Observation of the interface oscillation and the flow which originates due to the interface oscillation in Lake Nakaumi

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ABSTRACT: Lake Nakaumi connected with the Sea of Japan has a strong pycnocline. Wind and tide are external forces causing the interface oscillation. These external forces are classified by the diurnal period components from that over the day period components. We observed the interface oscillation and the flow which originates due to this oscillation using ADCP, STD, fish finder, new observation system (the track point system) and other equipment. It was deduced from the results that; (1) Yonago bay has longer period and larger amplitude interface oscillation than the central part of the lake. (2) As the interface oscillation originates by the strong wind in the central part of the lake, it can easily propagate into the Yonago bay. By the flow with this progressive wave, the mass of the bay inner part is transported in the mouth of bay direction.

1 INTRODUCTION

Lake Nakaumi connected with the Sea of Japan is a representative brackish lake in Japan. In brackish lakes, the flow field which controls water quality environment is regulated by meteorological conditions, then the study on the relationship between external forces (the changes in meteorological conditions), flow field and water quality environment has been advanced in Lake Nakaumi (Hibino et al., 1997, Fukuoka et al., 1999).

In this lake, a strong pycnocline has been formed, and this has become a cause of water quality problem such as depletion of oxygen in the bottom layer. The density interface always oscillates by inclinations and internal seiche that are originated by tides and wind drift. (In this paper, the movement of these interfaces is named the interface oscillation collectively.) Fukuoka et al. (1999) have clarified that the flow with the interface oscillation contributes to the transfer of the water mass, and it affected the water quality change in the Yonago bay from the observation. Therefore, it is necessary to analyze the external forces responsible for those oscillations.

In this study, the interface oscillation and the flow originating from this oscillation that characterizes the flow field are examined.

2 STUDY SITE AND METHODS

2.1 Study site

Lake Nakaumi is connected with the Sea of Japan by the Sakai Channel (length, 7.5km), and with Lake Shinji by the Ohashi River (length, 7.5km) as shown in Figure 1. The water area is 86.2km^2, and second biggest brackish lake in Japan. A stable pycnocline has been formed near 2~6m water depth in the

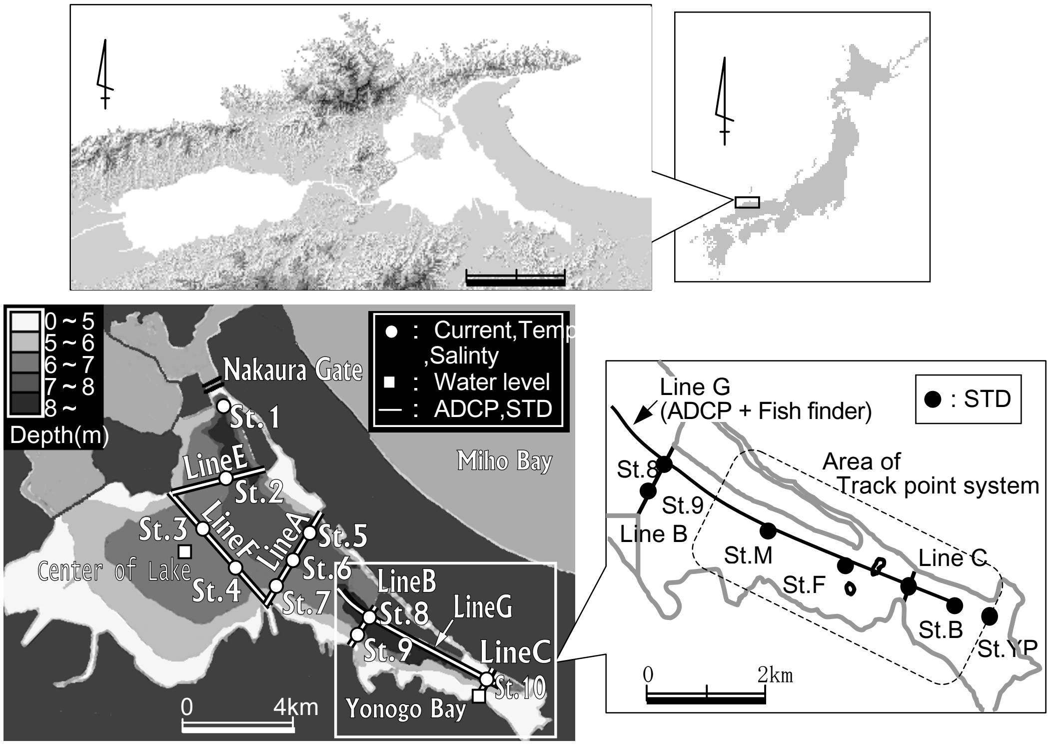


Figure 1: Location of Lake Nakaumi and observation points and the water depth distribution.

whole area throughout the annual by the density difference between water of salinity 5~10‰ in upper layer and water of salinity 25~30‰ in bottom layer. This Lake is divided into, the central part and the Yonago bay from topographical features. The Yonago bay exists in the southeast slenderly stretches, and is more enclosed. In regard to the bed shape, the valley landform (water depth, 8~14m) has been formed from the Nakaura gate to the Yonago bay. The water depth in center of lake is about 6.5m.

2.2 Methods

We carried out observations continuously in 1996/11/18-12/17 (for 30 days), 1997/9/22-10/6 (for 15 days) and 1998/9/13-10/12 (for 30 days), and during each period concentrated observations for one day in 1996/11/29-30, 1997/10/3-4 and 1998/9/28-29. In the continuous observations, current velocity and direction, water temperature and in upper layer (1m under the water surface) and bottom layer (1m above the bed) of St.1~10 (○ symbol in Figure 1) were observed. In the concentrated observations, vertical distributions of water temperature, salinity and flow condition were observed using STD, ADCP and fish finder in mainly the Yonago bay. Fish finder was operated to locate the density interface.

Moreover, in order to know the relationship between mass transport and flow, we developed a new observation system (the track point system) which tracked the horizontal position of the sampler. The track point system is composed of the transponder which is made to submerge in the water, the hydrophone which receives signals from that and the command display module which indicates its signals (paths) as shown in Figure 2. The transponder was submerged to a fixed depth by adjusting its density. The principle of the measurement is that the hydrophone which is fixed on the observation station sends pulse of 19 kHz in the constant period to the transponder, the transponder sends back the supersonic waves of 23~29kHz to the

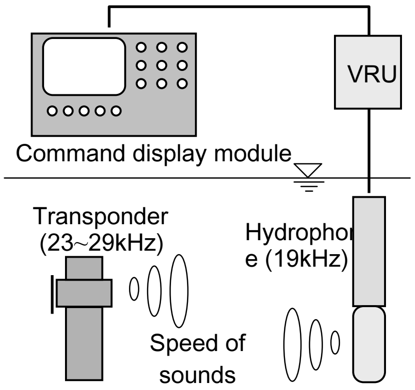


Figure 2: Composition of Track point system.

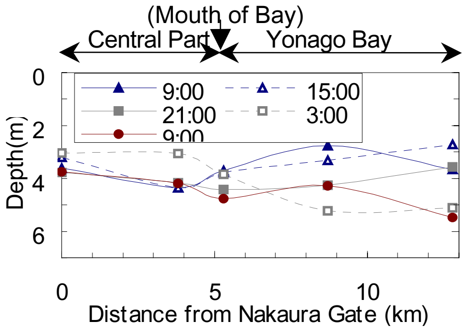


Figure 3: Temporal variations in longitudinal distributions of density interface from Nakaura Gate to Yonago Bay at 1996/11/29-30.

hydrophone at once when it receives pulse. And the position of the transponder is tracked from arrival time and incident angle of supersonic wave. The frequency of the transponder can be set up individually and suitably, and it is possible to release and chase more than one at the same time. Moreover, it confirms that it can be observed in the satisfactory precision in the range of about a radius of 1km with this device .

Besides, in both the center of lake and the head of Yonago bay (□ symbol, Figure 1), water temperature and salinity at 5 points in depth direction and water level, wind speed and direction are monitored throughout the year.

3 RESULTS AND DISCUSSION

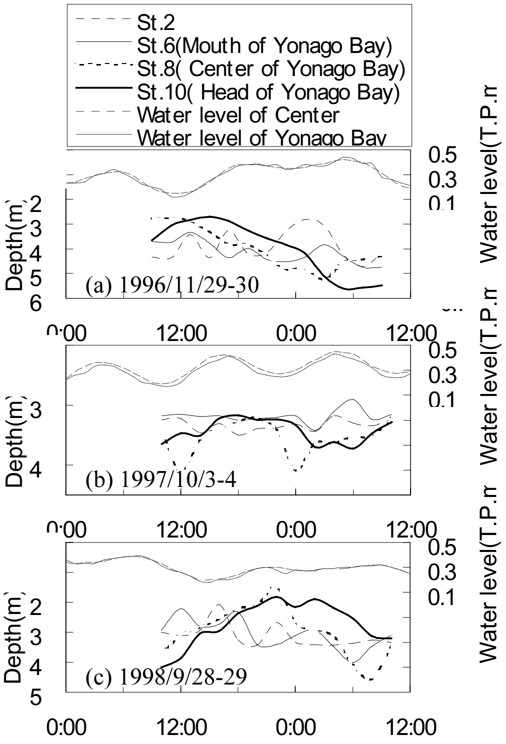


Figure 4: Temporal variations in position of density interface at St.2, 6, 8, 10, and water level at the center of lake and the head of Yonago Bay. (a)1996/11/29-30, (b)1997/10/3-4, (c)1998/9/28-29.

Temporal variations in longitudinal distributions of density interface from the Nakaura gate to the head of the Yonago bay in 1996/11/29-30 are shown in Figure 3. The point of node for the oscillation is near the mouth of the Yonago bay.

Figure 4 is corrected Figure 3 for the change in time, and added the water level. It is proved that the amplitude of the interface oscillation differs by the observation day. The amplitude of oscillation is proportional to the reduced gravity $\varepsilon \cdot g$ ($\varepsilon = \rho_2 - \rho_1 / \rho_2$; ρ_1 is density in upper layer, ρ_2 is density in bottom layer). The reduced gravity at 1997/10/3 is 3 times at 1996/11/29, therefore it is insufficient for explaining the difference in the amplitude (4~6 times). Consequently, it is probable that the resonance between external forces and interface oscillation have been generated.

The water level change in the center of the lake has almost no phase difference from the Yonago bay, in short, the water level rises and

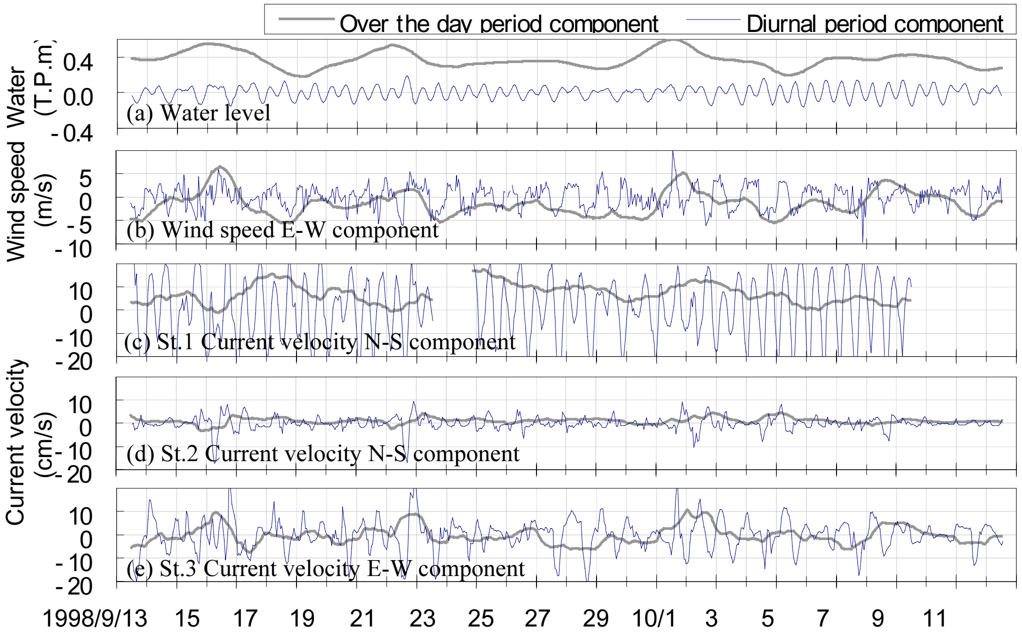


Figure 5: Temporal variations of (a)water level, (b)E-W component of wind speed at the center of the lake, N-S component of current velocity in upper layer at (c)St.1 and (d)St.2, and (e)E-W component of current velocity in upper layer at St.3 in 1998/9/13-10/12. They are classified by the ‘Diurnal period component’ from the ‘Over the day period component’.

falls simultaneously in the whole area in the lake. There is a low correlation between the water level change and the oscillation of the density interface on either time. Besides, clearly, the interface oscillation in the Yonago bay has longer period and larger amplitude than that in the central part of the lake. And, it has advanced in the Yonago bay.

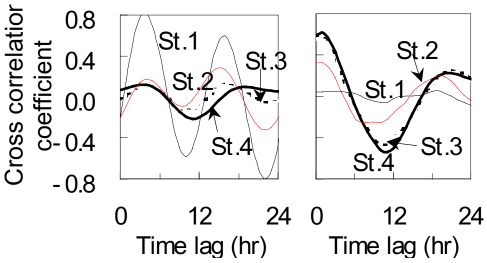
For further analysis, we divided the lake into two, the central part and the Yonago bay.

3.1 The interface oscillation and the flow in the central part of the lake

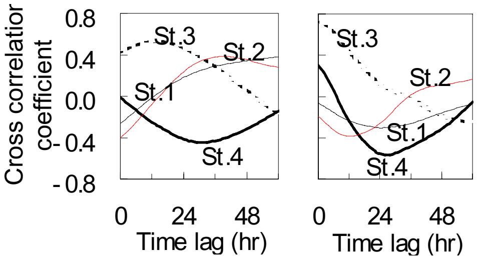
The wind in east-west direction is easy to excel by reason of the effect of nearby landform (Figure 1). And, shape of the lake is long in east and west. We examined mainly the flow in east-west direction.

The temporal variations of water level, east-west component of wind speed in the center of the lake, north-south component of current velocity in St.1, 2 upper layer, and east-west component of current velocity in St.3, 4 upper layer in 1998/9/13-10/12 are shown in Figure 5. They are classified by the ‘Diurnal period component’ from the ‘Over the day period component’. The ‘Over the day period component’ is 25 hours (24 hours for wind speed) shift mean value of the raw record, and the ‘Diurnal period component’ is the result of deducting this shift mean value from the raw record. In the ‘Diurnal period component’, the water level shows well the astronomical tide (semi-diurnal and diurnal tide), and the wind shows land and sea breeze. In the ‘Over the day period component’, variation in both water level and wind correspond well since both also originates from the climate change, and those shows approximate variations in the week period. Concerning the current velocity in the diurnal period, it is the biggest in St.1, and the smallest in St.2. And, obviously the variation in St.1 has the semi-diurnal period and corresponds to the semi-diurnal tide, however periodicity of the variation in St.2~4 isn't definite.

Cross correlation coefficient between current velocity in the direction of the main



(a)with water level (b)with wind speed
(Diurnal period component)



(c)with water level (d)with wind speed
(Over the day period component)

Figure 6: Cross correlation coefficient of current velocity (St.1-4 upper layer) with (a)(c)water level, with (b)(d)wind velocity in 1998/9/13-10/12. (a)(b): the 'Diurnal period component', (c)(d): the 'Over the day period component'.

current in St.1 ~ 4 upper layer and each water level, wind speed in 1998/9/13-10/12 are shown in Figure 6. The correlation between current and tide (or wind) is different in each point. Against the diurnal period change in tide and wind, the influence of tide excels in St.1 (the Nakaura gate), however the influence of the wind increases when leaving the Nakaura gate (Figure 6 (a), (b)). Therefore, about the diurnal period, the astronomical tidal current is dominant only near the Nakaura gate. And the flow due to and sea breeze is strong in the central part of the lake.

Cross correlation coefficient of current with changes of tide and wind in each point are closely similar (Figure 6 (c), (d)). But, an attention point is that the answer to the external forces (tide and wind) in St.3 is different from in St.4 in spite of both point is near and around the center of the lake. Though cross correlation coefficient in St.3 is positive, it is negative in St.4, and a time lag for about 24 hours to St.3. This suggests that horizontal circulation flow is generated by the external forces which originate due to weather changes.

3.2 The interface oscillation and the flow in the Yonago bay

Temporal variation of water level, NW-SE component of wind speed at the head of the Yonago bay, NW-SE component of current velocity at St.10, salinity in depth 3m point at St.10 are shown in Figure 7. The displacement of the density interface is judged from the temporal change of salinity in the 3m depth point located near this interface. The period of internal seiche and the reduced gravity calculated as a stationary wave in the bay in the simple two-layer model is shown too.

In the 'Over the day period component', the correlation between water level and wind is high. For example, the water level rises with the wind drift to the inner part of the bay (SE direction). Moreover, it is considered that this is promoted by the rise of water level and the easily blowing of west winds at the time of the low atmospheric pressure approach, and the fall of water level and the easily blowing of east winds when the high atmospheric pressure approaches. As for the 'Diurnal period component', the correlation between water level and wind is low. But, the time that the phase difference becomes small in both, comes periodically, because of the diurnal inequality and the difference in tide period (24 hours 50 minutes) and wind period (24 hours) (e.g. 9/22-25). Concerning the relation between current velocity and those external forces; the current velocity follows wind change more than water level change. As for the cross correlation coefficient of current velocity, it is 0.55 with wind speed and 0.36 with water level. On the other hand, concerning the relation between current velocity and interface oscillation, it can be said that the flow here follows the interface oscillation since change of both correspond to phase of 90 degrees (○, □ symbols). Before 9/26, the amplitude of oscillation is easy to become large, because the reduced gravity is comparatively small, and a resonance happens easily since the period of

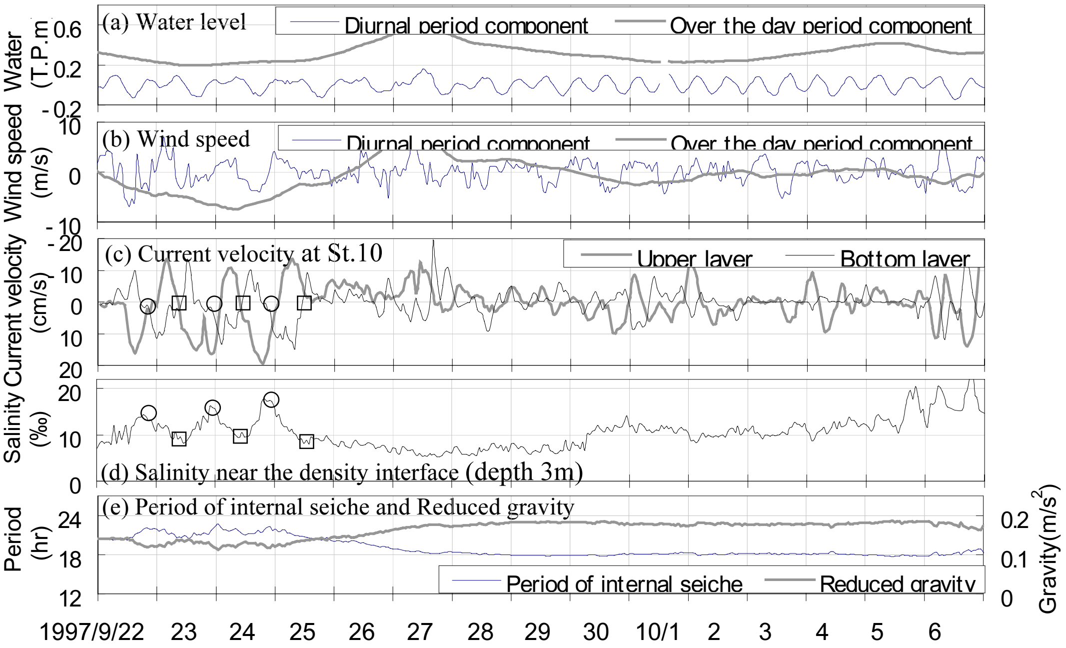
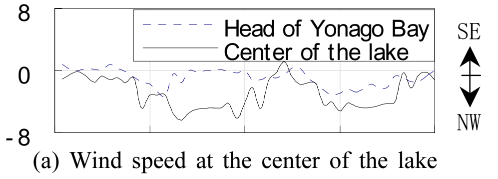


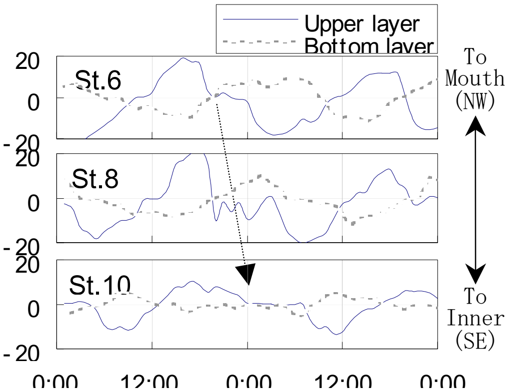
Figure 7: Temporal variations of (a)water level, (b)NW-SE component of wind speed at the head of the Yonago bay, (c)NW-SE component of current velocity at St.10, (d)salinity near the density interface (depth 3m), (e) the period of internal seiche and the reduced gravity in 1997/9/22-10/6.

internal seiche (period of proper oscillation, about 22 hours) is close to the period of the external forces (24-25 hours). As a result, current velocity (interface displacement) is large and periodicity of that variation is high. Conversely, after 9/26 current velocity is small. This is caused by that the reduced gravity and the period of internal seiche are changed by rain and the seawater inflow because of the approach of low pressure in 9/25-26.

As shown in Figure 4 as well, interface oscillation in the Yonago bay is easy to progress, this was also examined. The temporal variations of wind speed at the center of the lake and the head of the Yonago bay, and current velocity at St.6,8,10 in 1998/9/28-29 are shown in Figure 8. Each of them are shown in NW-SE components which correspond with the bay axis direction. Progress of forms of current velocity changes direction from the mouth to the head of the bay in about 1-2km/h (arrow in Figure 8 (b)). This corresponds well to the internal wave velocity calculated from density condition (1.6km/h). Wind usually is



(a) Wind speed at the center of the lake and the head of Yonago Bay



(b) Current velocity at St.6, 8, 10

Figure 8: Temporal variations of (a)wind speed and (b) Current velocity in 1998/9/28-29.

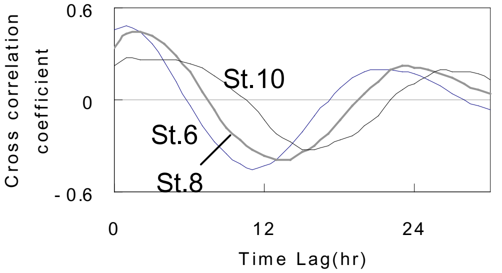


Figure 9: Cross correlation coefficient between NW-SE component of current velocity in upper layer (St.6, 8, 10) and NW-SE component of wind speed at the center of the lake in 1998/9/13-10/12.

gentler in the Yonago bay than in the central part of the lake as shown in Figure 8(a). Cross correlation coefficient between NW-SE component of current velocity at St.6, 8, 10 and NW-SE component of wind speed at the center of the lake in 1998/9/13-10/12 is shown in Figure 9. It is understood that the interface oscillation that originate by the strong wind in the central part of the lake propagate towards the Yonago bay in velocity of the internal wave.

3.3 The relations between the interface oscillation and vertical structure of the flow and the mass transport

In 1998/28-29, we carried out the observation using fish finder and ADCP simultaneously in order to examine the relationship between interface oscillation and vertical structure of the flow. The time change of density interface position measured by fish finder is shown in Figure 10. Interface oscillation is progressive, it generally oscillates in 24 hour period, and it is in the upward trend for 12 hours in the first half, it is in the downward trend in the latter half. The longitudinal distribution of the current velocity vector and the vertical distribution of the density in St.8, M, FC and BC at 9/28 10:00 and every four hours in 9/28 22:00-9/29 10:00 are shown in Figure 11. In the figure, the distribution of the local Richardson number Ri which calculated from the distribution of the density and flow

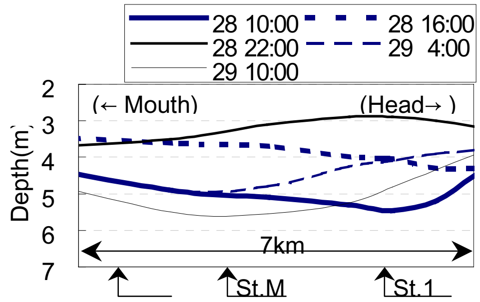


Figure 10: Temporal variation of density interface position measured by fish finder.

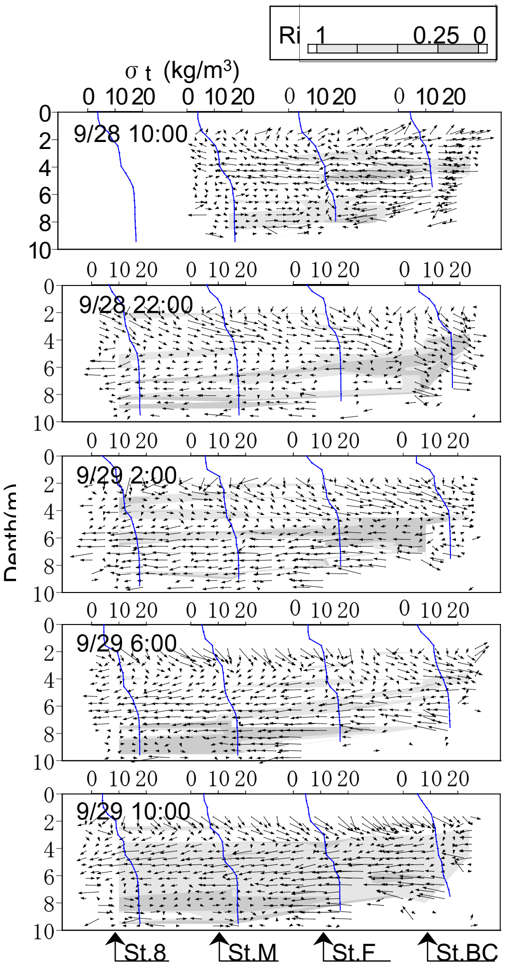


Figure 11: The longitudinal distribution of the current velocity vector and the local Richardson number and the vertical density profiles in St.8, M, FC and BC at 9/28 10:00 and every four hours in 9/28 22:00-9/29 10:00.

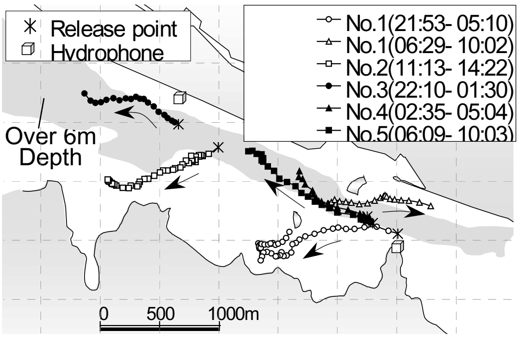


Figure 13: Results of released Transponders.

velocity has also been added. The vertical distribution of current velocity vector is longitudinally different, since interface oscillation had progressed. At 9/28 10:00, current velocity increases near the pycnocline. In 9/28 22:00-9/29 10:00 in which the interface has tendency to subside, the place where the current velocity is large has moved with progress of the interface. Then, at 9/29 10:00, current velocity is again larger in the pycnocline as the distribution in 24 hours ago. And, the shapes of pycnoclines are reversed at 9/29 10:00 from sharp in inner part and gentle in central part at 9/29 2:00 due to change of flow regime. However, it is comparatively stable in the pycnocline for Richardson number Ri more than 1/4.

We released the transponders in the inner part the Yonago bay from the ship, in order to know relation between the interface oscillation and the mass transport. Two transponders were released in the upper layer, and four in the bottom layer. Some of the results of the transponder release are shown in Figure 13. In the upper layer, it is understood that the mass transport easily influenced by the wind and the geographical features such as islands and a peninsula. However, in the bottom layer, masses are moved along the valley landform. And, it is understood that many masses in inner part bottom layer of the bay are transported in the mouth of bay direction due to the flow caused by the interface oscillation.

4 CONCLUSIONS

The flow which originated in the interface oscillation in Lake Nakaumi and that interface oscillation were examined. The following knowledge was acquired from the results.

(1) The diurnal period; the astronomical tidal current is dominant only near the Nakaura gate that is the connecting point with the sea. The flow due to the land and sea breeze is strong in the central part of the lake.

(2) In the Yonago bay; the interface oscillation is generated by wind and tide during the diurnal period. The interface oscillation in the bay have a longer period and a higher amplitude than that in the central part of the lake. This is because the period of proper oscillation is apt to approach period of external forces.

(3) Interface oscillation in the Yonago bay is easy to progress to the bay inner part direction from mouth of bay. This is because the interface inclination originated by the strong wind in the central part of the lake can easily propagate into the Yonago bay. The flow generated by this progressive wave allows for mass transportation from the inner part of the Yonago bay towards the central part.

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