Physical Environments of Brackish Lakes and Tidal Rivers
Putting Emphasis on Internal Oscillations

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Abstract

In brackish lakes and tidal rivers where a stable stratification with a sharp halocline usually exists, a characteristic aquatic environment often appears. One of serious environmental problems is an appearance of anoxic water mass in the lower layer at these water regions especially in summer because of weak vertical mixing and active dissolved oxygen consumption.

In such circumstances, internal oscillations frequently occur due to tide or/and wind and bring about an active movement of an anoxic water mass in the lower layer, and affects seriously the aquatic environment there.

Then I studied physical processes of the internal oscillations in Lake Nakaumi and The River Ohashi and found that the oscillations with a few meter amplitude frequently occur and propagate as internal Kelvin waves in the lake and the oscillations sometimes cause anoxic water intrusions through the Ohashi River into Lake Shinji.

1. Introduction

In Japan, there are many brackish lakes and tidal rivers where a stable stratification with upper fresh water and lower saline water causes a peculiar aquatic environment.

The aim of this presentation is to clarify the physical characteristics of brackish lakes and tidal rivers putting emphasis on internal oscillations and their effects on aquatic environments.

Our study field is a special estuarine region consisting of Lake Nakaumi, the Ohashi River and Lake Shinji, where the saline water from the Sea of Japan and fresh waters from many rivers inflowing into the lakes contact and mix under various meteorological and hydrological conditions. This water region is characterized by stable density stratification with a sharp halocline, except under extraordinary conditions such as very large flood or strong wind.

The stable stratification brings about weak vertical mixing between the upper fresh water and lower saline water and supresses the downward transport of dissolved oxygen. This often causes anoxic states in the lower saline layer, especially in summer when the oxygen consumption rate becomes very large owing to the active chemical and biological processes. This anoxic state in the lower layer controls the aquatic environment there, for example, it affects fishes and seriously impairs the growth of benthic organisms such as shells and seaweeds. The anoxic water mass does not stand still in the lower layer, but usually moves about corresponding to tides, river discharges and wind blowings.

Therefore, it is very important for us to investigate the occurrence and movement of the anoxic water mass in the estuarine regions to understand their effects on the aquatic environments both from the academic and practical points of view.

Then in collaboration with the fisheries experimental station of Shimane Prefecture, we investigated the changes in the distribution of anoxic water and the internal oscillation which strongly controls the occurrence and movement of the anoxic water mass in the brackish lake – Lake Nakaumi and the tidal river – the Ohashi River.

2. Observation Method

We observed the distributions of temperature(T),electric conductivity(EC) and dissolved oxygen concentration(DO) with multi-sensor instruments from a research vessel sailing around the regions as shown in Fig.1. The observation results show a stable stratification consisting of an upper layer with a smaller density in situ σ_t and a higher DO and a lower layer with a larger σ_t and a lower DO. The DO concentration in the lower layer becamed very low (nearly zero) during summer, inducing serious conditions for life forms in the lower and benthic layers.

Besides the above usual observation methods, we have developed a simple neutral buoy to directly measure the internal oscillation – a vertical movement of halocline where exists a sharp density gradient owing to a large difference of salinity between the upper and lower layers. The weight of the buoy could be adjusted using small metal ballast to make the apparent density of the buoy equal to that of the water in the halocline at the observation station. We set the buoy using a mooring system to follow the vertical movement of the halocline.

3. Results and discussion

We have repeated the field observations in our study regions several times during 1994 to 1996, but we will show only main results and briefly discuss them, selecting the most recent observation results about the distributions and movements of anoxic water in Lake Nakaumi and the intrusion of anoxic water into The Ohashi River.

3.1 The occurrence of an anoxic state in the lower layer of Lake Nakaumi

The occurrence of an anoxic state in the lower layer of Nakaumi during summer seasons has been well known from the observation results of the fisheries experiment station of Shimane Prefecture. The main causes are the bottom topography (a deep depression in Nakaumi), a stable stratification with a sharp halocline, and a large oxygen consumption rate in summer in the lower layer.

Besides the vertical distributions of DO concentrations, three dimensional distribution of DO and their temporal changes were obtained from a recent observation by a Kinki University Group (1997). This results illustrate that an anoxic water mass first appears in the southeastern region of the lake and expands toward the western region along the lake bottom. The saline water inflows from Nakaura waterway into Lake Nakaumi and spreads into a wide central basin along the lake bottom taking a form of density current, and after arriving at the western boundary – the exit of The Ohashi River, the water is entrained into the upper layer with a jet flow from the river and returns toward east through the upper layer.

It seems to take a long time (maybe about ten days and more by some estimation from numerical simulation and buoy tracing) for a water mass to pass through Lake Nakaumi inflowing upstream through the lower layer and outflowing downstream through the upper layer. During this long passage period, a small downward flux of oxygen from the upper layer and a large oxygen consumption rate in the lower layer promote the rapid decrease of DO concentrations in the lower layer.

3.2 Internal Oscillation

It is well known that a wind stress causes a set up of water surface and a drop of interface between two layers - halocline at the leeward side. Our simple estimation from the two layer model reveals that in Lake Nakaumi, a 7-8m/s wind along the east-west direction brings about a few centimeters set up of water surface and a few meters drop of the halocline level. Thus a daily change of wind due to sea and land breeze in summer with an ordinary speed of 7-8m/s may bring about internal oscillations with an amplitude of a few meters.

In shallow coasts with a small slope gradient of the order of 1/1000, a few meter rise of the halocline may cause a long horizontal creeping up of highly saline and anoxic water on a few kilometers. This means that an internal oscillation due to strong wind may have a serious effect on the biological life of coastal regions in brackish lakes.

Therefore, we investigated the internal oscillations in Lake Nakaumi about the occurrence conditions, amplitudes and periods, and propagating style of oscillatory waves. We set the neutral buoys at the fixed stations as shown in Fig. 1 and recorded the vertical movement of halocline and the results are compared with the hourly changes of vertical distributions of density in situ σ_t (=[ρ -1]×1000, ρ :density calculated from EC and T) and DO.

The result illustrates that the level of halocline measured from the neutral buoy record well agrees with the level of the layer with constant density σ_t =10.0 and with constant DO = 3.0 mg/l and so the height of halocline well corresponds to the upper boundary of the anoxic water mass with DO less than 3mg/l.

Fig.2 shows the time series change of wind vectors, water level and halocline level (internal oscillation) and it illustrates that water level changes caused with tide of amplitude about a few ten centimeters have some correlation with internal oscillation only at Pt. 3 near from the entrance of tidal wave, Nakaura waterway. Also it shows that the internal oscillations have an inverse phase between at Pt.1 and Pt.2 which are situated at western and eastern sides in the lake respectively. This means that the halocline level moves upward or downward corresponding to the windward or leeward side respectively as we can understand comparing the level motion with hourly change of wind direction in Fig.2(a).

Furthermore, we compared the phase differences of the internal oscillations between neibouring stations at Pt.4, 5 and 6 which are situated along a straight coastline at almost same water depth to investigate the propagating state of the internal osillation. The result is shown in Fig.3 which illustrates that an oscillatory wave was progressing with a consant propagation speed of 24 cm/s. This speed well coincides with the one calculated from the equation for the internal wave phase speed Ci which is expressed with the density difference between upper and lower layers, and each thickness of both layers.

Besides this observation result, the calculation of rotating propagation speed along the path Pt.1->2->3->1 reveals that the period of circulating propagation (about 24 hrs) is longer than that of inertial period (20.4hrs) and the period of internal Poincare wave (17hrs). From these facts, we considered that the internal oscillation in Lake Nakaumi propagates anticlockwisely as an internal Kelvin wave.

Finally we found that the internal oscillation is first caused mainly by wind stress at the lake surface, but the oscillatory motion propagate along the whole lake coast anticlockwisely and the vertical movement of halocline with a large amplitude occurrs in any point near the coast independently of wind direction which decided the initial direction of oscillating axis.

3. Creeping up of anoxic water into The River Ohashi

Frequently the saline and anoxic water mass creeps up into The River Ohasi and sometimes arrives at Lake Shinji and it gives some adverse effects on the environments in Lake Shinji .

Then it is necessary for us to investigate special conditions which may cause the intrusion of the anoxic water from Lake Nakaumi. We have carried out a field observation on the distribution of current, EC and DO along The River Ohashi by a boat sailing and on the internal oscillation with the neutral buoy at Pt.09 near the eastern mouth of the river simultaneouely. The observation by boat sailing had been repeated four times corresponding to various tidal phases.

Of course, anoxic water mass is rising up along the river bottom during ebb tide period, but the anoxic water with DO less than

3mg/l appears only under the halocline level in Lake Nakaumi during the rising up period of the level somewhat different from high tide period.

The horizontal distribution of DO along the bottom illustrates that DO values do not decrease rapidly toward upstream direction and this means that the oxygen consumption rate during the creeping stage through the river is not so large. Then the cause of the anoxic water intrusion into Lake Shinji seems to be a direct passing through of the anoxic water from Lake Nakaumi without a large oxygen consumption along the river course.

Conclusion

In conclusion, the following points were made clear about physical environments in the brackish lake and the tidal river which are characterized with stable stratification and a large internal oscillation.

1) Stable stratification and low circulation speed in Lake Nakaumi promote anoxic state in the lower layer.
2) Internal oscillations i.e. vertical movements of halocline in Lake Nakaumi are caused mainly by wind stress and partly by tidal action. Their large amplitude and rotating propagation style cause a large scale creeping up of anoxic water to the whole lake coast and into The River Ohashi.
3) Dissolved oxygen consumption rate during the passage of water mass through The River Ohashi from Lake Nakaumi to Lake Shinji is not so large and a main source of anoix water rising up into Lake Shinji is a direct inflow of anoxic water mass from Lake Nakaumi.
4) Countermeasures to prevent the spread of anoxic state in brackish lakes and tidal rivers should be planned on the basis of scientific studies on mechanism of occurrence and movement of anoxic water masses.

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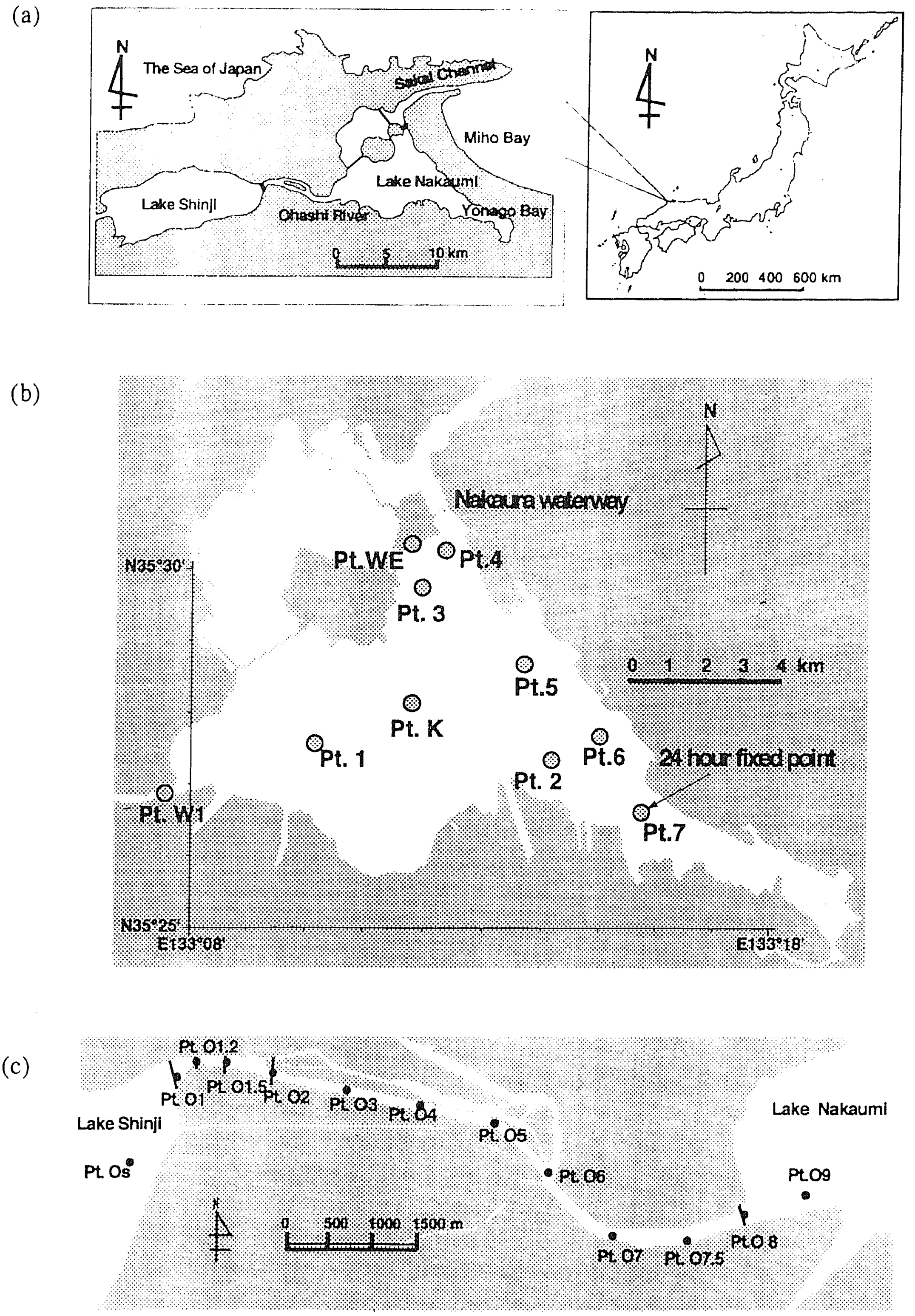

Fig. 1　Observation points in Lake Nakaumi and the Ohashi River

(a) Map of Lake Nakaumi and the Ohashi River

(b) Observation during 1995~1996 in Lake Nakaumi

(c) Observation from Aug. 27 to 28, 1996 along the Ohashi River

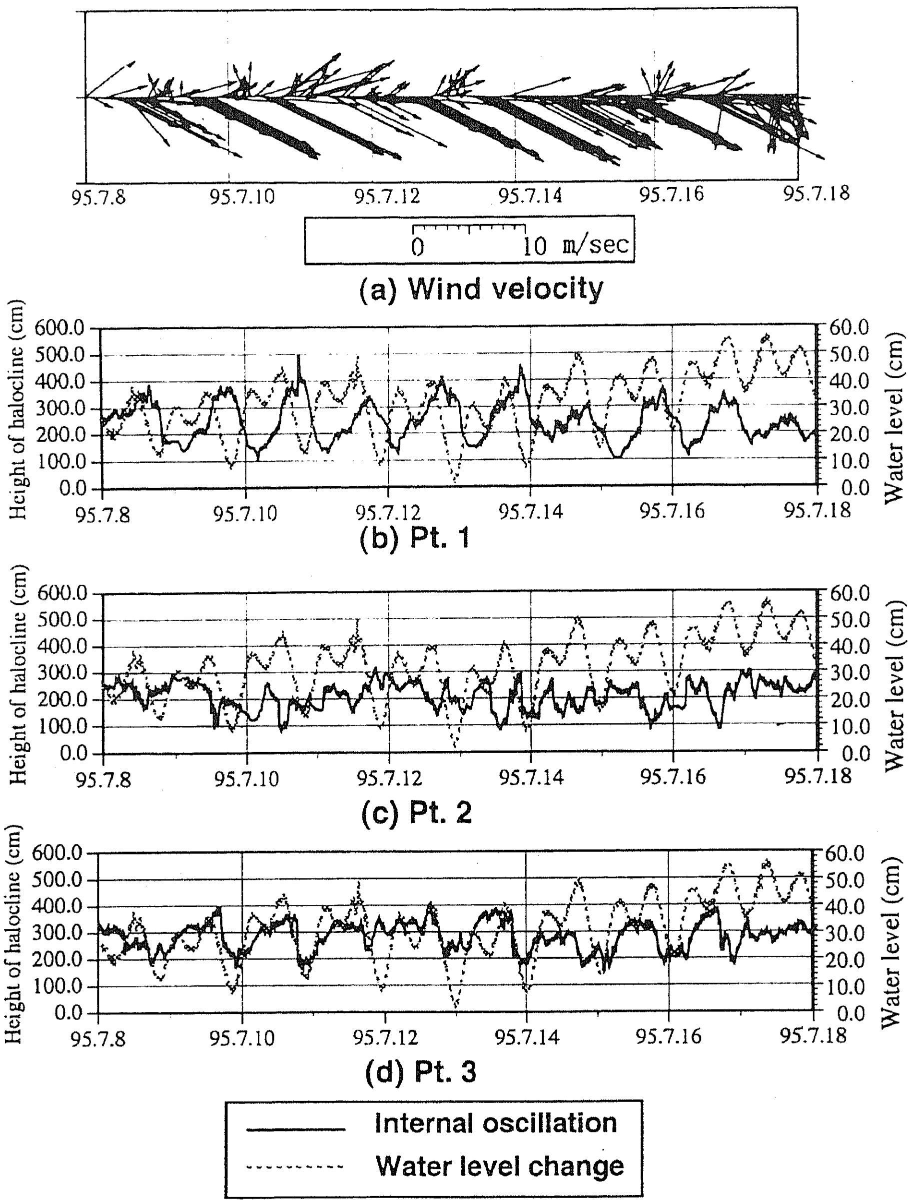

Fig.2 Temporal changes of wind velocity (a), and internal oscillations at Pt. 1 (b), Pt. 2 (c) and Pt. 3 (d) in Nakaumi from July 8 to 18, 1996 derived from the changes of the height of the halocline - the distance of the neutral buoy from the bottom

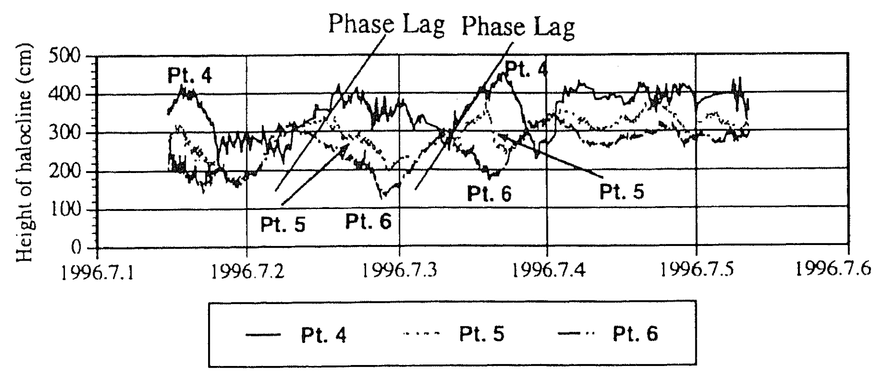

Fig.3 Phase lags of internal oscillations between neibouring stations Pt. 4, 5 and 6 along a straight line in Lake Nakaumi