CHAPTER 249

Study of Upwelling Phenomena of Anoxic Water 'A-oshio'

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ABSTRACT

The field data analyses and both two dimensional hydraulic and numerical experiments were performed to understand the physical features of the 'A-oshio' appearance in Tokyo Bay. Lots of field observations show that the 'A-oshio' phenomenon may be intimately related with the upwelling of the anoxic water in the bottom layer under the wind blowing towards off-shore for more than a couple of days. Therefore, the two-dimensional hydraulic and numerical experiments are performed for clarifying the wind-induced upwelling and mixing processes in a two-layered stratified flow system with a downstream open boundary, which is exposed to wind stresses at the water surface. In these experiments, the upwelling phenomena are found to occur only in the range of $Ri_* \times (2h_1/L) \leq 12.0$. The numerical experiments are quantitatively confirmed to show a good agreement with the results of field observation and hydraulic experiments.

INTRODUCTION

Recently, unique phenomena have been frequently observed in the head of Tokyo Bay in Japan during late summer to autumn. The color of surface water changes to milky-blue or milky-green when the northeast wind blows during a couple of days. Fisheries have been damaged by lots of perish of fishes and shellfishes. Such phenomena are called 'A-oshio' regarding to the color of water. 'A-o' means blue and 'shio' does a tide in Japanese.

According to lots of field observations, an 'A-oshio' phenomenon is considered to be accompanied by the upwelling of anoxic bottom water. When an off-shore wind blows, the surface water is transported towards off-shore induced

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by wind-driven surface stress ; hence, the bottom water moves upwards along a sea bed to make compensation for the transported surface water. The color of 'A-oshio' water is considered to be changed by the oxidation of sulfide included in the upwelled bottom water which becomes anoxic during summer under no vertical mixing due to the strong stratification and the biological activities. The 'A-oshio' phenomenon, therefore, is fundamentally different from 'Akashio' (a red tide in Japanese), which is biologically induced by the excess propagation of plankton. The 'A-oshio' phenomena, therefore, can be treated as the upwelling of anoxic bottom water from the physical view point and the oxidation from the chemical one.

Even though many field observations have carried out, the detailed mechanism of 'A-oshio' appearance has been left unsolved. The reason is that only several points-measurements are not sufficient to obtain the understanding of overall physical features. The present paper, therefore, is to examine the physical mechanism regarding to 'A-oshio' appearance.

First of all, the field data obtained in Tokyo Bay are analyzed to understand the physical characteristics during the 'A-oshio' appearance. Secondly, two-dimensional hydraulic and numerical experiments are carried out to clarify the interface movement and the upwelling phenomena in a two-layered stratified flow system exposed to wind stresses at the surface. A downstream condition is set to be opened in the similar sense as semi-enclosed coastal seas or small bays. There is few experiments with such a condition, although many experiments in an enclosed flume have been done for simulating the mixing processes occurred in the lakes or reservoir. The mixing process is unsteady and rapidly changed; hence the measurements in hydraulic experiments are too difficult. Therefore, the two dimensional numerical experiment with κ-ϵ turbulence model and non-hydrostatic assumption is also performed to support the physical understanding of 'A-oshio' in the quantitative sense.

FIELD OBSERVATION ABOUT 'A-OSHIO' IN TOKYO BAY

Previous Study About 'A-oshio' Phenomenon

Tokyo Bay is one of the highly eutrophicated bays in Japan. The topographical feature of Tokyo Bay is shown in Fig. 1. It has an area of 1200 km^2, and the average depth is about 17 m. The ratio of area less than 10 m depth against a total area is about 30%. The numbers of No.1 to No.13 as shown in Tokyo Bay indicate the location of observation stations conducted by The Environment Agency.

The bay is surrounded by metropolitan cities including Tokyo and many industrial factories where more than 24

million peoples live. A large amount of nutrients and organic matter have been drained into the bay. It is known that the eutrophic status of the bay is hypertrophic condition, and algal blooms have been occurred through a year. It makes the color of surface water change to reddish-brown, that is a red tide ('Akashio' in Japanese). The 'Akashio' recently tends to occur independent of season and worldwide coastal seas, especially in the urban coastal seas.

A shaded area shown in Fig.1 indicates the coastal waters where the 'A-oshio' has often appeared. In summer, an amount of discharged river water and the heat transfer through the sea surface make the stratification strength, which results in damping the vertical transfer of momentum and eutrophicated matters. The bottom water, hence, becomes anoxic due to the precipitation and the decomposition of organic matters produced by algal blooms and the hydrogen sulfide occurs in the bottom layer (Kakino (1986)).

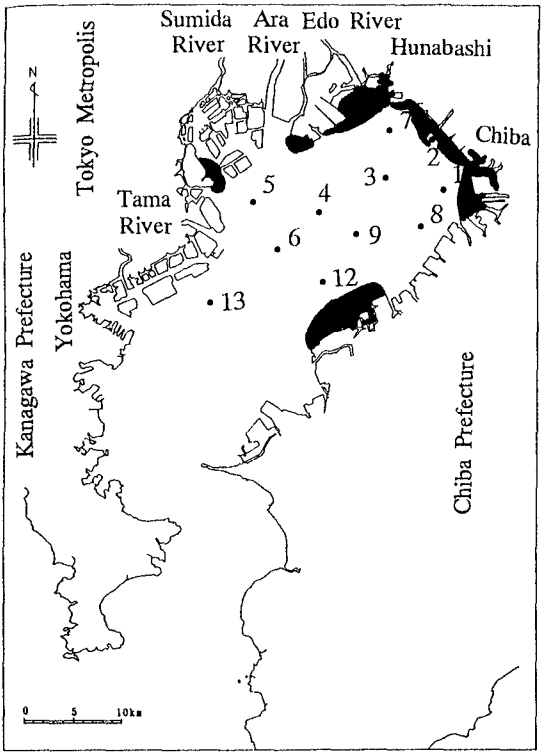


Figure 1. Topological feature of Tokyo Bay and observation stations. A shaded area indicates the coastal waters where 'A-oshio' has often appeared.

Figure 2 shows a photograph of the 'A-oshio' appearance observed on 8th September, 1988 in Hunabashi Port, which is located at the head of Tokyo Bay as shown in Fig. 1.

Table 1 shows the time variation of 'A-oshio' appearance, the perish of shellfishes and the production of a short-necked clam reported by Kakino(1986). For example, late in September 1985, 30,000 ton of short-necked clam perished which brought the economical damages about 3.6 billion yen for fisheries.

Tominaga et al. (1988) reported the presence of colloidal particles of sulfur in the boundary layer between surface oxygen-sufficient water and anoxic bottom water at the head of Tokyo Bay.

Figure 2. 'A-oshio' appeared in Funabashi Port located in the head of Tokyo Bay. This photograph was taken from air on 8th September, 1988.

Oceanographical and Meteorological Features of 'A-oshio'

The Environment Agency has conducted field measurements for 7 years from 1988 in order to clarify the mechanism of 'Aoshio' from the multi-view points such as physical, chemical, biological and ecological aspects. During the field observations from 22th July to 11th August, 1992, 'A-oshio' appeared during 3rd August to 6th August.

Figure 3 shows the time variation of wind velocity and direction observed by the Chiba Meteorological Observatory. It is of great interest that before the 'A-oshio' appearance the southwest (on-shore) wind stronger than 5

Table 1. Field data of 'A-oshio', perish of shellfishes and the year production of clam (Kakino; 1986)

Year	Month. Day	Appearance of Aoshio etc.	Influence to the Shellfish	Production of Clam (ton)
1975	late in September	Aoshio (middle or large scale)	partly perish of clam	22,099
1976				7,238
1977	8.10~8.16	Aoshio(large scale)	perish of clam	12,843
1978	7. 8~7.10	Aoshio(middle scale)	mass perish of clam	8,620
1979	6.13 7.16~7.17 8.14 9.30	Aoshio(small scale) Aoshio(middle scale) Aoshio(middle scale) Aoshio(middle scale)	negligible negligible negligible negligible	2,610
1980	8. 2~8. 5 8.26 9. 9 9.19 9.25	Aoshio(large scale) Aoshio(small scale) Aoshio(small scale) Aoshio(small scale) Aoshio(small scale)	negligible negligible negligible a few perish of clam negligible	6,979
1981	late in July	anoxic water	perish of clam	5,907
1982	7.27~7.29 bearly in August	Aoshio(large scale) turbid water	a few perish of clam perish of clam	3,843
1983	6. 8 6.18	Aoshio(small scale) Aoshio(small scale)	negligible negligible	2,972
1984				7,349
1985	6. 8.20 late in September	Aoshio(small scale) Aoshio(middle scale) Aoshio(large scale)	negligible negligible mass perish of clam (secondly water depravation)	

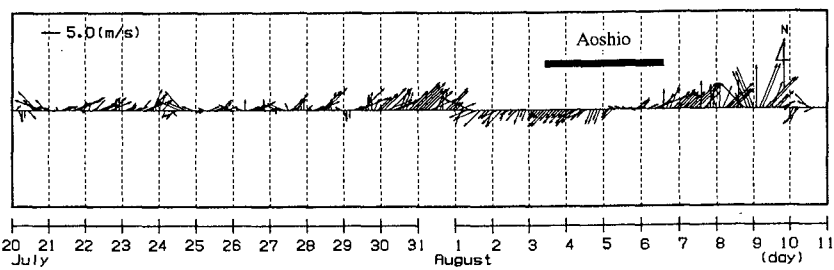


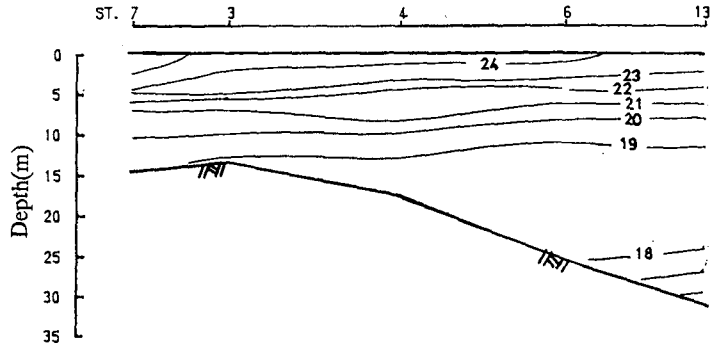
Figure 3. Time variation of wind velocity and direction at the Chiba Meteorological Observatory

m/s kept blowing from 30th July to 1st August, and in succession the northeast (off-shore) wind blew. The northeast or east northeast wind stronger than 5 m/s kept blowing from 1st August. The former event may play a role to make the stratification strengthen. Other observations show that there is heavy rainfall before the 'A-oshio' appearance. The authors point out that such events of south-west wind blowing or lots of rainfall are of fundamental importance in considering the mechanism of 'A-oshio' appearance. Namely, strong stratification is a necessary condition for 'A-oshio' appearance.

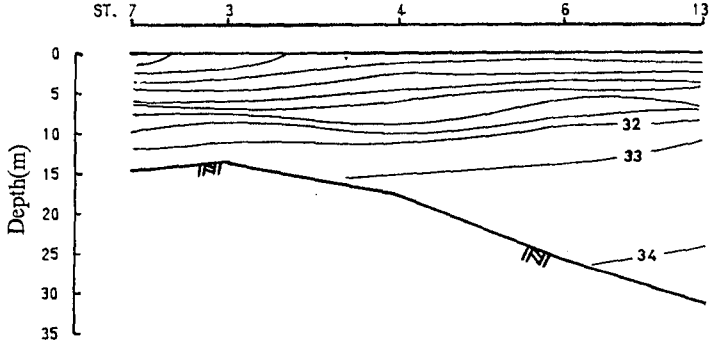
Figures 4 and 5 show the distributions of water temperature, salinity and dissolved oxygen (DO) along the vertical section from the stations No.7 to No.13, the location of which is shown in Fig.1. The measurements were conducted on 22th July and 4th August. The thermal stratification remarkably develops depending on heat flux through water surface in summer. The contours of temperature and salinity show a layered structure of 24 °C to 18 °C and of 26 ‰ to 34 ‰, respectively. The difference in water temperature between the upper and the lower layers is about 6 °C on 22th July. The contour lines of DO also show horizontal in the upper layer and the anoxic water less than 5 mg/l exists deeper than 5 m depth on 22th July. The contours of 0 and 1 mg/l DO, however, indicate no stratification but a curious tendency. It may be induced by the error in measurement at station No.6. It is found from these distributions except the profile of DO that the strong stratification develops on 22th July.

On the other hand, on 4th August, the contours of 22 °C temperature, 31.5 ‰ salinity and 4 mg/ℓ DO are upwelled to attain to water surface near No. 7 station. It is worth noting that the counter lines of 2 and 3 mg/ℓ DO tend to deepen gradually in the off-shore direction. Such a tendency is physically reasonable. If a wind blows off-shore in the long term, the water surface tends to lean upward in the same direction as wind-blowing, namely in the offshore direction in this case. And, the stratified interface leans downward in the offshore direction according to the balance of pressure. The 0 and 1 mg/ℓ DO contour lines is upwelled to -6 m depth at the station No. 7. As compared with Figs. 4 and 5, it is clarified that the upwelling of the hypolimnetic anoxic water was caused by the northeast wind blowing continuously for four days from 1st August.

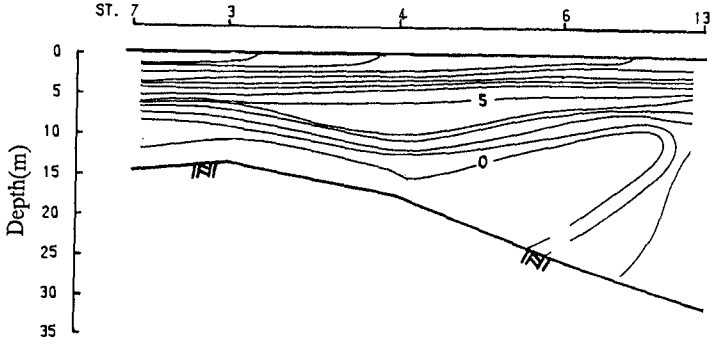
Joh (1989) pointed out that the formation of the anoxic water mass correlates well with the temperature difference between the surface and the bottom layers based on field data obtained in Osaka Bay. The same tendency was confirmed in Tokyo Bay by The Environment Agency (1991). It indicates that the stratification affects not only the upwelling phenomena but also the generation of anoxic water.



(a) Water Temperature (°C)



(b) Salinity (‰)



(c) DO (mg/ℓ)

Figure 4. Distributions of water temperature(°C), salinity (‰) and DO(mg/ℓ) on 22th July, 1992 along the vertical section from St.7 to St.13 as shown in Fig. 1

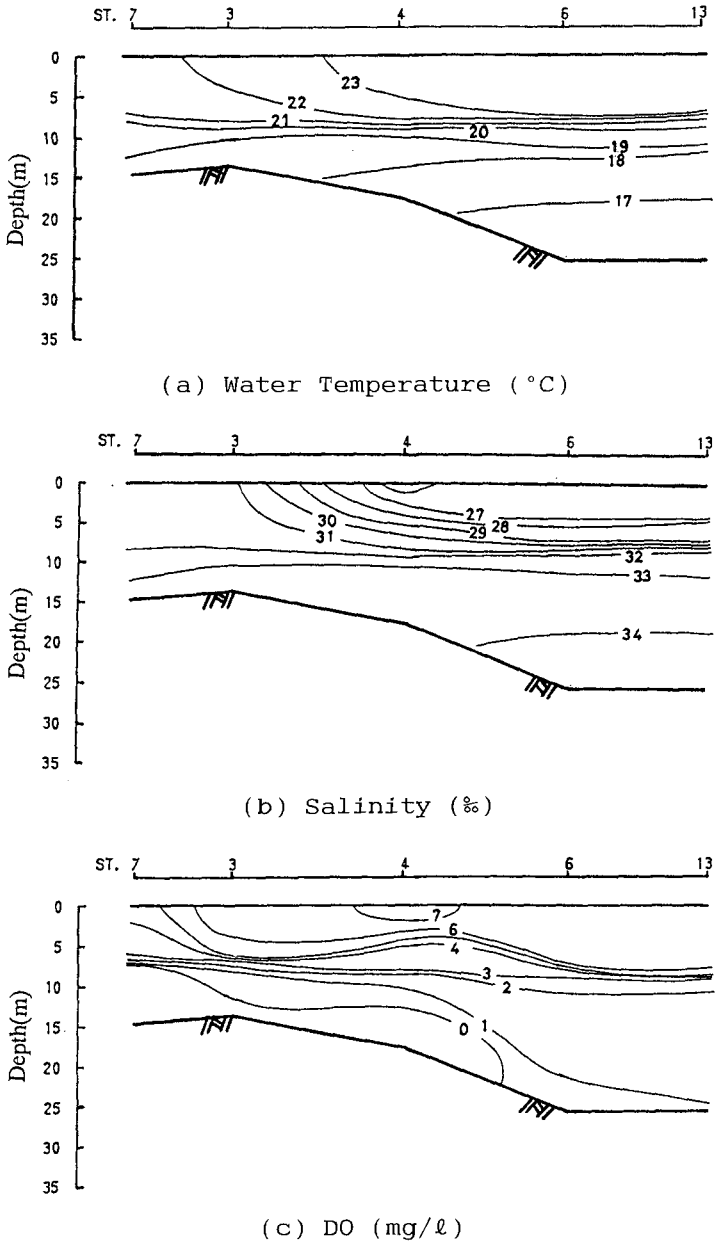


Figure 5. Distributions of water temperature(°C), salinity (‰) and DO (mg/ℓ) on 4th August, 1992 along the vertical section from St.7 to St.13 as shown in Fig. 1

Based on the above-discussed field observations, a conceptual sketch of 'A-oshio' appearance can be drawn as Fig. 6.

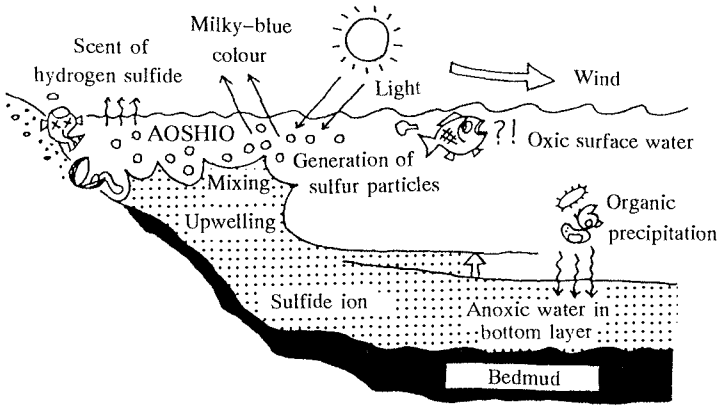


Figure 6. Conceptual sketch of 'A-oshio' appearance

TWO DIMENSIONAL HYDRAULIC AND NUMERICAL EXPERIMENTS

Both hydraulic and numerical experiments are carried out in the present study. It is because only the hydraulic experiments are too difficult to quantitatively understand the unsteady phenomena such as the flow movement and strong mixing processes at the stratified interface.

Setup of Hydraulic Experiments

The experimental facility is shown in Fig. 7. It is composed of a main test flume (an acrylic flume of 600 cm length, 15 cm width and 30 cm depth), a wind tunnel (6 shuttlecock of 100 cm and the maximum rotation of 1500 rpm) and a large tank (300 cm length, 200 cm width and 25 cm depth) connecting with the downstream end of the test flume. The experiments were conducted in a stratified flow system with two layers of fresh water and salt water. The degree of stratification depends on the density of salt water. The initial thickness of the upper layer was always kept to be 10 cm. Mean velocities in the upper layer were measured using a LDV (Laser Doppler Velocimetry) and the analyses of tracer trajectories. Two 35 mm cameras and a video camera were used to observe the movement of the stratified interface and its mixing process. The density profiles were measured using a salinometer.

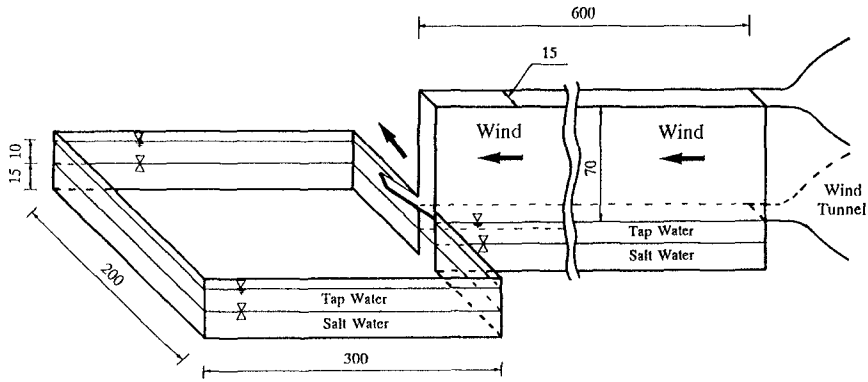


Figure 7. Experimental facility of two-layer stratified flow system with wind tunnel

Setup of Numerical Experiments

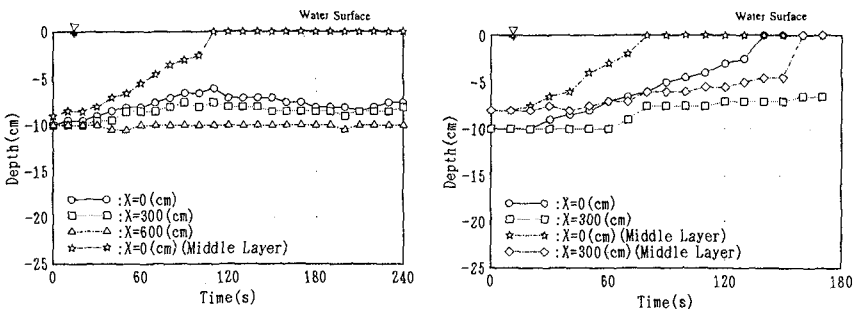
A two-dimensional numerical experiment was also performed under the same physical conditions as hydraulic experiments. The governing equations were composed of the continuity equation, the longitudinal and vertical momentum equations and the diffusion equation of density. The non-hydrostatic model of SIMPLE method (Patankar, 1980) was used. The κ-ϵ model was used to represent turbulent transfer of momentum and scalar quantities. The standard values were used for the unknown constant values including the κ-ϵ equation. The resolution was 7.5 cm and 1 cm in the longitudinal and vertical directions, respectively. The hydraulic conditions are as follows; the friction velocity due to the wind stress at the water surface u_* = 6.5 cm/s, the upper layer depth h_1 = 10 cm, and the range of Ri_* = 23~1090 and $Ri_* \times (2h_1/L)$ = 0.76 ~ 36.3 depending on the density difference, in which L is the length of flume, in other words, the distance of the wind blowing.

EXPERIMENTAL RESULTS AND DISCUSSION

Spigel and Imberger(1980) proposed that the mixed-layer dynamics in lakes or reservoirs could be classified into four regimes in terms of Wedderburn number defined as We = $Ri_* \times (2h_1/L)$. It means the product of the Richardson number and the aspect ratio of the two-layered stratified flow system. Furthermore, Thompson and Imberger (1980) indicated on the basis of numerical experiments that the stratified interface could be upwelled to attain the water surface in the case of the Wedderburn numbers 'We' less than 3 or 4. Since the present experiment with an open downstream condition is a little different from the

experiment of Imberger et al., $Ri_* \times (2h_1/L)$ is used as the dimensionless parameter.

The time variation of observed density interface is shown in Fig. 8 in the case of $Ri_* \times (2h_1/L) = 36.3$ and 12.0. The observation points are the upstream, the center and the downstream of hydraulic flume. In these figures, the axis of ordinates indicates the water depth, while the axis of abscissas does the passing time after the wind blowing starts. That is, the water depth $h_1 = -10$ cm indicates the initial position of the interface. The middle layer is defined as the water mass mixed with fresh water and salt water, which usually lies upon the density interface. In the case of $Ri_* \times (2h_1/L) = 36.3$, the stratification due to density difference is so completely superior to the wind shear during the experiments that the vertical mixing and the variation of the density interface hardly occur during the wind blowing. On the other hand, in the case of $Ri_* \times (2h_1/L) = 12.0$, it is observed that the mixed layer at the upstream end upwells after about 70 seconds, and the density interface does after 110 seconds.

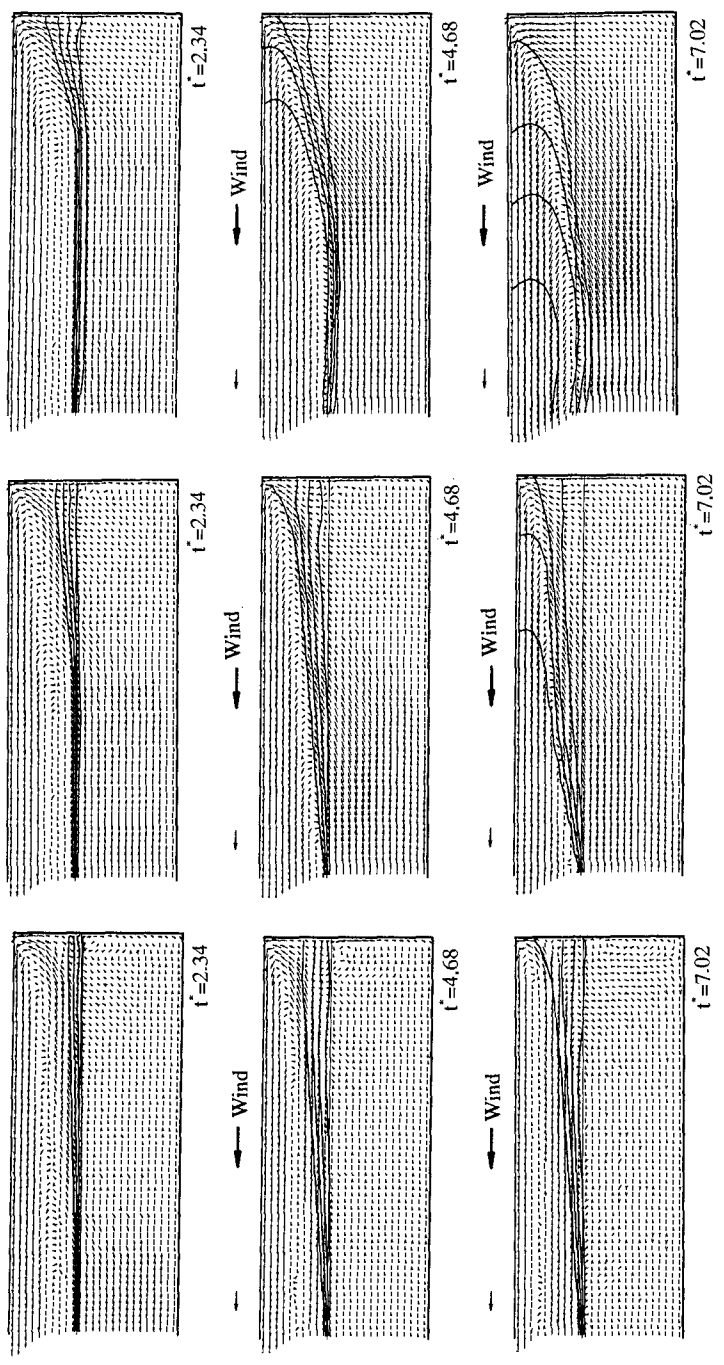


(a) $Ri_* \times (2h_1/L) = 36.3$ (b) $Ri_* \times (2h_1/L) = 12.0$

Figure 8. Time variation of density interface during wind blowing

Figure 9 shows the time variation of velocity and density difference fields obtained by numerical experiments in the flume with the open downstream condition. The values of $Ri_* \times (2h_1/L)$ are 36.3, 12.0 and 3.1. And the value of t^* shown in the figures is the dimensionless passing time after the wind blowing, which is defined as $t^* = tu_*/h_1$. The density difference between fresh water and salt water are plotted every 20% from 10% by the contour lines.

It was confirmed by authors' experiments(1994) with a closed downstream condition that the results of numerical experiments are in a good agreement with those of hydraulic experiments. In the case of an open downstream bound-

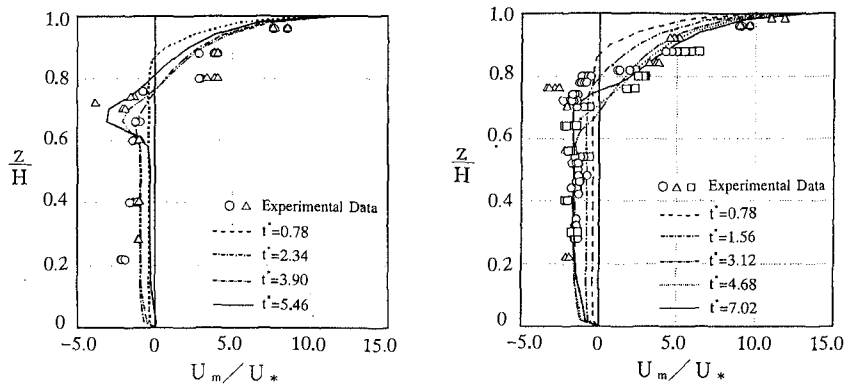


(a) $Ri_* \times (2h_1/L) = 36.3$ (b) $Ri_* \times (2h_1/L) = 12.0$ (c) $Ri_* \times (2h_1/L) = 3.1$

Figure 9. Effects of stratification on the distributions of velocity and density difference fields in a two-layered stratified flume with an open downstream condition

ary condition, vertical circulation in the upper layer of the flume is not observed. The density interface upwells at the upstream side and the mixing occurs in the same manner as the closed flume experiments in cases of larger Wedderburn number. (See; Yoon et al.(1993)) On the basis of both hydraulic and numerical experiments, it is found that the upwelling of density interface at the upstream end occurs in the range of $Ri_*\times(2h_1/L)$ less than 12.0. The deepening of density interface is observed only for the case of weakly stratification, $Ri_*\times(2h_1/L)$ = 3.1. In the present computation, the vertical position of stratified interface is postulated to be fixed as h_1 = -10 cm and the gradients of all hydraulic variables are constant at the downstream condition. Therefore, when the entrained volume into the upper layer is not balanced with the compensated one, which is inflowed in the lower layer from the connected large tank, the stratified interface is possible to deepen with time. It is not sure whether the deepening phenomena is caused by the postulated downstream condition or not, but it may be one of the reason of the deepening.

Figure 10 shows the comparison of computed vertical profiles of mean velocity with observed ones in the case of $Ri_*\times(2h_1/L)$ = 36.3 and 12.0. The computed mean velocity gives a good agreement with measured ones at the middle section of the flume. It may be suggested from this figure that the upper layer flows in the same direction as the wind blowing, while the lower layer flows in the reverse direction in order to compensate the entrained volume of the lower layer to the upper layer.



(a) $Ri_*\times(2h_1/L)$=36.3 (b) $Ri_*\times(2h_1/L)$=12.0

Figure 10. Comparison of computed vertical velocity profiles with observed ones

APPLICATION TO NUMERICAL EXPERIMENTS TO TOKYO BAY

It is easy on the basis of above discussion to evaluate whether the 'A-oshio' appears or not in the head of Tokyo Bay by the calculation of $Ri_* \times (2h_1/L)$ based on field data obtained. Table 2 shows the observed hydraulic values during 'A-oshio' appearance in Tokyo Bay. $\Delta\rho$ means the difference in density between the upper and the lower layers, h_1 ; thickness of the upper layer, W_{10} ; wind velocity at 10m upper from water surface, L ; longitudinal length of Tokyo Bay and T_m ; the calculated time for upwelling of density interface to water surface.

According to Table 2, it is confirmed that the 'A-oshio' phenomena, namely the upwelling of anoxic water in the lower layer, would occur in the range of $Ri_* \times (2h_1/L)$ less than 10.0 in the limits of obtained field data. The values are within the computation criterion value of $Ri_* \times (2h_1/L) = 12.0$. As shown in Table 2, the condition of 'A-oshio' appearance is that the wind of mean velocity over 4 m/s blows continuously for more than two or three days. It shows a good agreement with the previously observed results during 'Aoshio' appearance, too.

Table 2. The values of $Ri_* \times (2h_1/L)$ during 'A-oshio' appearance in Tokyo Bay

Observed Date	$\Delta\rho$ (kg/m^3)	h_1 (m)	W_{10} (m/s)	Ri_*	$\frac{2h_1 Ri_*}{L}$	Tm (hr)
16-17, July, 1979	4.0	10.0	3.3	25,000	10.0	49.3
20-21, Aug, 1985	10.0	7.5	4.2	28,940	8.7	31.3
5-6, June, 1986	4.0	7.5	3.0	22,680	6.8	38.4

Where, $\Delta\rho$:difference of density between upper layer and lower one, h_1 :depth of upper layer, Ri_* :Richardson number, L :longitudinal length of Tokyo Bay, Tm:time for upwelling of density interface to water surface

CONCLUSIONS

The data analyses of many field observations and the two dimensional hydraulic and numerical experiments were conducted in order to make clear the hydraulic conditions of 'A-oshio' appearance in Tokyo Bay. The following conclusions can be obtained.

(1) 'A-oshio' phenomena can be treated as the upwelling phenomena of the anoxic water in the bottom layer under the wind blowing towards offshore for more than a couple of days based on lots of field observations.
(2) In the two dimensional hydraulic and numerical experiments, the upwelling phenomena are found to occur only in the range of $Ri_* \times (2h_1/L) < 12.0$.
(3) The results of numerical experiments are also confirmed to agree well with those of hydraulic experiments.

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