating or a positive wind stress curl above the lake is the triggering process of the first gyre. But the energy of the gyre has been observed to increase during the stratified season. However, the stratified season is also the period when typhoons hit the lake, generating upwelling and internal waves.

We simulated Lake Biwa's response to the Typhoon Manyi, September 16th 2013, and we show the analysis of the results. Looking at the vorticity instead of the horizontal velocity field, we highlighted the presence of a positive vorticity patch at the centre of the lake, corresponding to a water rotating cyclonically, several days after the relaxation of a typhoon-generated upwelling. The positive-vorticity patch was created at the boundary north of the western delta and was detached because of centrifugal instability.

South of the western delta, we showed the periodic occurrence of substantial positive vorticity at the boundary that appear to be linked to the gyre-like structure in the centre of the lake. This positive vorticity event is related to the propagation of the internal Kelvin wave first mode, increasing during the trough-crest phase of the wave and decreasing during the crest-trough period.

Our results provide a comprehensive explanation about the reason why the energy of Lake Biwa's first gyre is maximum during September and October each year. Our results also suggest a possible transfer of energy from the internal wave field toward the first gyre due to boundary effect.

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