FLOW AND WATER QUALITY CHANGE IN BRACKISH LAKE DEPENDING ON THE CHANGE IN METEOROLOGICAL CONDITIONS

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Abstract: Lake Nakaumi that is a brackish lake has strong pycnocline, so that dissolved oxygen in the bottom layer is often depleted. Brackish lake is subject to composite meteorological, oceanographic and hydrological influences that give them complex flows. The meteorological characteristics exerting influences on Lake Nakaumi, together with the flows in the lake caused by meteorological change and its water quality distribution, were examined in order to clarify the relationships between meteorological change, flows and water quality environment in the lake. The following results were obtained; (1) The meteorological changes giving rise to the external forces (wind, and water level difference between the waters) generating the flows involve combinations of atmospheric pressures and wind direction at times when strong winds occur. (2) Seawater inflow and wind-driven current by approach of the low atmospheric pressure carry dissolved oxygen into bottom layer of Yonago Bay. (3) During the period of mild weather, internal wave in the back of Yonago Bay is different from that generated in the other area of the lake. The anoxic water mass moves from the back of the bay towards the center.

Keywords: brackish lake Lake Nakaumi atmospheric pressure, pycnocline wind-driven current dissolved oxygen

1. INTRODUCTION

The environs of lakes are the sites for varied human activities. These activities result in various kinds of wastewater concentrating in lakes. Additionally the fact that water generally dwells in lakes for long time periods means that there now exist many lakes that have problems of water quality degradation.

Changes in the water quality of lakes are closely connected with the flow fields. As shown in Figure 1, brackish lakes in particular are subject to composite meteorological, oceanographic and hydrological influences that give them complex flows. Accordingly the present study sets out to grasp comprehensively the changes in the flow and water quality of brackish lakes through the example of Japan's Lake Nakaumi.

The sequence used in the discussion will be the following: External forces - Flow in the Lake - Water quality changes. To begin with we will clarify the conditions, resulting from frequently occurring combinations of atmospheric pressures and winds at Lake Nakaumi, that constitute the characteristic external forces causing flow within this lake. Following that we will examine the flows generated by the external forces, such as wind-driven currents and inflow/outflow among bodies of water. Finally

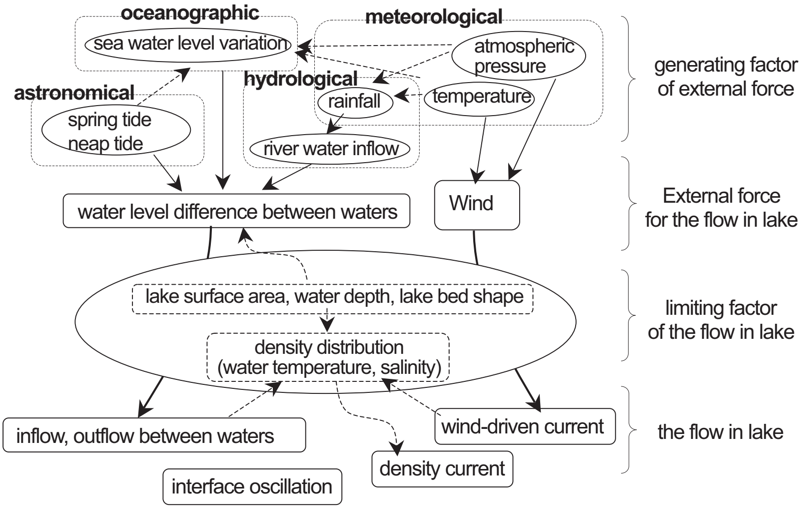


Figure 1 Relationship between meteorological phenomena, hydrological phenomena, astronomical phenomena, oceanographic phenomena and flow in a brackish lake

we will turn our attention to dissolved oxygen (DO) as indicative of the relationship between the water quality environment and flow, and examine how flows act on the temporal and spatial distribution of anoxic water masses.

2. OVERVIEW OF LAKE NAKAUMI

Lake water from Lake Shinji (with salinity around 1/10 that of seawater) flows into Lake Nakaumi via the Ohashi River, and seawater from the Sea of Japan flows into Lake Nakaumi through the Nakaura Gate (see Figure 2). With a water surface area of 86.2 km^2, Lake Nakaumi is Japan's 5th largest lake. The southeastern part of the lake is a long, thin projection from the main body known as Yonago Bay, which receives domestic wastewater from the surrounding urbanized areas, making it the part of Lake Nakaumi with the highest pollution levels.

Figure 3 gives sample vertical distributions of water temperature, salinity, density and DO in Lake Nakaumi. In almost the whole of this lake a pycnocline of the kind seen in this figure is present at or near a depth of 2 to 6m all the year round, so that the lake has a stable stratificational structure[1)]. The pycnocline inhibits the conveyance of matter between the upper and lower layers, making it difficult for the lower layer to be supplied with DO. As a result the lower layer tends to become anoxic.

3. CHARACTERISTICS OF EXTERNAL FORCES CAUSING FLOWS

Each lake has its own peculiar topographical features and geographical configuration, and furthermore is subject to composite meteorological, oceanographic and hydrological influences. This means that the characteristics of the dominant external forces in each individual.

The main external forces causing flows in Lake Nakaumi can be cited as (1) differences between the water levels of the Sea of Japan, Lake Nakaumi and Lake Shinji resulting from water level fluctuations in each of these waters due to meteorological and astronomical effects, and (2) winds arising from changes in the distribution of atmospheric pressure.

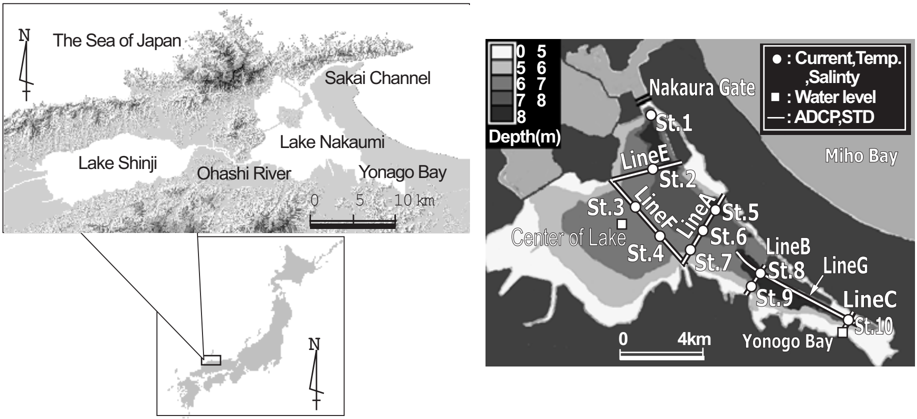


Figure 2 Location of Lake Nakaumi and observation points and the water depth distribution.

(1) WATER LEVEL FLUCTUATION IN THE WATER BODIES AND WATER LEVEL RESPONSIVITY BETWEEN THEM

Since Lake Nakaumi is a body of water that forms a connected system with the Sea of Japan (Miho Bay) and Lake Shinji, fluctuations in the sea level and inflow of floodwater give rise to water level differences between these three bodies of water. The influences exerted by astronomical tide and meteorological conditions on fluctuation in the water levels of the Sea of Japan and Lake Shinji may be characterized as follows[1), 3)]. (1) The phase difference between Miho Bay and Lake Nakaumi is around 2 hours, so that changes in the sea level are transmitted to Lake Nakaumi with hardly any attenuation. (2) In Lake Shinji the phase lag is around 8 hours, so that there is hardly any transmission of astronomical tides from the sea. Thus, changes in atmospheric pressure are the only influence causing changes in that lake's water level. (3) When atmospheric pressure changes occur continuously for several days, water level differences of several tens of centimeters occur between Lakes Nakaumi and Shinji. (4) Precipitation also results in a relatively higher water level in Lake Shinji.

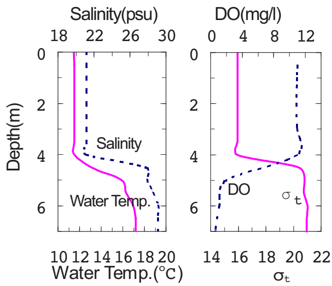


Figure 3 Vertical distributions of DO, density, salinity, and water temperature.

(2) WIND CHARACTERISTICS IN LAKE NAKAUMI AND ITS ENVIRONS

Figure 4 shows the proportions of wind of various speeds and directions occurring with various atmospheric pressures at Lake Nakaumi. Atmospheric pressures are categorized into high, "middle" (medium) and low atmospheric pressure, with the latter further divided into falling and rising low atmospheric pressure.

There is a tendency for strong winds to blow along an east-west axis throughout the year. This is due to the effects of the surrounding geography; the lakes are sandwiched between mountain land on the north and south. When atmospheric pressure is in the medium and high ranges (Figure 4 (c) and (d)), meteorological conditions are calm and the winds are mostly weak, with speed no more than 6m/s, their direction being mostly northeasterly to east-northeasterly and southwesterly to westerly. These can be considered to be land and sea breezes. When air pressure is low, by contrast, strong winds occur with high frequency. At times of low and falling atmospheric pressure (Figure 4 (a)) there are highly frequent strong west winds as well as northeast winds, while at times of low but recovering (rising) atmospheric pressure ((b)) there is a tendency for even stronger west winds to blow.

From the above, the combinations of atmospheric pressure, wind direction and wind speed that are prone to occur may be stated as the following three: (1) Calm meteorological conditions during medium to high atmospheric pressure. (2) Strong northeasterly winds at times during medium to high atmospheric pressure. (3) A transition from northeast winds (during falling low atmospheric pressure) to westerly winds (during pressure recovery) when low atmospheric pressure passes.

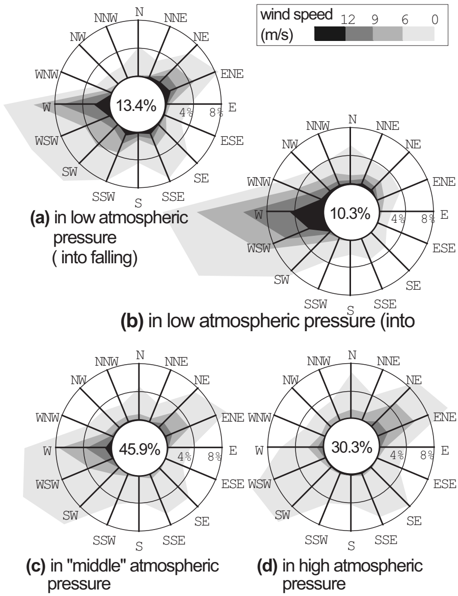


Figure 4 Generation proportion of the wind speed and direction (proportion as each atmospheric pressure condition for the whole is shown in central circle)

4. CHARACTERISTICS OF FLOWS

The external forces (meteorological, oceanographic and hydrological) causing flows possess various time scales. Accordingly it is necessary to ascertain the predominant flow phenomena for each time scale.

At Lake Nakaumi the main time scale division is into half to one day for land and sea breezes and astronomical tides on the one hand, and several days to several weeks for winds and water level fluctuations due to meteorological changes on the other.

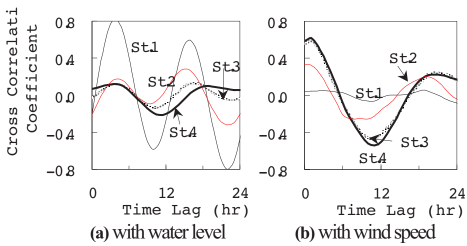


Figure 5 Cross correlation coefficient of current velocity (St.1-4 upper layer) with (a)water level, with (b)wind speed (the 'Diurnal period component').

(1) LAKE-FLOW GENERATED BY EXTERNAL FORCES WITH PERIOD OF HALF TO ONE DAY

Figure 5 shows the cross correlations of the upper layer main current axial velocity at each of stations 1 through 4 with the water level and the wind speed. Specifically, this figure gives the "diurnal period components" for these items. The correlation with water level is high at station 1, located close to Nakaura Gate, whereas the correlation with wind speed increases the further away one moves from Nakaura Gate. Thus as regards diurnal period flow components, the effects of astronomical tides are dominant only in the vicinity of the Nakaura Gate, while in the greater part of the lake's interior it is land and sea breezes that are the predominant factor driving the flow.

(2) LAKE-FLOW RESULTING FROM DAY-TO-DAY METEOROLOGICAL CHANGES

The flows resulting from day-to-day meteorological changes are the wind-driven currents due to changes in atmospheric pressure distribution and the inflows/outflows due to level differences between the waters that are generated by atmospheric pressure variations and floodwater inflow. We

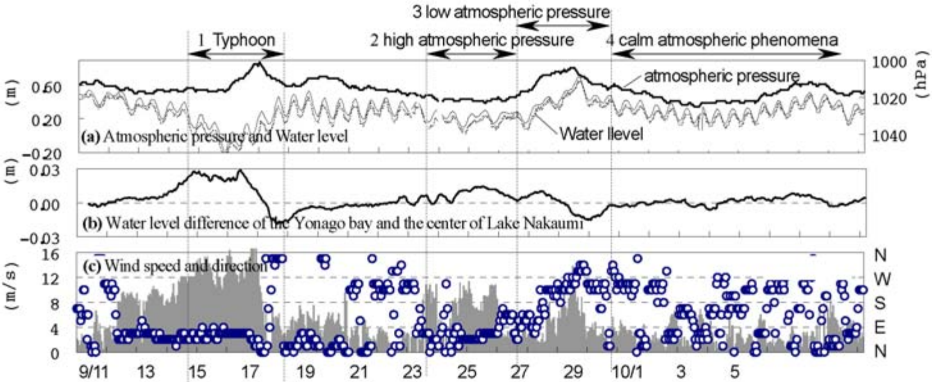


Figure 6 Temporal variations of (a) atmospheric pressure and water level, (b) water level difference, (c) wind speed and direction 1997/9/11-10/6

will now look at each of these two flows individually.

a) Wind-driven currents caused by wind arising from changes in atmospheric pressure distribution

Figure 6 shows the temporal variations during the period 11th September to 6th October 1997 in (a) atmospheric pressure and water level, (b) water level difference between the center of Lake Nakaumi and its Yonago Bay portion, and (c) wind direction and speed. Four characteristic meteorological conditions occurred during this period: (1) the passing of a typhoon, when northeast winds of around 16 m/s blew continuously, (2) a time of high-pressure strong winds, when northeast winds of around 10 m/s enveloped in high atmospheric pressure blew continuously, (3) the coming of low atmospheric pressure, when the transition to low atmospheric pressure caused strong winds to blow that progressively altered their direction from east to west clockwise, and a rise in the water level occurred, and (4) a time of calm weather when the atmospheric pressure recovered again, no strong winds blew, and land and sea breezes predominated. (1) is a characteristic Japanese meteorological phenomenon that is seen frequently during the summer and autumn in this country.

b) Inflows/outflows due to level differences between the waters resulting from atmospheric pressure distribution variations

Normally, inflow to Lake Nakaumi from Lake Shinji is prone to occur when atmospheric pressure is on a rising trend, and inflow to Lake Nakaumi's lower layers from Miho Bay when atmospheric pressure is on a falling trend. Figure 7 shows temporal variations (a) in the atmospheric pressure and the water levels of Lakes Nakaumi and Shinji, and (b) in the salinity at depths of 0.5 and 1m below surface in the center of Lake Nakaumi during the period 10th to 25th November 1996, plus (c) in the current velocity in the upper and lower layers of Lake Nakaumi at stations 2, 3, 4 and 12 from 18th to 25th of the month stated.

Let us examine as an example the times when atmospheric pressure is on a rising trend (18th-19th and 21st-22nd November in Figure 7). As the atmospheric pressure begins to rise, the water level situation changes from one in which there is a lag in the water level response between Lakes Nakaumi and Shinji to one in which the level of Lake Shinji is relatively higher than that in Lake Nakaumi ((a) in the figure). In response to this, inflow occurs from Lake Shinji to Lake Nakaumi via the Ohashi River ((c)). Thereafter the salinity of the upper layer at the center of the lake falls some 12 hours later ((b)), and furthermore the influence of inflows appears at stations 2 and 3 as indicated by the broken arrow lines ((c)). On the other hand, no influence of inflows is observed at station 4. This means that the inflow/outflow caused by water level difference between the waters consists predominantly of flow in the direction linking the Nakaura Gate with the Ohashi River, and thus has little effect on Yonago Bay. Moreover the fall in salinity at the center of the lake is greater at 0.5 m than at 1.0 m below the surface,

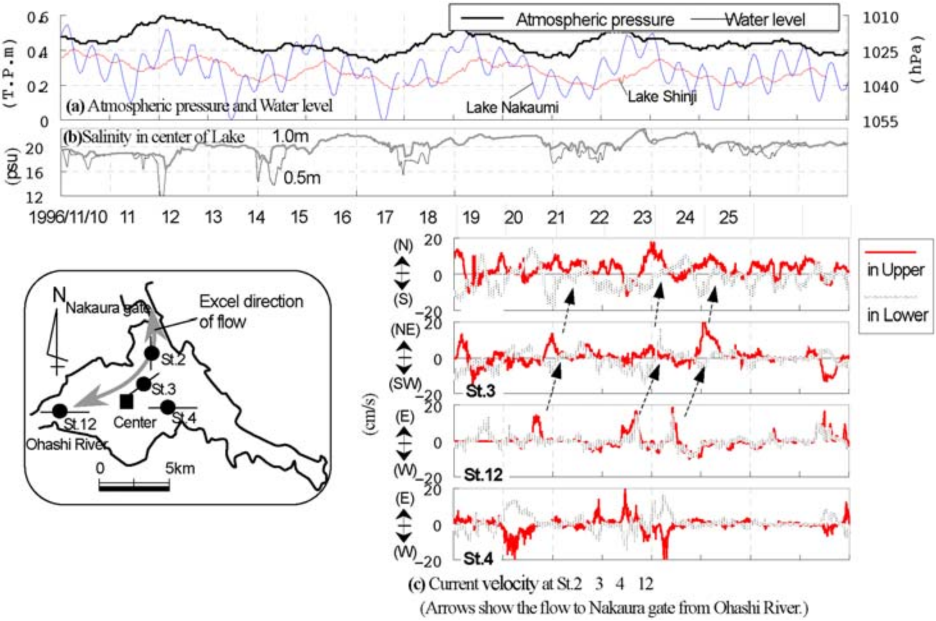


Figure 7 Temporal variations of (a) atmospheric pressure and water level, (b) salinity at Center of Lake , (c) current velocity at St.2 3 4 12 (1996/11/10 11/25)

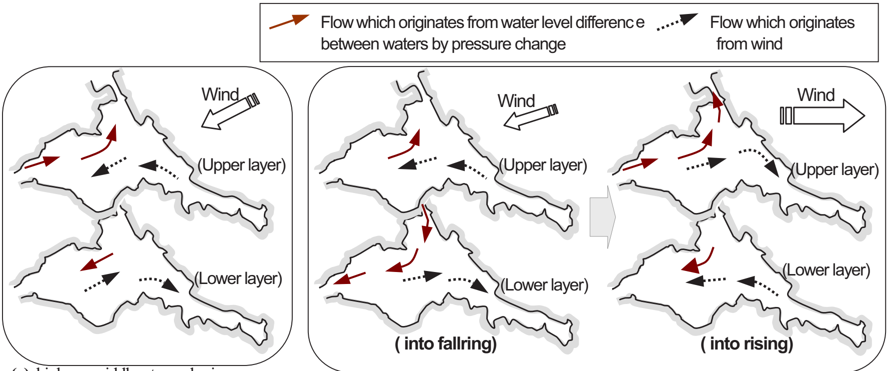
which demonstrates that inflowing freshwater penetrates near the surface in the manner of a density current.

c) Correlation of wind-driven currents and the inflow/outflow between waters

Figure 8 summarizes the lake-flowss as those occurring with particular combinations of atmospheric pressure and wind direction/speed. Specifically these are the flows that occur (a) when there is medium to high atmospheric pressure and strong winds blow from a north northeasterly to easterly direction, and (b) when low atmospheric pressure comes and a change takes place from northeasterly to strong westerly winds.

The relatively higher water level that occurs in Lake Shinji in the case of (a) makes freshwater prone to flow into the upper layer of Lake Nakaumi through the Ohashi River, and this gives rise to a current in the upper layer extending from the Ohashi River inlet to the center of the lake and thence to the Nakaura Gate. But the direction of the wind-driven current produced by the northeast winds is in the opposite direction, and as a result a horizontal circulating current is prone to occur.

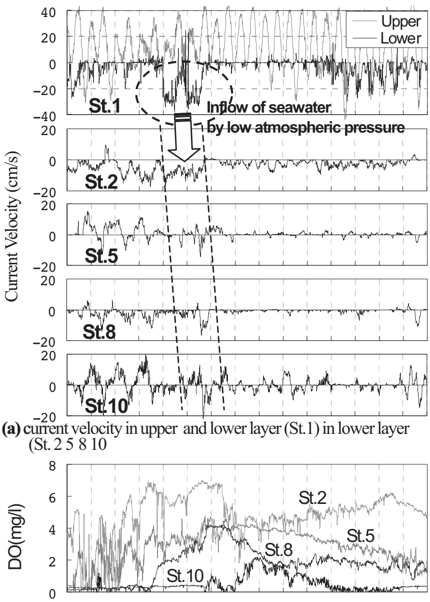
In the case of (b) (coming of low atmospheric pressure), when the atmospheric pressure is falling seawater is prone to flow into the lower layer of the lake from the sea, and furthermore the east winds act to make the water around the center of the lake flow out into the lower layer of Yonago Bay; this may be considered the combination of conditions most favorable for the supply of DO-rich water to the bay's lower layer. On the other hand when the atmospheric pressure starts to recover (rising again from its lowest point) the winds change to strong westerly and additionally there begins an inflow into the lake's upper layer from Lake Shinji, which has a lag of half to one day; if the west winds are sustained, the flow mobility within Lake Nakaumi will be increased through synergistic effects.



(a) high or middle atmospheric pressure with strong east wind

(b) low atmospheric pressure (it changes to the strong west wind from east wind).

Figure 8 Summary of the flow under the characteristic weather condition in Lake Nakaumi.



(a) current velocity in upper and lower layer (St.1) in lower layer (St. 2 5 8 10

(b) DO in lower layer

Figure 9 Temporal variation of current velocity and DO (1997/9/22-10/6)

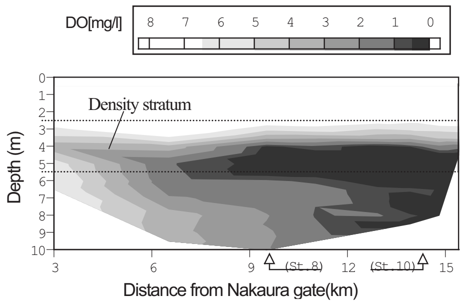


Figure 10 Longitudinal distribution of DO (1997/10/3 10:00)

5. INFLUENCE OF FLOWS ON HORIZONTAL AND VERTICAL DISTRIBUTION OF WATER QUALITY

Accordingly we will examine the pycnocline behavior and water quality variation caused by wind-driven currents and inflows of seawater and river water, so as to clarify the relationships between weather, flows and water quality. Focusing mainly on DO as water quality parameter, we will examine in what ways the flows act on the temporal and spatial distribution of anoxic water masses.

Figure 9 shows (a) the velocity of the current along the Nakaura Gate to Yonago Bay axis at stations 1, 2, 5, 8 and 10; and (b) the temporal variation in lower layer DO at stations 2, 5, 8and 10. Large scale inflow of seawater into the lower layer occurs only for a several days at a time, when low atmospheric pressure passes over the Japan sea causing a rise in the level of the sea beyond the lake (period (3), coming of low atmospheric pressure). The influence of such seawater inflow gradually reaches as far as Yonago Bay (station 10), but only thanks to the synergistic effects of the wind-driven density

currents. From 25th to 27th September the shift to low atmospheric pressure caused the wind direction to change progressively clockwise from an easterly starting point and increased the wind speed. In terms of lake-flows, this probably resulted in the inflowing seawater that headed for the lower layer at the center of the lake (stations 2 and 3) being effectively carried into Yonago Bay (stations 7 and 8) by the wind-driven density currents generated by the east-to-south shift in wind direction. Subsequently the fall in atmospheric pressure bottomed out during the afternoon of 27th September and the wind direction changed to westerly, whereupon inflow into the lower layer of Yonago Bay ceased.
Such inflow of seawater that occurs with the coming of low atmospheric pressure causes a rise in DO that extends into Yonago Bay. This serves to demonstrate that the horizontal distribution of water quality within the lake is subject to the influence of meteorological conditions to a large degree.
Next we will look at the relationship between seawater inflow and the vertical configuration of water quality. Figure 10 shows the longitudinal and vertical distributions of DO from the vicinity of the Nakaura Gate up to Yonago Bay at a time of calm weather (around 10:00 on 3rd October 1997). It can be seen from this figure how the high-DO seawater flows in the manner of a density current into the lower layer. This serves to demonstrate that the flows caused by meteorological change can also have the effect of rejuvenating the vertical configuration of water quality.

6. CONCLUSIONS

The principal conclusions are as follows.
1) The meteorological changes giving rise to the external forces (wind, and water level difference between the waters) generating the flows involve combinations of atmospheric pressures and wind direction at times when strong winds occur. They are of 2 kinds: a change from northeast to east wind occurring at times of high atmospheric pressure, and a change from east wind to strong west wind occurring together with the coming or passing of low atmospheric pressure.
2) As regards the characteristics of the lake-flows generated by the external forces: Flow in the direction linking the Nakaura Gate with Lake Shinji predominates in the inflow/outflow of seawater and Lake Shinji water due to water level differences between the waters resulting from atmospheric pressure changes. Yonago Bay is close to stagnant but wind-driven currents produced by strong winds increase its slow water replacement rate.
3) As regards the effects of flows on the water quality distribution: One such effect is produced by seawater inflow when low atmospheric pressure comes to the lake. In calm weather oxygen consumption is continuously in progress in the lower layer of Yonago Bay, resulting in an anoxic state in that layer. This anoxic state is however temporarily alleviated when such seawater inflow produced by low atmospheric pressure reaches the extremities of Yonago Bay. Further, inflow of seawater or river water produced by meteorological changes produces the effect of altering the lake's vertical density distribution, which subsequently exerts influences on its flow mobility.

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