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日本琵琶湖中内波的垂直构造*

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P332.3

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提　要　在实施一个大型国际合作项目（BITEX'93）期间，作者在琵琶湖进行了一个大规模的内波野外观测．9台垂直系留的湖流观测及其旋转谱分析的结果表明：除了众所周知的开尔文波以外，在表层有风的日变化造成的周期为24h的顺时针旋转的强迫振荡．在温跃层，Poincare波的第一调式（mode）占主导地位．Poincare波使温跃层附近的湖流以周期16－18h顺时针旋转．在底层，周期为11h的不旋转的重力波非常明显．以上结果表明，在垂直方向的不同水层占主导地位的内波是不同的．

利用湖流的观测来研究内波的周期变化是一个很重要的方法．该方法可以把Poincare波从重力波中区分出来．地转效应是导致流场及风场旋转的根本原因．因此，控制该湖成层期内波的主要动力过程可归结为：风应力、成层、地转效应及湖岸制约．

关键词　琵琶湖　内波　流场观测　垂直构造

湖流

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Vertical Structure of Internal Waves in Lake Biwa, Japan

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Abstract　Field observations on internal waves in the North Basin of Lake Biwa were carried out during Biwako Transportation Experiment (BITEX'93). Rotary spectrum analyses of current show that beside the fundamental internal Kelvin waves, in the top epilimnion, there were waves rotating clockwise with a period of 24h which are thought to be wind－induced oscillations. In the thermocline, pure Poincare waves of their first mode were found, which were the governing mode at the depth. The Poincare waves made the current at that depth rotate clockwise with a period of 16 － 18h. In the hypolimnion bottom, seiches with a period of 11h were found which were not rotating and purely gravitational. All of these illustrate that there are different kinds of governing internal waves in different vertical zones.

Internal wave research by current measurement, an important method, can distinguish the Poincare waves from internal seiches. The earth rotation effects are responsible for the current rotation, as well as wind rotation phenomena. Thus, the important physical factors on internal wave dynamics during strati-

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fication period in the lake seem to be wind stress, stratification, Coriolis force and shore constraints.

Key Words Lake Biwa, internal waves, current measurement, vertical structure

Lake Biwa is a typical deep lake in the mid-latitude, Japan. During stratification period, there are three permanent gyres in the North Basin. The first one is located in the north part rotating counterclockwise, and the second one is in the middle rotating clockwise. The third one exists in the south part, rotating counterclockwise but it is relatively weak and unstable[1]. In the north and the middle part of the North Basin, the permanent movements, the gyres, are dominant and much stronger than the periodic ones, the internal waves. Therefore, one can expect that research on internal wave mechanics will be easy in the south part of the North Basin.

Several theoretical works and observations on internal wave mechanics have been carried out[2-8]. Firstly, in the Great Lakes of North America, researches show typical characteristics of free motions in large lakes. Using a simple theoretical *model Great Lake* with a circular basin of constant depth, containing two layers of fluid of slightly different density, subject to rotation, and having a diameter comparable to the dimensions of the Great Lakes, Csanady[3,9-11] illustrated the existence of some main classes of free internal waves. The most typical internal waves are Kelvin waves, rotating counterclockwise with a period more than the half pendulum day, and Poincare waves, rotating clockwise with a period slightly shorter than the half pendulum day. This model was thought to be overidealized and revised into a long rotating channel model[12]. In Lake Michigan, current observations by the thirty-eight station network were carried out over the approximate 2-year period in the Project GLIRB[13]. These observations confirmed the theoretical models mentioned above and indicated that the observed rotary currents in the interior of the lake to be a direct consequence of the excitation of the lower internal Poincare modes. Secondly, in small size lakes internal waves have been described by a lot of authors, which are basic, pure gravity uninodal form of free oscillation (for instance, Mortimer[14]). However, the internal wave dynamics in intermediate size lakes like Lake Biwa has not been well understood.

By field observations and numerical simulations, Kanari[15,16] confirmed the existence of internal Kelvin waves and pointed out that there exists only one mode of Kelvin waves in Lake Biwa. By continuous current measurements, Endoh, *et al*[17] illustrated the seasonal variation in periods of internal Poincare waves in the north part of the North Basin and emphasized that the water movement in the hypolimnion is strongly controlled by the internal waves.

In summer of 1993, continuous measurements of temperature and currents were carried out at several selected depths in the south part of the North Basin. Multiple kinds of internal waves were detected including linear, nonlinear, free and forced internal waves. A conspicuous aspect of these observations is the discovery of a vertical structure of internal waves.

The present paper describes this observation and emphasizes the vertical structure of these internal waves as illustrated with the rotary spectral analyses.

1 Field observation

1.1 Instrument locations(Fig.1)

By using a concept of "equivalent depth", Csanady[18] verified that the effect of depth variation across the transverse sections is likely to be quite small in the Great Lakes of North America. However, this effect is not negligible in Lake Biwa because the singular regions, where the thermocline surface intersects the bottom, occupy a large percentage of the transverse sections. The effects of such singular regions are hard to elucidate for the mathematical difficulty. During BITEX'93, for the simplicity of theoretical analyses and also for the significance of internal wave observation, nine current meters (ACM) were moored vertically on Sta. N with depth of 52m (Fig. 1), which is located in the middle of a transverse section. On the west side of the lake, an anemometer was supported to record wind velocity and direction. Another anemometer was installed in the middle of the lake (Fig.1). As well known, the wind characteristics is variable over the lake. These anemometers provided quite reliable wind information just near the observation point of current.

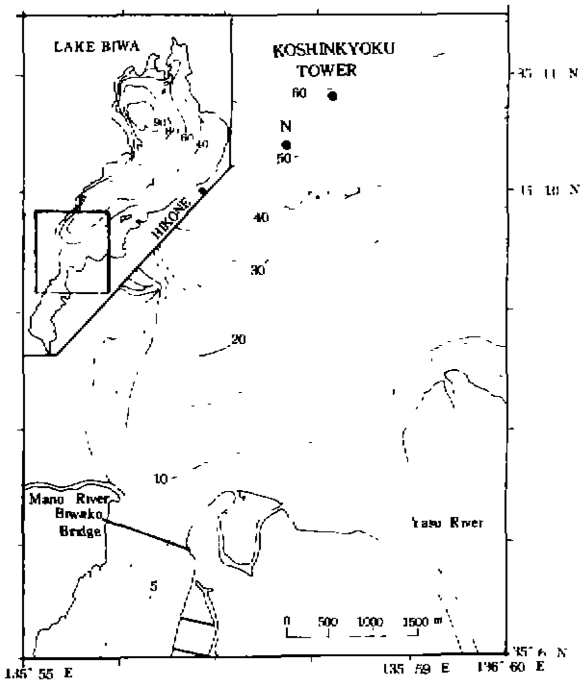


Fig.1 A map of the transition between north and south basins of Lake Biwa. The depths contours at 10m internal are shown by solid lines. St.N carries 9 electromagnetic current neters. The Koshinkyoku tower carries an automatic anemometer St Horai carries another automatic anemometer

It should be mentioned that these devices were only a part of the instrumentation during BITEX'93.

2.2 Design of the mooring system (Fig.2)

A schematic map of the mooring system is shown in Figure 2. The sensors of the nine electromagnetic current meters are located at depths of 8.7m, 13.5m, 17.8m, 22.5m, 27.2m, 36.6m, 45.8m, 49.5m and 51.4m, respectivehy. The current meters are equipped with temperature, conductivity, pressure, turbidity sensors as well as three dimensional current sensors. The burst time of this measurement was 10min, and the sampling number was 30 at each burst time. One of the anemometer was installed on an automatic meteorological station (Sta. Horai) with sensors of wind velocity, wind direction, air temperature, radiation and precipitation. The other anemometer was installed on a tower floating in the middle of the lake, which is called Koshinkyoku (Fig.1). The current meters and the anemometers were interrogated at 10 min inter-

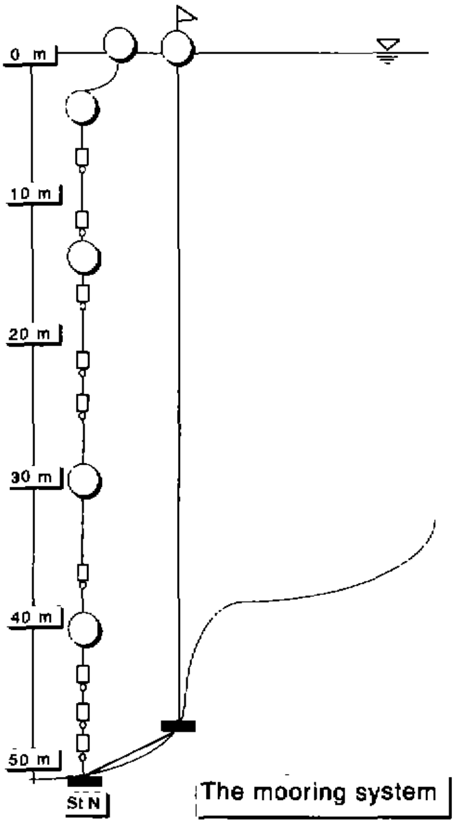


Fig.2 Schematic diagram of the mooring system The current meter chain was moored at 52m depth with 9 electromagnetic current meters at various selected depths(8.7－51.4m)

vals. The current observation was carried out from August 13th until September 13th, 1993, while the anemometer was done from August 22nd to September 11th, 1993. The current meters and the anemometers were operated simultaneously almost throughout the observation period. The mooring system as shown in Figure 2 has not been used in Lake Biwa by other authors and is thought to be specifically useful to show the vertical structure of internal waves.

In this paper, internal waves are classified in terms of periodicity and rotary characteristics of currents. This periodicity sometimes is strongly interrupted by some aperiodic events such as typhoons and other synoptic meteorological disturbances. Furthermore, some spectrum analyses methods like FFT (Fast Fourier Transform) have a disadvantage of instability. Therefore, a large volume of samples in necessary for this kind of analyses. For internal wave analyses with a period of 24h or more, the data with a time length of at least 30d are thought to be needed to calculate the spectrum accurately.

1.3 Wind during the observation period

During the observation period, there were three typhoons passing over the lake, that is, Typhoons No. 9311, No.9313 and No.9314, among which Typhoon 9313 was strongest in wind velocity.

According to Edagawa[19], the local winds in the north part of Lake Biwa are rotating clockwise with a period of 24 h. Similar phenomena were also detected by our anemometer during the observation period. The fundamental feature of the winds over Lake Biwa was the rotating winds with 24h period superimposed by some events such as typhoons and other synoptic meteorological disturbances. In other words, periodic components were superimposed by some aperiodic components.

2 Rotary spectrum analyses

2.1 Data processing

Current and wind data by BITEX'93 are processed by performing spectral analyses. Contrary to rivers, the current in lakes flows in every directions, i.e., in the range of 360 degree. The spectrum analyses by one-direction component are not enough to display current in lakes twodimensionally, which stimulates the usage of Rotary Spectrum Analyses[20].

By the combination of current components, a complex function can be acquired as follows:

$$z(t) = u(t) + iv(t) \tag{1}$$

where $u(t)$ is the time series of North-South component of current, and $v(t)$ is East-West component.

The complex Fourier transform of $z(t)$ is as follows:

$$Z(\omega) = \int_{-\infty}^{\infty} z(t)e^{-i\omega t}\mathrm{d}t \tag{2}$$

The complex inverse-Fourier transform of $Z(\omega)$ can be obtained:

$$z(t) = \int_{-\infty}^{\infty} Z(\omega)e^{i\omega t}\mathrm{d}t \tag{3}$$

Eq.(2) can be divided into two parts, that is:

$$Z_+(\omega) = \int_{-\infty}^{\infty} z(t)e^{-i\omega t}\mathrm{d}t; \quad Z_-(\omega) = \int_{-\infty}^{\infty} z(t)e^{i\omega t}\mathrm{d}t \tag{4}$$

Finally, the counterclockwise spectrum is defined as:

$$S_+(\omega) = [2\pi Z_+^*(\omega)Z_+(\omega)]/T \tag{5}$$

to express the tendency for current to rotate counterclockwise. Similarly, the clockwise spectrum is defined as:

$$S_-(\omega) = [2\pi Z_-^*(\omega)Z_-(\omega)]/T \tag{6}$$

to express the tendency for current to rotate clockwise, where T is the time length of the data, while $Z_+^*(\omega)$ and $Z_-^*(\omega)$ are the conjugate complex of $Z_+(\omega)$ and $Z_-(\omega)$ respectively.

The FFT method is chosen to deal with the huge volume of the data. In order to filter out high frequency components in the spectra, which will not be discussed in this paper, Hanning filter[21] was used. To overcome the instability disadvantage of FFT method, following process was carried out; By sub-samples of the data, that is, a selected portion of the data, several spectrum functions (clockwise or counterclockwise) can be obtained, for instance, $S_i(\omega)$. The average of these spectrum functions is as follows:

$$\overline{S}(\omega) = \frac{1}{n}\sum_{i=1}^{n} S_i(\omega) \tag{7}$$

where n is the total number of the sub-samples. The averaged spectrum functions will be used for analyses.

2.2 Results of the rotary spectrum analyses

The 9 ACM current meters were arranged vertically at Sta. N, which formed a current meter chain and covered a range from the eplimnion to the hypolimnion. The strength levels of current at each layer were different from each other, which makes the spectrum functions at each layer to be quite different even by orders. In order to compare these spectrum functions with each other, non-dimensional spectrum functions are defined as:

$$\widetilde{S}(\omega) = S(\omega)/\max[S(\omega)] \tag{8}$$

where max[$S(\omega)$] is the maximum of the spectrum function $S(\omega)$. The non-dimensional spectrum is called relative spectrum.

Figure 3 shows the counterclockwise (a) and clockwise (b) power spectral distribution of current at the 9 layers respectively. All the values are expressed by the relative spectrum mentioned above. In Fig. 3(a), the spectra have dominant energy peaks at about 11h in the hypolimnion and the other dominant energy peaks at about 48h in almost all layers except surface and bottom layers. Other relative maxima in the individual spectral distribution are less conspicuous (though with some exceptions). So there are two kinds of major internal waves with periods of 11h and 48 hours respectively in the counterclockwise meanings.

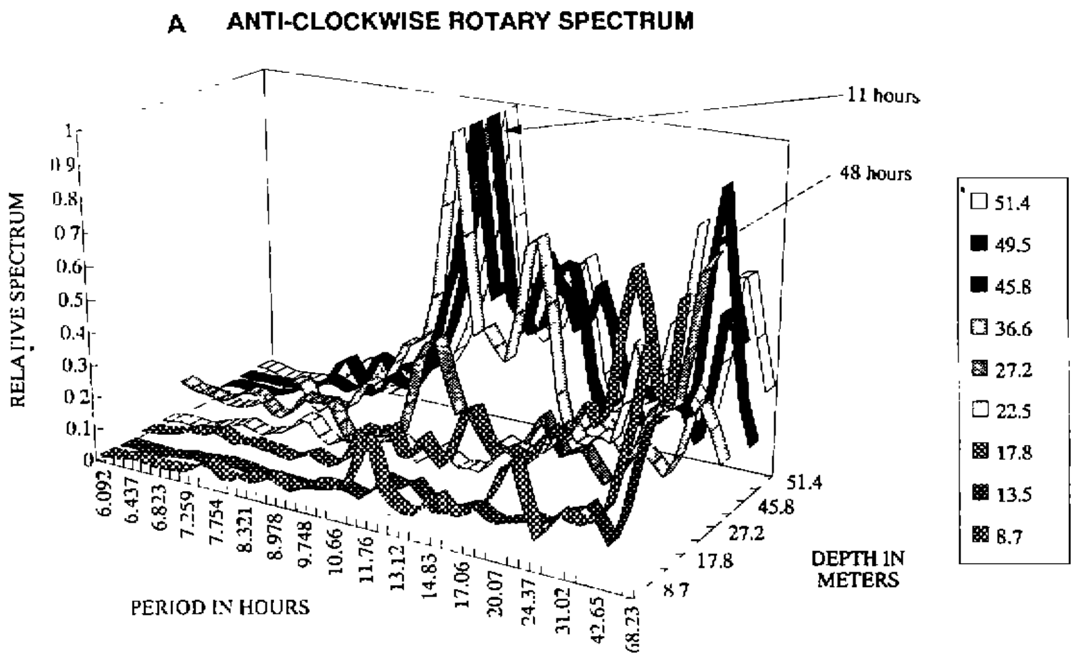
In Fig. 3(b), there are 3 dominant peaks. In the hypolimnion, energy peaks at about 11h are dominant. The peaks at about 16 – 18h are governing in the metalimnion. Lastly, the dominant peak with a period of 24h at 8.7m, the upmost layer in our mooring system, can be clearly seen.

As will be explained later, the spectrum peak at 8.7m with a period of 24h is extraordinary to the traditional theories. To analyze it further, the rotary spectrum (clockwise and counterclockwise) of current at this depth is shown in Figure 4(a), in which the spectrum peak, pointed by an arrow, is not only a relative maximum in clockwise spectrum but also a governing peak between clockwise and counterclockwise spectra. Figure 4(b) shows the rotary spectrum distribution of wind on Horai automatic meteorological station, in which the clockwise spectrum peak, pointed by an arrow, is a governing peak between clockwise and counterclockwise spectra. The spectrum of wind on Koshinkyoku tower station also shows a peak with the period of 24h but less conspicuous.

3 Discussion

The rotary spectrum analyses indicate that there were several kinds of internal waves with different periods prevailing in different layers. It is interesting to investigate them individually.

Firstly, in the surface layer (the epilimnion), a clockwise spectrum peak with a period of 24h is dominant (Fig. 3(b)), which disagrees with the traditional internal wave theories. According to Csanady[3], the internal waves with a period longer than the half pendulum day (about 21h in Lake Biwa) should rotate counterclockwise, which was confirmed by Kanari[16] to be internal Kelvin waves of their first mode. The discrepancy between the observations and these theories suggests that the peak was not caused by internal process and promotes us to search for the cause from outside. The rotary spectrum analyses of current and wind (Fig. 4) give us a reliable evidence that the waves in the epilimnion were wind-induced oscillations. More directly, the correspondence between wind and current can be found in Figure 5. This direct inspection is perhaps more objective than spectrum analyses. A careful inspection of wind (in the upper part of Fig. 5) reveals a conspicuous daily cycle mainly along the lake's axis. At the Koshinkyoku station, this signal was weaker and sometimes overshadowed by relatively strong wind gusts, which reveals the



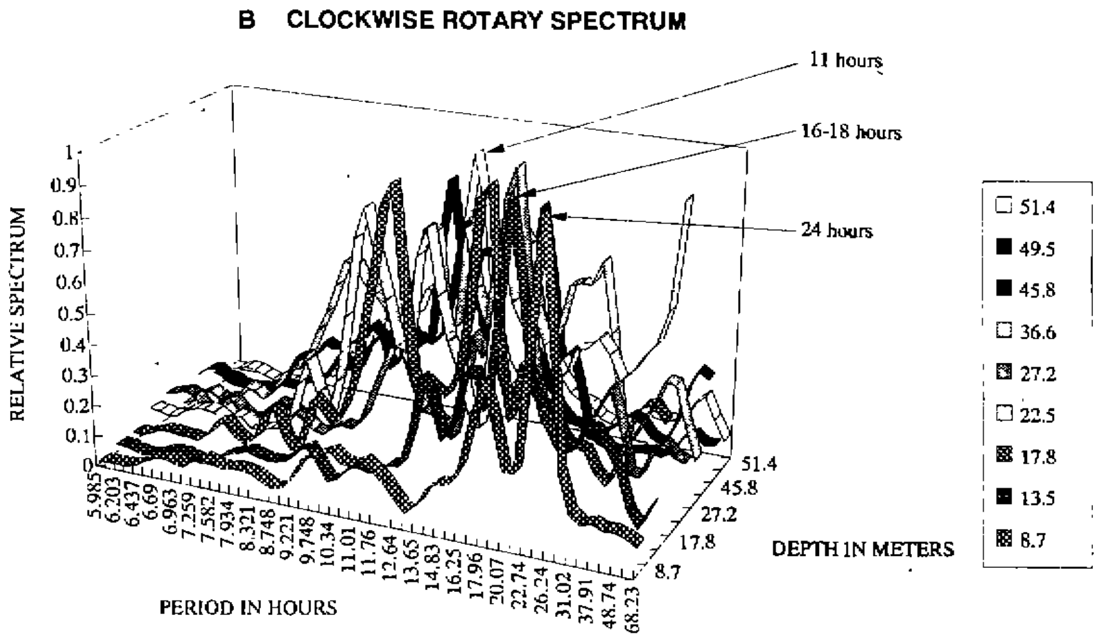
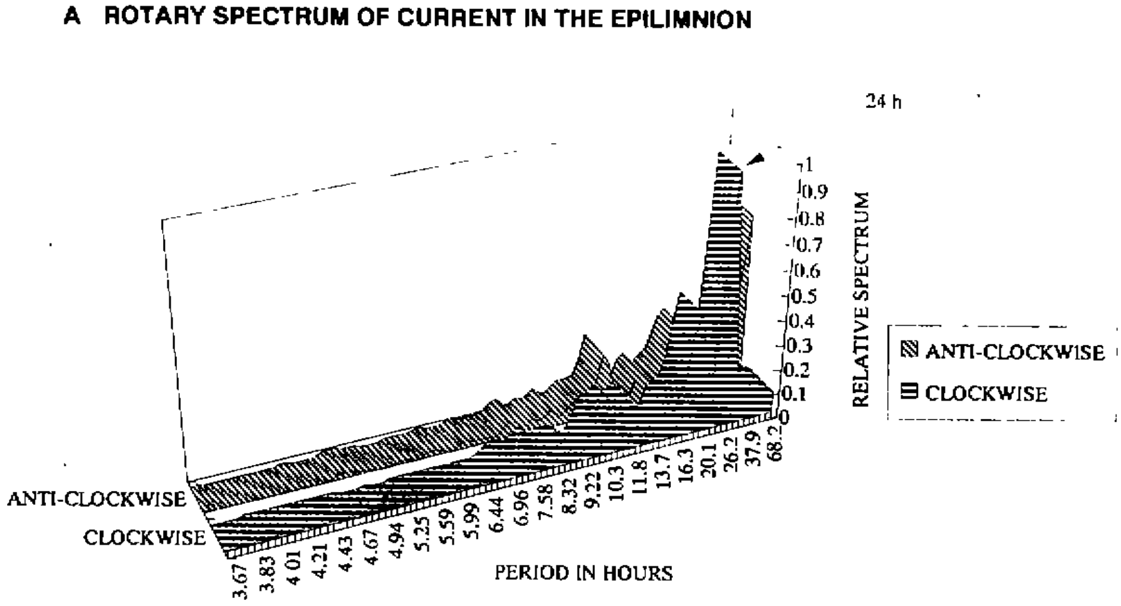


Fig. 3 The distribution of anti-clockwise rotary spectra (a) and clockwise rotary spectra (b) of current in the 9 layers. Current data from Aug. 13th to Sep. 13th, 1993 were used for the spectrum analysis



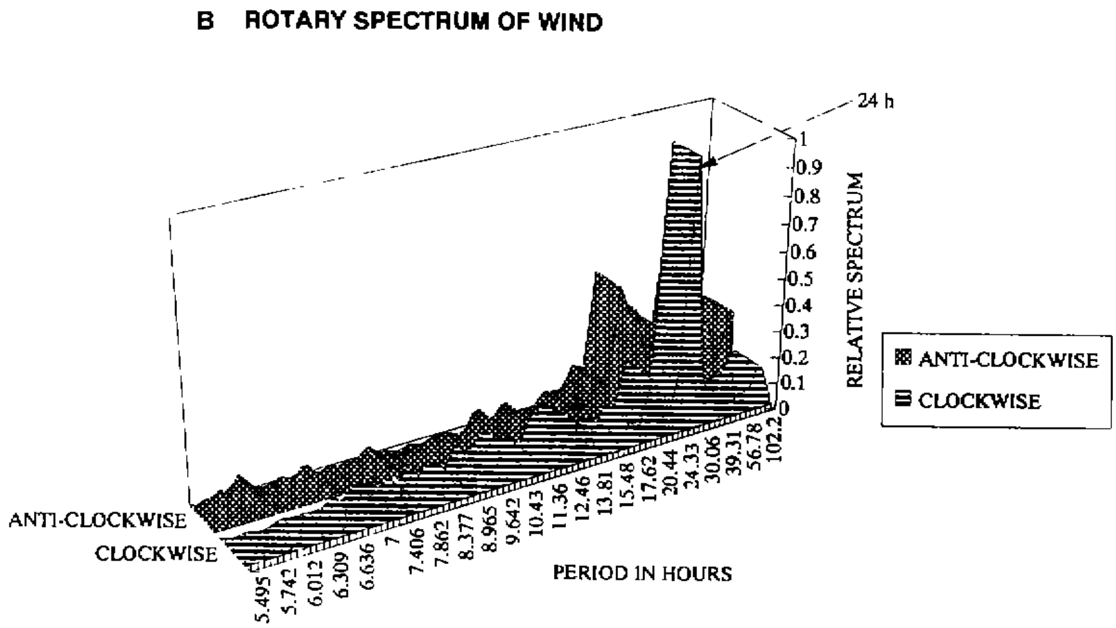


Fig.4 Rotary spectra of current (a) at 8.7m depth and of wind(b) on St. Horai. Current data from Aug.13th to Sep 13th, as well as wind data from Aug. 22nd to Sep. 11th, 1993 were used for analysis

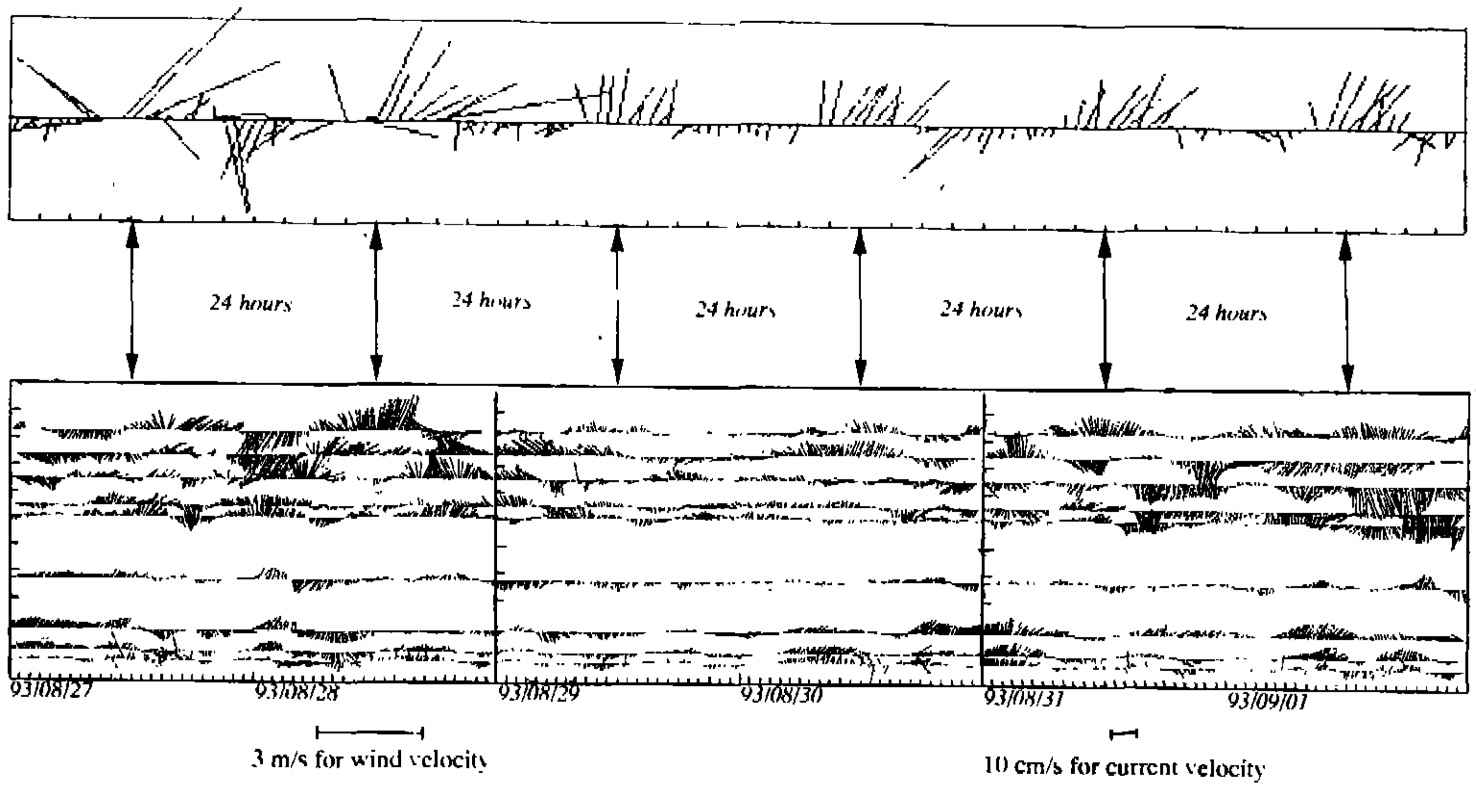


Fig.5 Wind velocity at St. Horai and current vectors at St.N in the 9 layers from Aug. 27th to Sep. 1st, 1993 with the north axix positive upward and the east axis positve to the right.

The arrows are poltted at high noons which are also the time for wind and current to reach their maximum velocities.

The scales of wind velocity and current are shown at the bottom.

spatial inhomogeneities of wind over the lake. The daily cycle of wind shows that the wind over Lake Biwa seems to be channeled along the lake by the mountains on the two sides. The result of direct inspections that the current was in-phase with the wind confirms again that the oscillations in the epilimnion were produced by resonant wind forcing (Fig. 5). It is noteworthy that these oscillations only appeared in the epilimnion and can not be seen by temperature measurements because surface layer is an isothermal zone.

Secondly, the internal waves rotating counterclockwise with a period of 48h and rotating clockwise with a period of 16 – 18h were dominant in the metalimnion as shown in Fig. 3. the former were internal Kelvin waves, which have been investigated by Kanari[16] and out of the range of this paper. Its periodicity and rotating characteristics indicate that the latter were internl Poincare waves. Internal Poincare waves were governing in the metalimnion even in the normal wind situations.

Finally, near the bottom, the dominant peaks with a period of about 11h existed both in the counterclockwise spectra and in the clockwise spectra (Fig. 3), which means that these oscillations were not rotating but purely gravitational. A direct inspection of current near the bottom reveals that the analyses mentioned above are generally right but not exactly right. This inconsistency is thought to be the result from the influence of internal waves in the metalimnion (clockwise and counterclockwise ones), because sometimes the internal waves with large amplitudes can be triggered by strong winds.

These internal waves presented above compose a vertical structure, as shown in Figure 6, which seems to be caused by basin constraints. According to Csanady[10], the generation of internal waves in lakes, which are much longer than they are wide, can be studied on the assumption that end effects are negligible. By this assumption, this kind of lakes can be abstracted by a long rotating channel model. One can not expect that this model give an accurate description of internal waves in Lake Biwa, but some qualified results should be possible.

By this two layer model, the frequencies σ_n of internal free oscillations in a lake can be obtained as follows[12]:

$$\sigma_n^2 = f^2 + C_2^2\left(\frac{n\pi}{b}\right)^2, n = 1, 3, 5, \cdots \quad (9)$$

$$C_2 = \{g(\rho' - \rho)hh'/[\rho + (h + h')]\}^{1/2} \quad (10)$$

where C_2 is the propagation velocity of internal waves; f the Coriolis parameter; n the mode number; b the width of the lake; h and h' are top and bottom layer equilibrium depths respectively; ρ and ρ' are densities correspondingly.

Eq. (9) shows that the frequencies of internal waves are determined by the earth rotation effects and basin constraints (through the width b). In large size lakes such as the Great Lakes in North America, b is very large, which makes the second term on the right side of Eq. (9) much smaller than the first term. Therefore, the earth rotation effect is the governing factor, and the internal waves rotate clockwise with a period of near the half pendulum day (the period corresponding to the frequency f). Contrarily, if the width b is small, the second term on the right side of Eq. (9) will overcome the first term to become dominant, and the internal waves become purely gravitational waves, on which the earth rotation has less effects. Because of its mid-width in the metalimnion in Lake Biwa (relative to the Rossby radius of deformation), the frequencies of internal waves in it are determined by the combination of the earth rotation effect and the basin constraints. However, near the bottom of the lake, the width is much smaller, which makes the internal waves to be almost purely gravitational waves without rotation, that is, non-rotating seiches. Therefore, it is the basin constraints that produced the vertical structure of the internal waves in Lake Biwa.

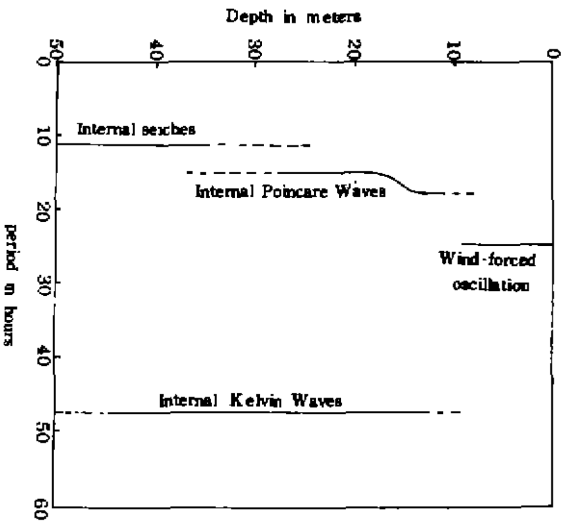


Fig 6 Vertical structure of internal waves at St. N in Lake Biwa during stratification period

4 Conclusions

The vertical structure of several kinds of internal waves was discovered in Lake Biwa. This structure can be summarized into following conclusions as described in Tab. 1. The fundamental internal waves are Kelvin waves, which affect the current in almost all the depth, but in the epilimnion and near the bottom, the influences are secondary. The internal Poincare waves are dominant in the metalimnion, especially at the mid-thermocline where the river intrusions often occur. One can expect that the internal Poincare waves may have considerable improtance in the dispersion of any effluents discharged from rivers. Near the bottom, the internal gravitational seiches are governing. The dominance of such motions near the botton should again have interesting consequences for the maintenance of the benthic nepheloid layer, which is often observed near the bottom of the sampling point in summers. The topographic constraints effects are thought to be responsible for this structure.

Tab. 1 Periodic internal waves in Lake Biwa observed in BITEX'93

Periodic internal waves	Kelvin waves	Wind-forced oscillations	Poincare waves	Transverse seiches
Period	2d	24h	16 − 18 h	11.372 h
Rotational direction	Anti-clockwise	Clockwise	Clockwise	Non-rotational
Free or forced oscillation	Free	Forced	Free	Free
Effective depth	All depth	Epilimnion	Metalimnion	Hypolimnion
Effective mode	First mode		First mode	First mode

Another conspicuous feature of the internal waves in the lake is that their wave parameters such as the frequencies are changeable place to place. The global characteristics of the internal waves in the lake has not been well understood. Further research may be productive if several point observations with similar mooring systems as mentioned in this paper are carried out.

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